Energy Technology Perspectives 2020

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Energy Technology Perspectives 2020

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Foreword

Technology will largely determine our energy future. The International Energy Agency (IEA) has long been cognizant of this, which is why for more than a decade we have produced the *Energy Technologies Perspectives* (*ETP*) series to help inform policy makers as they plan for the sustainable and resilient energy systems that people and businesses will need in the years to come.

When I became Executive Director of the IEA in late 2015, it was clear to me that the ETP was in need of a revamp to increase its relevance for decision makers in government and industry. My objective was to prepare "a global guidebook on clean energy technologies" for policy makers and others seeking to navigate the fast-evolving technological developments across a wide range of energy-related sectors. With the publication of this report, *Energy Technologies Perspectives* 2020, I believe we have come close to reaching that objective.

This report is an essential contribution to the global conversation on energy. As the report's rigorous analysis makes clear, achieving international climate goals hinges on dramatically scaling up clean energy technologies to reduce greenhouse gas emissions. And having those technologies ready in time hinges on a rapid acceleration in innovation. In the *ETP Special Report on Clean Energy Innovation* that was published in July, we examined the innovation element of that challenge. This report, *ETP-2020*, gives the full picture, analysing the major energy technology challenge the world faces and identifying the needs and opportunities that result from it.

Today, I am increasingly optimistic about the world's clean energy future, despite the grave challenges we face. *ETP-2020* shows that we know what needs to be done to develop and deploy the technologies that can put emissions on a sustainable path. The spectacular success of solar PV in becoming the cheapest source of power in many economies and the impressive rise of offshore wind demonstrate the ability of clean energy technologies to break through if governments put in place the right policies to support their expansion.

At the same time, more and more governments around the world are backing clean energy technologies as part of their economic recovery plans in response to the Covid-19 crisis – as was made clear by many of the 40 Ministers who attended the IEA Clean Energy Transitions Summit on 9 July 2020. The private sector is also upping its game, with some oil and gas majors betting their futures on becoming lower-carbon energy companies and top information technology companies putting increasing resources into renewables and energy storage. Moreover, investments in

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clean energy projects can benefit from the extended period of extremely low interest rates in some regions that appears likely following the massive easing of monetary policy by central banks in response to the Covid-19 crisis.

As the ETP analysis underscores, energy innovation will be crucial. Despite the disruption and uncertainty caused by the pandemic, I see reason for optimism there, too. Investment in clean energy start-ups by venture capital funds and companies rose to a new record in 2019. And governments and businesses are finally putting serious resources into the clean energy potential of hydrogen, which this report makes clear will be critical for reaching net-zero emissions.

However, my optimism should not be mistaken for naivety. Even if these encouraging trends continue, there are significant challenges to overcome. For instance, more work needs to go into mapping out pathways for fair and inclusive clean energy transitions for all parts of the world. Moreover, huge portions of the global energy sector are yet to make reducing their emissions a top priority.

The major challenge studied in depth in this report is how to tackle emissions from the vast amount of existing energy-related infrastructure around the world. The enormous fleets of inefficient coal plants, steel foundries, chemical facilities and cement factories – many of them recently built – are set to produce enough emissions in the coming decades to put international climate goals out of reach. But, as *ETP-2020* shows, we can develop the technologies to address this through smart policies and investments today.

The transformation of ETP has been three years in the making and has involved a tremendous amount of hard work from the team behind it. I would particularly like to thank Timur Gül for leading the overhaul of the series and his team for the research, modelling and writing that has produced these important reports. I look forward to many more ETP publications full of valuable insights and guidance in the years to come.

Dr. Fatih Birol

Executive Director

International Energy Agency

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Executive summary

Achieving our energy and climate goals demands a dramatic scaling up of clean energy technologies

To avoid the worst consequences of climate change, the global energy system must rapidly reduce its emissions. Calls to reduce global greenhouse gas emissions are growing louder every year, but emissions remain at unsustainably high levels. International climate goals call for emissions to peak as soon as possible and then decline rapidly to reach net-zero in the second half of this century. The vast majority of global CO_2 emissions come from the energy sector, making clear the need for a cleaner energy system. Global CO_2 emissions are set to fall in 2020 because of the Covid-19 crisis, but without structural changes to the energy system, this decline will be only temporary.

Achieving net-zero emissions requires a radical transformation in the way we supply, transform and use energy. The rapid growth of wind, solar and electric cars has shown the potential of new clean energy technologies to bring down emissions. Net-zero emissions will require these technologies to be deployed on a far greater scale, in tandem with the development and massive rollout of many other clean energy solutions that are currently at an earlier stage of development, such as numerous applications of hydrogen and carbon capture. The IEA's Sustainable Development Scenario – a roadmap for meeting international climate and energy goals – brings the global energy system to net-zero emissions by 2070, incorporating aspects of behavioural change alongside a profound transformation in energy system technology and infrastructure.

This report analyses over 800 technology options to examine what would need to happen for the world to reach net-zero emissions by 2050. The report focuses primarily on the Sustainable Development Scenario, but it also includes a complementary Faster Innovation Case that explores the technology implications of reaching net-zero emissions globally by 2050. The analysis seeks to assess the challenges and opportunities associated with a rapid, clean energy transition. The report covers all areas of the energy system, from fuel transformation and power generation to aviation and steel production.

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Transforming the power sector alone would only get the world one-third of the way to net-zero emissions

Many governments have ambitious plans for reducing emissions from the energy sector. Some governments have even put net-zero ambitions into law or proposed legislation, while others are discussing their own net-zero strategies. Many companies have also announced carbon-neutral targets. The success of renewable power technologies gives governments and businesses some cause for optimism. But reaching these targets will require devoting far more attention to the transport, industry and buildings sectors, which today account for more than 55% of CO_2 emissions from the energy system.

Spreading the use of electricity into more parts of the economy is the single largest contributor to reaching net-zero emissions. In the Sustainable Development Scenario, final electricity demand more than doubles. This growth is driven by using electricity to power cars, buses and trucks; to produce recycled metals and provide heat for industry; and to supply the energy needed for heating, cooking and other appliances in buildings.

Reaching net-zero emissions in 2050 would require a much more rapid deployment of low-carbon power generation. In the Faster Innovation Case, electricity generation would be about 2.5 times higher in 2050 than it is today, requiring a rate of growth equivalent to adding the entire US power sector every three years. Annual additions of renewable electricity capacity, meanwhile, would need to average around four times the current record, which was reached in 2019.

Electricity cannot decarbonise entire economies alone

Hydrogen extends electricity's reach. On top of the surging demand for electricity from across different parts of the economy, a large amount of additional generation is needed for low-carbon hydrogen. The global capacity of electrolysers, which produce hydrogen from water and electricity, expands to 3 300 GW in the Sustainable Development Scenario, from 0.2 GW today. In order to produce the low-carbon hydrogen required to reach net-zero emissions, these electrolysers would consume twice the amount of electricity the People's Republic of China generates today. This hydrogen forms a bridge between the power sector and industries where the direct use of electricity would be challenging, such as in the production of steel from iron ore or fuelling large ships.

Carbon capture and bioenergy play multifaceted roles. Capturing CO_2 emissions in order to use them sustainably or store them (known as CCUS)[1] is a crucial technology

[1] Our forthcoming *ETP Special Report on CCUS* provides our most in-depth look yet at this critical technology family and its role in reaching net-zero emissions.

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for reaching net-zero emissions. In the Sustainable Development Scenario, CCUS is employed in the production of synthetic low-carbon fuels and to remove CO_2 from the atmosphere. It is also vital for producing some of the low-carbon hydrogen that is needed to reach net-zero emissions, mostly in regions with low-cost natural gas resources and available CO_2 storage. At the same time, the use of modern bioenergy triples from today's levels. It is used to directly replace fossil fuels (e.g. biofuels for transport) or to offset emissions indirectly through its combined use with CCUS.

A secure and sustainable energy system with net-zero emissions results in a new generation of major fuels. The security of today's global energy system is underpinned in large part by mature global markets in three key fuels – coal, oil and natural gas – which together account for about 70% of global final energy demand. Electricity, hydrogen, synthetic fuels and bioenergy end up accounting for a similar share of demand in the Sustainable Development Scenario as fossil fuels do today.

The clean energy technologies we will need tomorrow hinge on innovation today

Quicker progress towards net-zero emissions will depend on faster innovation in electrification, hydrogen, bioenergy and CCUS. Just over one-third of the cumulative emissions reductions in the Sustainable Development Scenario stem from technologies that are not commercially available today. In the Faster Innovation Case, this share rises to half. Thirty-five percent of the additional decarbonisation efforts in the Faster Innovation Case come from increased electrification, with around 25% coming from CCUS, around 20% from bioenergy, and around 5% from hydrogen.

Long-distance transport and heavy industry are home to the hardest emissions to reduce. Energy efficiency, material efficiency and avoided transportation demand (e.g. substituting personal car travel with walking or cycling) all play an important role in reducing emissions in long-distance transport and heavy industries. But nearly 60% of cumulative emissions reductions for these sectors in the Sustainable Development Scenario come from technologies that are only at demonstration and prototype stages today. Hydrogen and CCUS account for around half of cumulative emissions reductions in the steel, cement and chemicals sectors. In the trucking, shipping and aviation sectors, the use of alternative fuels – hydrogen, synthetic fuels and biofuels – ranges between 55% and 80%. Highly competitive global markets, the long lifetime of existing assets, and rapidly increasing demand in certain areas further complicate efforts to reduce emissions in these challenging sectors. Fortunately, the engineering skills and knowledge these sectors possess today are an excellent starting point for commercialising the technologies required for tackling these challenges.

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Emissions from existing assets are a pivotal challenge

Power and heavy industry together account for about 60% of emissions today from existing energy infrastructure, climbing to nearly 100% in 2050 if no action is taken. Reaching net-zero will depend on how we manage the emissions challenge presented by these sectors' long-lasting assets, many of which were recently built in Asian economies and could operate for decades to come. The situation underscores the need for hydrogen and CCUS technologies. Ensuring that new clean energy technologies are available in time for key investment decisions will be critical. In heavy industries, for example, **s**trategically timed investments could help avoid around 40% of cumulative emissions from existing infrastructure in these sectors.

Governments will need to play the decisive role

While markets are vital for mobilising capital and catalysing innovation, they will not deliver net-zero emissions on their own. Governments have an outsized role to play in supporting transitions towards net-zero emissions. Long-term visions need to be backed up by detailed clean energy strategies involving measures that are tailored to local infrastructure and technology needs. Effective policy toolkits must address five core areas:

- Tackle emissions from existing assets
- Strengthen markets for technologies at an early stage of adoption
- Develop and upgrade infrastructure that enables technology deployment
- Boost support for research, development and demonstration
- Expand international technology collaboration.

Economic stimulus measures in response to the Covid-19 crisis offer a key opportunity to take urgent action that could boost the economy while supporting clean energy and climate goals, including in the five areas above.

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Introduction

Objective

The *Energy Technology Perspectives (ETP)* series has been informing the global energy and environment debate since 2006. Meeting the policy goals of energy security, economic development and environmental sustainability can only be achieved through energy technology development and innovation. Understanding the opportunities and challenges associated with existing, new and emerging energy technologies is critical to improving policy making to meet those goals.

A cleaner and more secure energy sector requires the rapid uptake and use of a wide range of technologies, some of which are still at an early stage of commercial development or deployment, or still at the prototype stage. But technological change takes time: for example, solar photovoltaics (PV) and batteries took decades to be commercialised and become economically competitive. Moreover the evolution of existing and emerging technologies in terms of technical performance and cost is inherently uncertain – the success of PV and batteries was far from assured when they were developed and launched – and that uncertainty increases as we peer further into the future.

The primary purpose of this edition of the *ETP* is to help decision makers in government and industry to meet the challenges of a cost-effective transition to a clean energy system with net-zero emissions, while enhancing energy security and ensuring access to modern energy services for all. *ETP* has evolved to improve its usefulness and relevance; it focuses throughout on exploring the opportunities and risks that surround the scaling up of clean energy technologies in the years ahead. It sets out where the key technologies stand today, their potential for wider deployment to meet energy policy goals, and the opportunities for and barriers to developing selected new technologies in the coming decades. It also looks at how past experiences can help governments design more effective policies to encourage innovation from research and development to market deployment. In addition, using a systems approach it looks at what governments and stakeholders need to do to accelerate the development and deployment of clean energy technologies with a particular focus on those that address multiple policy objectives.

What we mean by clean energy technology

Energy technology refers to the combination of hardware, techniques, skills, methods and processes used in the production of energy and the provision of energy services, i.e. the way we go about producing, transforming, storing, transporting and using energy. It follows that technological change in the energy sector refers to

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changes over time in the types of technology that are used at various stages of the energy supply chain. Technological progress results from investment in basic and applied research, and from the development, demonstration and commercialisation of new technologies (see Chapter 6 for a detailed discussion of this innovation process and how to accelerate it).

Clean energy technology comprises those technologies that result in minimal or zero emissions of carbon dioxide (CO_2) and pollutants. For the purposes of this report, clean energy technology refers to low-carbon technologies which do not involve the production or transformation of fossil fuels – coal, oil and natural gas – unless they are accompanied by carbon capture, utilisation and storage and other anti-pollution measures.

The International Energy Agency (IEA) defines low-carbon energy technologies as: renewable energy sources (renewables[1]), nuclear power; carbon capture, utilisation and storage (CCUS); hydrogen derived from low-carbon energy sources; technologies that improve the efficiency of energy transformation (e.g. switching from incandescent to light-emitting diode [LED] lighting); other non-fossil power and storage options; and cross-cutting technologies that result in minimal emissions of CO_2 and pollution. Clean energy sources are growing in importance, but they still account for only around one-fifth of energy supply worldwide. In other words, the energy system in its present state is unsustainable.

Scope and analytical approach

The analysis in this report is underpinned by global projections of clean energy technologies derived from the IEA's in-house *ETP* model, a quantitative framework composed of four interlinked modules covering energy supply (production and transformation), and energy use in the buildings, industry and transport sectors (see online documentation of the ETP Model).[2] Depending on the sector, the modelling framework includes 28 to 40 world regions or countries. The projection period in this report is 2019 to 2070 – ten years beyond the end-point of the previous *ETP* in 2017. The most recent year of complete historical data is 2019, though preliminary data are available for some countries and sectors for the first-quarter of 2020 which accordingly have been used to adjust the projections.

We employ two scenarios to describe possible energy technology pathways over the next half century. The **Sustainable Development Scenario** – the focus in this report – sets out the major changes that would be required to reach the key energy-related

[1] Renewables include bioenergy, though this energy source is sometimes used unsustainably (e.g. if not entirely replaced with replanted biomass) and in an unhealthy manner (e.g. the indoor use of wood for cooking on an open stove).

[2] www.iea.org/reports/energy-technology-perspectives-2020/etp-model.

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goals of the United Nations Sustainable Development Agenda, including an early peak and rapid subsequent reductions in emissions in line with the Paris Agreement, universal access to modern energy by 2030 and a dramatic reduction in energy-related air pollution. The trajectory for emissions in the Sustainable Development Scenario is consistent with reaching global net-zero CO_2 emissions by around 2070.[3] The **Stated Policies Scenario** takes into account energy- and climate-related policy commitments already made or announced by countries, including the Nationally Determined Contributions under the Paris Agreement. The Stated Policies Scenario provides a baseline from which we assess the additional policy actions and measures needed to achieve the key energy and environmental objectives incorporated in the Sustainable Development Scenario.

Neither scenario should be considered a prediction or forecast. Rather the scenarios offer valuable insights of the impacts and trade-offs of different technology choices and policy targets and provides a quantitative approach to support decision making in the energy sector and strategic guidance on technology choices for governments and stakeholders. The *ETP* scenarios are broadly consistent with those presented in the 2019 edition of the IEA's flagship publication, *World Energy Outlook (WEO)*[4], however the time horizon is extended to 2070 to underpin a more technology focussed view of the energy system. As well, the *ETP* scenarios incorporate updated assumptions for gross domestic product (GDP) and energy prices which have been affected with the outbreak of the global Covid-19 pandemic.

This report draws on strategic discussions during an *ETP-2020* consultation meeting with high-level energy officials and experts from government, industry, financial institutions, academia and international organisations on 3 July 2019. In addition from insights, feedback and data obtained at two high-level workshops that the IEA organised in Paris on accelerating energy innovation (18 December 2019) and carbon capture, utilisation and storage (5 February 2020).[5] It also draws on information and views provided by those who work on the IEA's broad portfolio of Technology Collaboration Programmes, which bring together more than 6 000 experts from key companies and research institutions in 53 countries in order to accelerate energy technology innovation.

[3] An additional Faster Innovation Case in Chapter 6 explores the technology innovation needs for reaching net-zero emissions already in 2050.

[4] *WEO-2019* (IEA, 2019) was released in November 2019. For more details, see: www.iea.org/topics/world-energy-outlook.

[5] Information about these events can be found at www.iea.org/weo/events.

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Structure of the *ETP-2020*

Chapter 1 reviews the current status of clean energy technologies worldwide and puts the challenges ahead in context, setting out the urgent need to reduce emissions and improve air quality, assessing historic trends in energy technology and discussing the possible implications of the Covid-19 crisis for clean energy technology. It also assesses projected CO_2 emissions from existing energy assets, and their implications for long-term global emissions reductions.

Chapter 2 sets out the key projections for energy and CO_2 emissions in the Sustainable Development Scenario and describes how the energy sector will need to change relative to current trends in order to meet the energy-related United Nations Sustainable Development Goals. It details the technology pathways required to meet those goals, the central role that technologies such as electrification, hydrogen, CCUS and bioenergy could play in the energy transition to net-zero emissions and the current state of readiness of those technologies.

Chapter 3 provides a detailed overview of the technology opportunities in each energy sector stem for the transition to net-zero emissions. It sets out the structural changes required in the industry, transport and buildings sectors together with the developments needed to provide these end-use sectors with low-carbon fuels.

Chapters 4 and 5 delve more deeply into the technological needs in selected energy end-use sectors, sometimes referred to as "hard-to-abate", where cutting emissions substantially is likely to prove particularly difficult because technological solutions do not yet exist or are relatively costly. Many of these are in heavy industry (chemicals, steel and cement) and long-distance transport (maritime shipping, aviation and long-haul trucking). Both chapters identify the technological opportunities, costs and trade-offs involved in the selected areas to achieve net-zero emissions for the energy sector as a whole.

Chapter 6 takes a broad look at energy innovation, pinning down innovation needs in the Sustainable Development Scenario and assessing them relative to progress to date on clean energy innovation. It explores past experiences in bringing new energy technologies to market, identifies potential additional opportunities and looks at strategies for accelerating innovation in clean energy technology. We consider the potential of innovation to support a clean energy transition to net-zero emissions by 2050 in the Faster Innovation Case, which amongst others includes consideration of technologies that are today in the very early stages of development.

Chapter 7 sets out key recommendations for the development of long-term clean energy transition plans, including recommendations dealing with the management of existing CO_2-intensive energy assets, the creation of markets for clean energy technologies at an early stage of adoption, the development of priorities for new clean energy infrastructure and for the development and demonstration of clean energy technologies.

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Chapter 1. Clean energy technologies – the state of play

- The need for clean energy technology has never been more important. The way we currently produce and consume energy is unsustainable, and while technology is not the only ingredient to a cleaner energy future, there is no credible path to net-zero emissions without a significant and speedy ramping up of clean energy technologies across the entire energy sector.
- The carbon footprint of the global energy system has been reduced in waves driven by government policies. For instance, construction of nuclear reactors surged in the 1960s and 1970s, but slowed down thereafter. More recently wind and solar PV have seen rapid expansion, led by policy support in Europe, United States, the People's Republic of China ("China" hereafter) and India. The expansion of wind power is evidenced since the late 1990s and today accounts for over 5% of global power supply. Solar PV expansion was not too far behind and now accounts for about 2.5% of global power supply. Biofuels for transport has expanded steadily to reach 3% of global transport energy requirements today, mainly due to blending mandates and production targets in Brazil, United States and European Union.
- Clean energy technology progress, however, has been slow in end-use sectors. Energy efficiency has been the main means of moderating growth in CO_2 emissions in end-use sectors. Some progress has been made, notably in the development of electric cars, which accounted for 2.6% of global sales in 2019. The momentum for critical technologies such as hydrogen and CCUS is also increasing. If the world is to reach net-zero emissions this century, faster progress will be needed in end-use sectors, which accounted for 55% of energy and industry-related CO_2 emissions in 2019.
- Progress in deployment of clean energy technologies has been outpaced by overall energy demand growth. In 2019, CO_2 emissions from fossil fuel combustion reached more than 33 gigatonnes (Gt), a record high. Many existing energy assets are still young, particularly in Asia. Around 45% of installed fossil-fuelled power generation capacity in Southeast Asia was built within the last ten years, and 70% within the last 20 years. Much of the infrastructure for the production of steel, cement and chemicals is also relatively young, particularly in China. The global average age is 10-15 years, compared with a typical lifetime of 30 years for chemical plants and 40 years for steel and cement plants. Existing energy infrastructure could lead to nearly 750 $GtCO_2$ of additional emissions by 2070 if unchanged. This would exhaust the majority of the remaining CO_2 budget compatible with limiting the global temperature rise to "well below 2°C", let alone 1.5°C as set out in the Paris Agreement.

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Introduction

Tackling climate change, securing energy supplies and ensuring clean air and water for all require a transformation of the way we produce and consume energy. Accelerating the transition to clean energy technologies is central to that transformation in the face of persistent increases in energy demand. Fossil fuels continue to dominate world energy supply, despite the growing contributions of renewables and steady progress in making energy use more efficient. But there is still time to get back on track and meet key the energy-related UN Sustainable Development Goals by adopting the cleanest and most efficient technologies that are currently available without delay, and by developing new technologies.

Clean energy technology is a necessity

The need for clean energy technology has never been more important. The way we currently produce and consume energy is unsustainable and considered in the context of continuing economic growth and an increasing global population underlines the need for a sounder approach. Climate change caused by anthropogenic emissions of greenhouse gases is among the toughest challenges faced by humanity. The combustion of fossil fuels contributes around two-thirds of global greenhouse gas (GHG) emissions[1] and the bulk of CO_2 emissions, so the energy sector must be at the front line of efforts to tackle climate change. Rising fossil energy use in emerging economies is deteriorating air quality with serious consequences for public health.

It is unrealistic to expect humanity to slash its consumption of energy by simply going without energy services on a large scale. What is needed is a sustained and complete shift to clean energy technologies that provide the energy services we need but that do not emit GHG or pollute the air (or land and water). This shift also enhances energy security by reducing dependence on imported sources of energy over often vulnerable supply chains. This transition has been underway for decades, but has much further to go.

[1] The remaining one-third of GHG emissions are linked to CO_2 emissions from industrial processes and agriculture, forestry and other land use, as well as non-CO_2 emissions in the energy sector (mainly methane) and other sectors, such as agriculture.

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Box 1.1 What does the most recent climate change science tell us?

In late 2018, the Intergovernmental Panel on Climate Change (IPCC) published a special report on the impacts of global warming of 1.5 degrees Celsius (°C) above pre-industrial levels compared with an increase of 2°C, based on the assessment of the latest available scientific, technical and socio-economic literature (IPCC, 2018). The report finds, with a high degree of confidence, that human activity has already caused 0.8 to 1.2°C of warming, and that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. It warns that many of the physical impacts of climate change may escalate in a non-linear fashion as the global temperature rises: in other words, the effects of 2°C of warming are likely to be far worse than those of 1.5°C. It also underlines the urgency of the need for action: combined national efforts to reduce emissions so far fall far short of what is needed to be on track to limit global warming to 2°C, let alone 1.5°C.

Source: IPCC (2018).

Tackling the climate crisis

Climate scientists agree that there is a strong and incontrovertible link between global GHG emissions caused by human activity, their concentration in the atmosphere and average global air and sea temperatures. The global average annual concentration in the atmosphere of CO_2 – the most important anthropogenic greenhouse gas – reached 410 parts per million (ppm) in 2019, up 3 ppm (0.6%) on the previous year. This is a major increase from pre-industrial levels, which ranged between 180 and 280 ppm. These higher concentrations are responsible for increasing the global average temperature of the planet by about 1 degree Celsius, leading to an increase in global sea levels of about 20 centimetres, the melting of glaciers and reduced sea ice, along with broader changes in weather patterns. Increased CO_2 levels in the atmosphere dissolve into the upper ocean waters and are also causing the world's oceans to become more acidic.

Since the first United Nations conference on climate change in Rio de Janeiro in 1992, the global community has attempted to forge agreements on tackling climate change. The main forum for negotiation is a series of annual international governmental gatherings known as Conferences of the Parties (COP). The Paris Agreement reached at COP-21 in December 2015, which entered into force in November 2016, sets a target of limiting future increases in global temperature to "well below 2°C" above pre-industrial levels and calls for efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Article 4 of the Paris Agreement includes the aim of reaching a global peak in emissions of greenhouse

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gases "as soon as possible", recognising that this will take longer for emerging economies than for others, and making rapid reductions thereafter to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHG, i.e. net-zero emissions of GHG in the second half of this century.

Nationally Determined Contributions (NDCs) are at the heart of the Paris Agreement and will be critical to its success. NDCs embody efforts by each signatory country to reduce national emissions and adapt to the impacts of climate change. Article 4 requires each Party to prepare, communicate and maintain successive NDCs, including measures to mitigate domestic emissions, taking into account its domestic circumstances and capabilities. Together, these climate actions will determine whether the world achieves the long-term goals of the Paris Agreement, namely an early peak in emissions and net-zero GHG emissions in the second half of this century. At the time of writing, at least 122 national and regional jurisdictions, including the European Union, had set or were actively considering long-term net-zero emissions targets, in some cases for dates before 2050. These economies together accounted for 30% of global GDP and 20% of energy-related CO_2 emissions in 2019.

The four COPs since the Paris Agreement have focussed on specific climate-related problems, such as water scarcity and sustainability, and on the technical aspects of implementing various aspects of the Agreement. The remaining issue to be resolved relates to Article 6, which describes rules for a carbon market and other forms of international co-operation. COP-25 in Madrid in December 2019 failed to reach agreement on this matter. The 2020 COP was postponed due to the Covid pandemic and rescheduled for 2021 in Glasgow. COP-26 will also review progress in reaching the goals of the Paris Agreement, seek to ratchet up near-term efforts to curb GHG emissions and look to establish long-term plans for achieving net-zero emissions.

Clearing the air

The need for clean energy technology is not just about dealing with the climate crisis. Energy production and use is the leading source of air pollution caused by human activity. Air pollution has an enormous impact on public health: nine-out-of-ten people around the world breathe polluted air every day. This causes more than 5 million premature deaths each year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections. The total death toll is significantly higher than deaths from HIV/AIDS, tuberculosis and road injuries combined (3.7 million deaths). Outdoor (ambient) pollution is the biggest killer, accounting for 3 million premature deaths, but around 2.5 million also die prematurely from indoor air pollution from

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combustion of fuel for cooking and heating. The biggest impact is in emerging economies, where more than 2.6 billion people still do not have access to clean cooking (IEA, 2019a).

Most types of clean energy technology help to reduce air pollution as well as to cut GHG emissions. For example, power generation from nuclear or renewable energy sources (with the exception of bioenergy) do not emit GHG directly, and energy-efficient technologies can reduce pollution by decreasing the amount of fossil fuel inputs. In the case of CCUS, emissions of the main air pollutants – nitrogen oxides (NOx), sulphur dioxide (SO_2) and particulate matter (PM) – depend on the type of technology adopted and whether pollution control equipment is installed.

Enhancing energy security

Decarbonisation of the supply mix could also enhance energy security by reducing dependence on imported oil and gas that can be prone to disruption and price volatility. Reduced demand for fossil fuels resulting from increased reliance on local clean energy sources such as wind and solar power, as well as from more efficient use of energy, could also relieve pressure on energy prices, making energy more affordable for households and businesses. The long-term trend of electrification and the rising share of variable renewable technologies in electricity generation are shifting the focus of energy security to the reliability and resilience of electricity systems, which will become increasingly important to economic development and prosperity. This highlights the importance of technological advances in providing electricity system flexibility, as well as of adequate investment in all aspects of electricity generation and transmission and distribution infrastructure.

Energy and emission trends and drivers

The global energy system is akin to a tanker: it has enormous momentum and takes a lot of time to change direction. Analysis of historical trends in energy supply and use and associated GHG emissions shows that they follow very steady long-term paths. Most changes have occurred very gradually. Technology development and market introduction have taken time even when there has been a spike of interest in the use of particular energy technologies, such as the boom in the construction of nuclear power reactors in the 1970s and 1980s, the upsurge in combined-cycle gas turbines (CCGTs) in the 1990s, wind turbines in the 2000s and solar photovoltaic (PV) panels in the 2010s. This is reflected in the long-term trends in energy-related CO_2 emissions: the steady growth in renewables has not been enough to offset continued increases in emissions from the use of fossil fuels.

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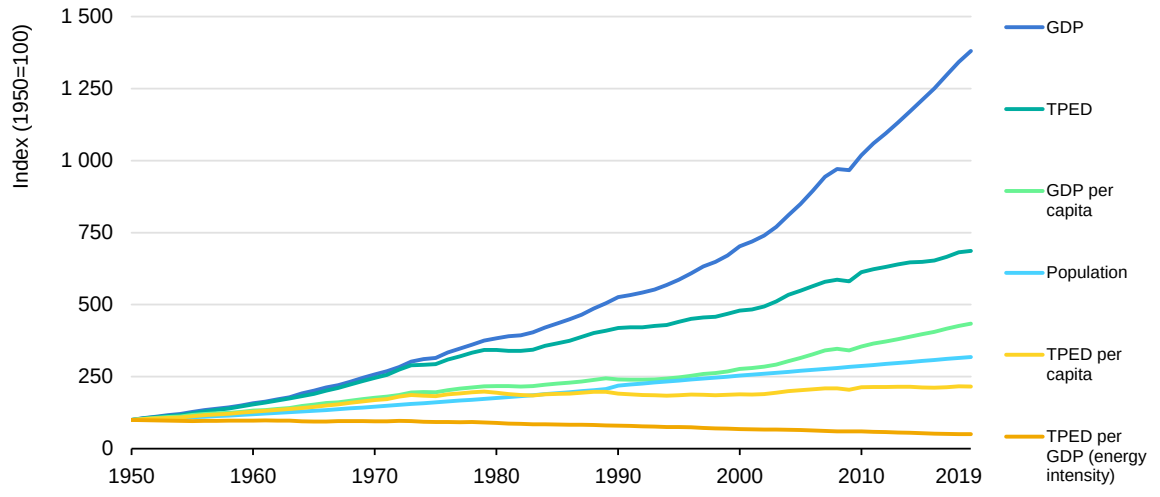
Global energy trends

The link between prosperity and energy use is a two-way street

Energy has been central to economic development, and global energy use, GDP and population have all risen sharply since the beginning of the 19th century. Total primary energy use worldwide reached 14 400 million tonnes of oil equivalent (Mtoe) in 2019, 45% higher than in 2000 and an estimated 16-fold higher than in 1900 (Figure 1.1). GDP has increased by 160% and by 80% on a per capita basis since 1990. The number of people in the world swelled from around 1 billion in 1800 to roughly 7.7 billion today. Population growth accelerated in the first half of the 20th century to peak at around 2% per year in the late 1960s but since has slowed to an estimated 1.1% in 2019 (UNPD, 2019).

The inexorable increase in global energy use since the end of the 18th century has been at once the driver and the effect of economic development. Energy use however has generally increased more slowly than GDP (which is linked, in turn, to population) as a result of structural economic shifts, saturation effects and efficiency gains. Over the period 2000-19, for every one percentage point rise in global GDP (expressed in real purchasing power parity [PPP] terms), energy demand increased by around 0.6% (Figure 1.1). In other words, energy intensity – energy consumption per unit of GDP – has been declining steadily. Today, the world needs 20% less energy to produce one dollar of economic output than it did only 19 years ago.

Figure 1.1 Global total primary energy demand, population and GDP, 1950-2019



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Note: TPED = total primary energy demand.

Energy demand has historically been driven by GDP and population, reaching a sevenfold increase from 1950.

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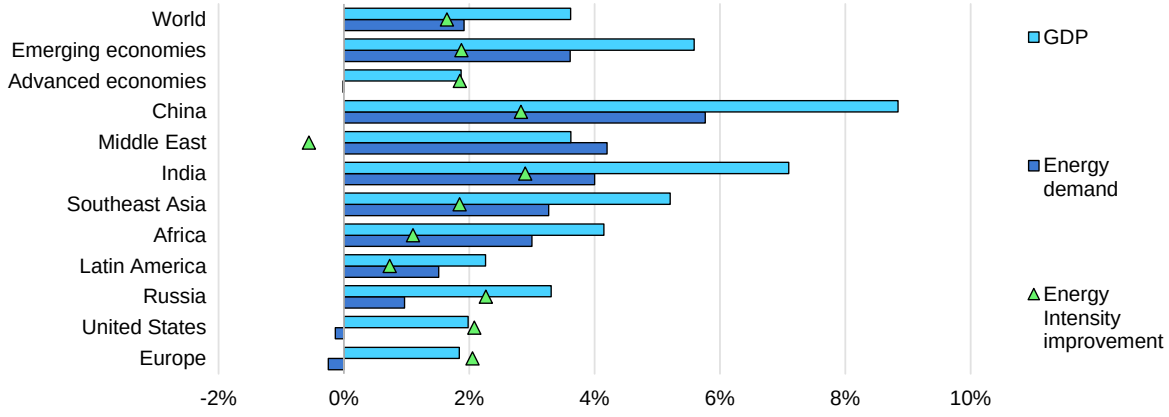
The precise relationship between GDP and energy demand differs between and within countries and regions, as well as over time (Figure 1.2). For advanced economies, energy intensity has fallen by 1.8% per year since 2000, with modest growth in GDP being accompanied by nearly unchanged primary energy demand. In some advanced economies, energy demand has declined. For example, in Europe energy use peaked in 2006 and was 10% lower in 2019; in the United States, demand peaked in 2007 and was practically the same value in 2019 while GDP increased. In emerging economies as a group, annual energy demand increased by about 3.6% in the 2000-19 period while GDP rose about 6%, with energy intensity falling 1.9% per year, slightly more rapidly than in advanced countries. Nonetheless, on average energy intensity levels remain considerably higher in the emerging economies than in the advanced ones. For example, 0.12 tonnes of oil equivalent (toe) of energy is needed to produce USD 1 000 of output on a PPP basis in China, compared with just 0.10 toe in the United States and 0.07 toe in Europe.

Shifts in the economic centre of gravity of the world economy are mirrored by the global energy market. Most of the 20th century increase in economic activity and energy needs up to the 1970s occurred in Europe and North America. Since then, the economic rise of China and the rest of Asia has been the main driver of energy demand growth, particularly in recent years. Advanced economies accounted for 38% of global primary energy demand in 2019 compared with 63% in 1971. Emerging economies in Asia today account for 36% of global energy demand compared with less than 15% at the beginning of the 1970s.

Figure 1.2 Annual change in GDP, total primary energy demand and energy intensity in selected countries/regions, 2000-19



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Note: Energy intensity is measured as total primary energy demand per unit of GDP. GDP is measured in PPP terms.

Energy intensity of the global economy improved on average by 1.6% per year due to structural changes, saturation effects and efficiency gains.

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The global energy system has become cleaner in waves

The fuels and technologies used to meet the growth in energy demand over the last century have undergone considerable change as successive waves of technological innovation have affected the energy sector. An early wave of innovation in the 20th century expanded the use of oil and subsequent waves increased the use of natural gas, the development of nuclear power and, more recently, non-hydro renewable energy power generation technologies (Figure 1.3). For the most part, each wave has brought forward energy technologies with lower carbon footprints than those that went before, i.e. the share of coal in energy supply declining in overall terms for most of the 20th century after its rapid growth to fuel industrialisation in the 18th and 19th centuries. However, since the inception of the 21st century, the share of coal in the global energy supply mix has increased with the economic boom in China. The share of traditional biomass, which was almost the only source of energy in many parts of the world a century ago, has steadily declined as the availability of other fuels has expanded.

Oil is in relative decline: its share of the global energy mix peaked in the mid-1970s at just under 50%. Broader energy diversification was in evidence in the last quarter of the 20th century with increased use of natural gas and the development of nuclear power led by the United States, the Russian Federation ("Russia" hereafter), Japan and some European countries. It also saw the link between energy use and GDP start to weaken with higher energy prices stimulating investment in more efficient energy technologies. Since 2000, there have been two major energy stories: the rise of China as an economic power and energy consumer, and the surge in investment in modern renewables for power generation, especially in Europe, United States, China and India: it is however worth noting that the increased share of renewables in the global energy mix has barely offset the declining share of nuclear power over the period.

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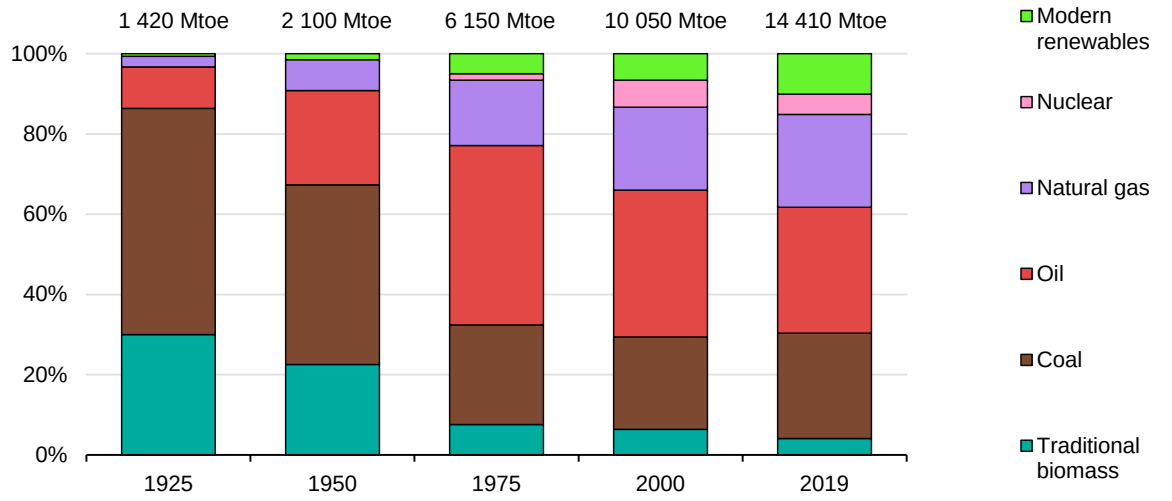
Figure 1.3 Global primary energy demand by fuel, 1925-2019



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Note: Modern renewables includes all uses of renewable energy with the exception of traditional use of solid biomass.

Coal and traditional biomass have declined over the last century while first oil and then gas, nuclear power and renewables emerged in successive waves. Since 2000 the share of oil and nuclear has declined while that of coal has increased.

A persistent trend has been the rising share of electricity in final energy use, initially in industry and buildings and more recently in the transport sector. This reflects the fact that some energy services, such as lighting and refrigeration, in practice can only be provided by electrical devices, as well as the environmental, technical and economic advantages of electricity. Electricity now accounts for about one-fifth of total final energy consumption worldwide compared with an estimated one-tenth in 1970 and one-sixth in 2000. Consequently, the share of primary energy to produce electricity has risen from about 22% in 1970 to 37% in 2000 and 38% in 2019.

Technological change has accelerated since 2000

The last two decades have seen a marked acceleration in the pace of technological change, but the share of clean energy sources in the global energy mix remains relatively small at just under one-fifth in 2019 – a similar share to that at the beginning of the 1970s. The share of modern non-hydro renewables has increased significantly, especially since 2000, but this has been more than offset by a decline in the share of nuclear (Figure 1.4). Bioenergy remains the single largest category of low-carbon energy sources, accounting for 9% of total primary energy demand in 2019 (with a roughly equal split between traditional biomass and modern bioenergy), followed by nuclear power (5%), hydropower (3%) and solar and wind (1%). Not all bioenergy is clean energy, however, since some of it is used in unsustainable and polluting ways.

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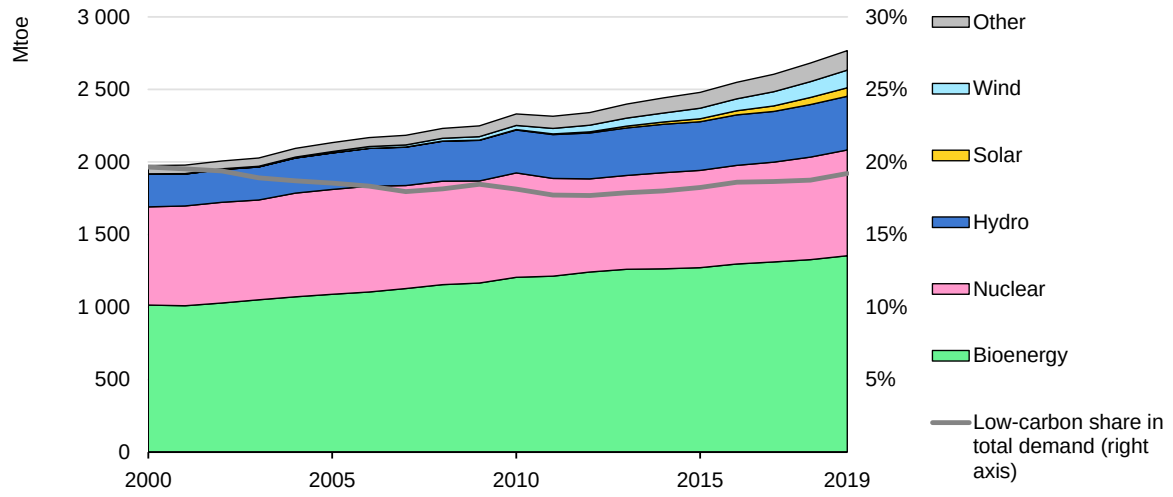
Figure 1.4 Primary demand for low-carbon energy sources, 2000-19



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Notes: Mtoe = million tonnes of oil equivalent. Other includes geothermal and marine energy.

Bioenergy remains the single largest category of renewables, though solar PV and wind power have increased the fastest in recent years.

Technological change in the power sector

The overall share of clean fuels in total power generation rose steadily through the 1970s and 1980s, fell back in the 2000s as coal-fired generation in Asia surged, then started to rise again in 2013. Coal accounted for 38% of global electricity generation in 2019 – just one percentage point lower than in 2000 – but in 2019 more of it was generated in new plants employing supercritical, ultra-supercritical and other technologies that achieve a higher thermal efficiency than traditional subcritical combustion technology and thus emit less CO_2 per kilowatt-hour (kWh) generated. The share of subcritical plants in total coal-fired power generation worldwide fell from 75% in 2000 to around 40% in 2019, and a number of the most inefficient plants have been shut in recent years, notably in China.

The expansion of renewables-based power generation technologies has been a major clean energy technology success story. Investment in wind power took off in the late 1990s, and wind power now accounts for over 5% of all the power generated on the planet. The boom in solar PV started later but has increased at a rapid pace in recent years. Solar PV now meets over 2.5% of global electricity needs, with generation having increased by around 25% in 2019 to over 710 terawatt-hours (TWh). Dramatic declines in the cost of wind turbines and solar PV panels in recent years have boosted investment: solar PV costs have fallen by close to 80% since 2010 (Figure 1.5). In many cases, both technologies are now cost-competitive with conventional thermal generating options, including gas-fired CCGTs (IEA, 2019b). Their success has its origins in R&D efforts that date back decades, supported by significant amounts of

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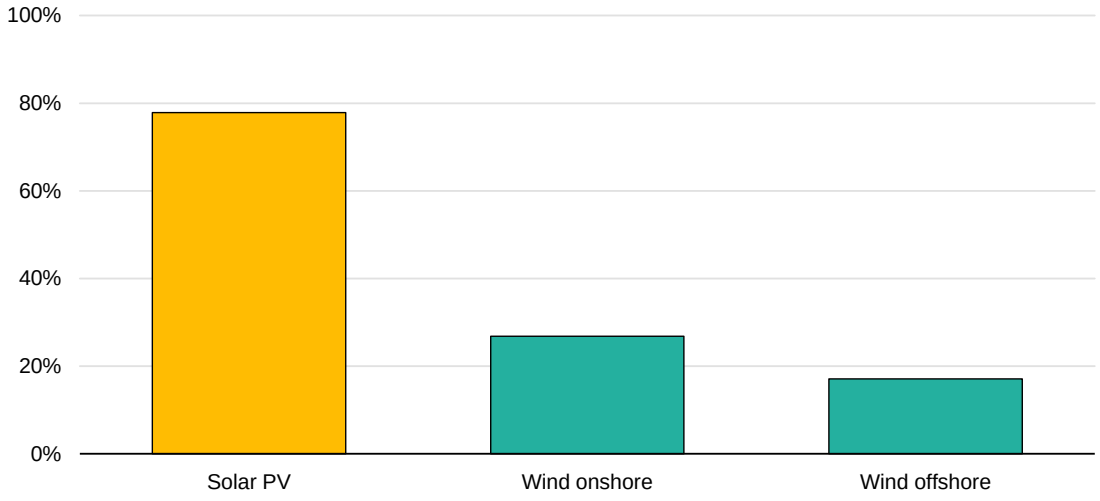
public funding, and their commercialisation around the world has been underpinned by a mix of various regulatory and economic instruments, including feed-in tariffs and minimum targets for generation from renewables in electricity systems (see Chapter 6).

Figure 1.5 Reduction in capital cost since 2010 for PV and wind power generation technologies



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Source: Based on IEA (2019b).

Significant cost reductions in solar PV and wind technologies have led to a major shift in investment and a rapid transformation of the generating mix.

The other main change in the power sector since 2000 has been the stagnation of nuclear power, with a sharp slowdown in the rate of commissioning new reactors, especially in advanced economies. The world's first nuclear power plant to generate electricity for the grid started operation in the Soviet Union in 1954. The construction of nuclear reactors worldwide surged in the 1960s and 1970s, driven by governments on the back of technological progress and rising oil prices that led many countries to diversify their power mix. The number of construction starts for new nuclear power plants slumped in the late 1980s and 1990s in the wake of lower fossil fuel prices and accidents at Three Mile Island and Chernobyl, but started to pick up again in the late 2000s, mainly in emerging economies. Interest in building new nuclear plants then fell again after the Fukushima-Daiichi nuclear accident (IEA, 2019c). Today there are 54 nuclear power reactors under construction, 39 of which are in emerging economies (IAEA, 2020).

Technological change in alternative fuels

The global supply of biofuels – liquid transport fuels produced from renewable bioenergy feedstock – has expanded steadily since the 2000s, mainly in response to

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policy incentives such as blending mandates and production targets aimed at diversifying transport fuel use and reducing its environmental impact. Except in Brazil, however, they remain more expensive to produce than conventional oil-based fuels. They met around 3% of global road transport fuel needs in 2019, up from less than 1% in 2000, driven to a large extent by Brazil, United States and European Union: they also accounted for around 0.01% of total aviation fuel consumption through blending.

The use of biofuels for transport is by no means new. The first diesel engines were designed to run on peanut oil, and the Ford Model T produced over the first three decades of the 20th century was designed to use hemp-derived biofuels. Today, most biofuel supply comes from conventional ethanol and biodiesel production processes that were developed decades ago, though recent advances have improved the performance of plants and lowered costs. A growing share of biofuels now comes from advanced technologies, notably hydrotreated vegetable oil produced from waste feedstock, which accounted for 8% of biofuels production in 2018. By contrast, investment in lignocellulosic ethanol production, which makes use of farm and forestry waste, has not taken off as originally expected. The process of converting lignocellulosic materials to ethanol is more complex than that used to convert starch and sugars into ethanol, and the future of this type of biofuel hinges on the success of research and development (R&D) aimed at lowering costs at every stage of the lignocellulosic ethanol production and supply chain, as well as on its integration with conventional ethanol plants and other biorefineries (see Chapter 5 for the use of biofuels in the transport sector).

Hydrogen technologies have received considerable attention in recent years. Like biofuels, hydrogen is not "new" – it was used to fuel early internal combustion engines over 200 years ago, to contribute to the composition of city gas from the 18th century till the first half of the 20th century, and to provide lift to balloons and airships in the 18th and 19th centuries, while its use for non-energy purposes as input to ammonia fertiliser production (derived from fossil fuels and, earlier, from electricity and water) has helped feed a growing global population. Since the mid-20th century, it has also been used in oil refining for hydrogenation purposes. Hydrogen today is mainly used for oil refining and as feedstock in the chemical industry. Almost all of it still comes from fossil fuels, emitting today more than 800 million tonnes of carbon dioxide ($MtCO_2$).

At the point of use, hydrogen can be burned or converted in such a way as to produce no harmful emissions[2] and, if produced without emitting any GHG, it has the potential to make a huge contribution to a sustainable energy system. The principal barrier to the uptake of low-carbon hydrogen is its high cost, which is partly the result of the lack of economy of scale in production, supply and use (IEA, 2019d). Another main challenge is the long-standing problem of how to develop supply infrastructure in tandem with end-use equipment: why develop hydrogen cars if there is no

[2] NO_x emission however may increase in hydrogen rich fuel combustion. (See, for example, www.hy4heat.info/ for more on the challenges to reduce NOx emissions of hydrogen appliances)

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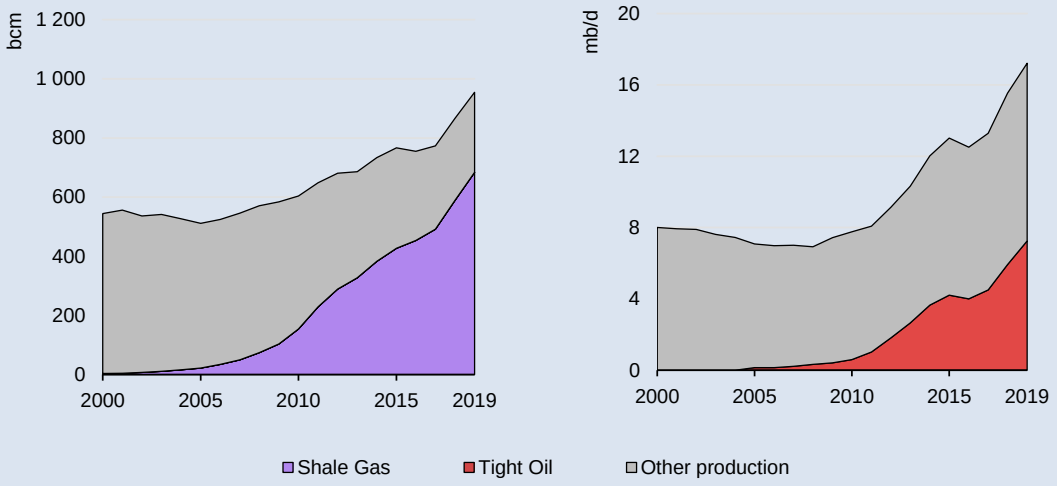
distribution network, and why develop a distribution network if there are no hydrogen cars? Technical and trade regulations also have hindered the development of the hydrogen industry in some cases. Today, however, low-carbon hydrogen is enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly, and the costs of key technologies such as electrolysers falling as production increases. The case for hydrogen to play a major role in a future cleaner energy system is becoming increasingly clear, especially in sectors where CO_2 emissions are hard to reduce (see Chapters 2-5).

Box 1.2 The shale revolution?

Technology change in the energy sector has not been limited to clean energy technologies. One major supply-side development over the past two decades has been the remarkable boom in production of shale gas and oil in the United States, which has transformed the country from a major importer to a net exporter of both fuels. Shale gas output reached a record high of 680 billion cubic metres (bcm) in 2019, contributing more than two-thirds of total US natural gas supply – up from 3 bcm, or less than 1%, in 2000. This boom spurred a similar surge in tight oil production, which took off in the early 2010s and surpassed 7 million barrels per day (mb/d) in 2019 – more than 40% of US crude oil output and 8% of world production. One effect of the surge in shale gas output has been to lower natural gas prices across North America, boosting demand for gas in power generation, pushing out coal and lowering CO_2 and pollutant emissions.

US production of shale oil* and gas, 2000-19



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* Light crude oil contained in low permeability shale or tight sandstone formations.

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The shale boom resulted from a number of factors, including technological innovation (e.g. horizontal drilling, hydraulic fracturing) that stemmed in large part from government R&D programmes initiated in the late 1970s. Other government incentives, including tax credits for unconventional production, also helped to make investment in shale gas profitable, together with private land and mineral rights ownership, high natural gas prices in the 2000s, favourable geology, the availability of abundant water resources and well-developed gas pipeline infrastructure. The techniques that were first developed for gas and the subsequent cost reductions that came with learning and the scaling up of production were transferred to the oil sector, yielding equally spectacular results. Shale production outside the United States has not yet developed to anywhere near the same extent because geological, operational, regulatory and economic factors (as well as social acceptance in some regions) have not been as favourable.

Technological change in energy end use

On the demand side, technical gains in the efficiency of energy end use – measured as the amount of energy needed to provide a given energy service, such as a lumen of lighting or a joule of mechanical energy – have been the primary way to temper the growth in global energy use to fuel rising economic activity over the past two decades. We estimate that, if these gains had not occurred since 2000, energy demand in the major economies that account for some 70% of global demand would have been a thumping 1 200 Mtoe, or 19%, higher. Structural economic changes, involving a shift to less energy-intensive services and lighter industry, also helped to slow overall demand growth, even though these structural changes actually contributed to demand increases in transport and buildings over the period. The improvement in efficiency gains is reflected in the downward historical trend in energy intensity across most sectors, though there are signs of a slowdown in some, notably the services and residential sectors (Figure 1.6). This slowdown, in part, is because of an easing of policy action, particularly with respect to the scope and strength of efficiency standards (IEA, 2019e).

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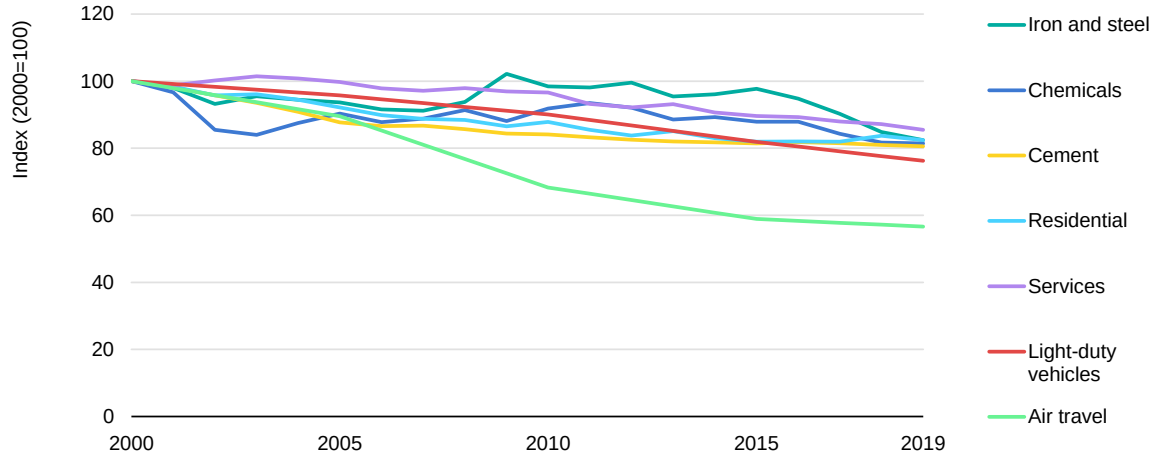
Figure 1.6 Global average energy intensity in selected end-use sectors, 2000-19



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Notes: Intensity is measured as energy use per dollar of value added in the industry and services sectors; per tonne of steel in the iron and steel sub-sectors; per tonne of primary chemicals in the chemical and petrochemical sub-sectors; per tonne of clinker in the cement sub-sector; per square metre of floor space in the residential sector; and per passenger kilometre in the transport sector. Cement here refers to the energy intensity of clinker, which is the most energy-intensive portion of cement production and where energy-efficient equipment changes can have the largest effect.

Improvements in energy intensity over two decades are diminishing in some sectors reflecting structural shifts in economies and weakening efficiency policy efforts, particularly for performance standards.

Policy has been a major driver of energy efficiency improvements. In the buildings sector, for example, appliances and equipment subject to minimum energy performance standards accounted for one-third of the energy used in 2019 (IEA, 2020a) and the stringency of the mandatory policies has risen in most countries since 2000. In the case of LEDs, which use far less electricity energy than incandescent, fluorescent or halogen lightbulbs, demand increased in the late 2000s in response to lower prices made possible by technical advances and economies of scale, as well as by policies to limit the sale of the most inefficient incandescent bulbs (see Chapter 7). Market-based solutions, such as using bulk procurement and energy service providers, have also helped drive LED costs down, boosting uptake. India has demonstrated that it is possible to deploy LEDs rapidly on a large scale when the right financing and market mechanisms are in place. India has one of the largest LED markets in the world thanks to the national Unnat Jyoti by Affordable LEDs for All programme, which uses bulk procurement to offer LED bulbs at low prices. LEDs now make up nearly half of total residential lightbulb sales worldwide, and more than 350 million LED lamps have been sold since 2015.

In transport, vehicle fuel economy has improved enormously in recent years, thanks in large part to fuel efficiency and emissions standards. The global average fuel consumption of newly registered light-duty vehicles (LDV) dropped from 8.8 litres

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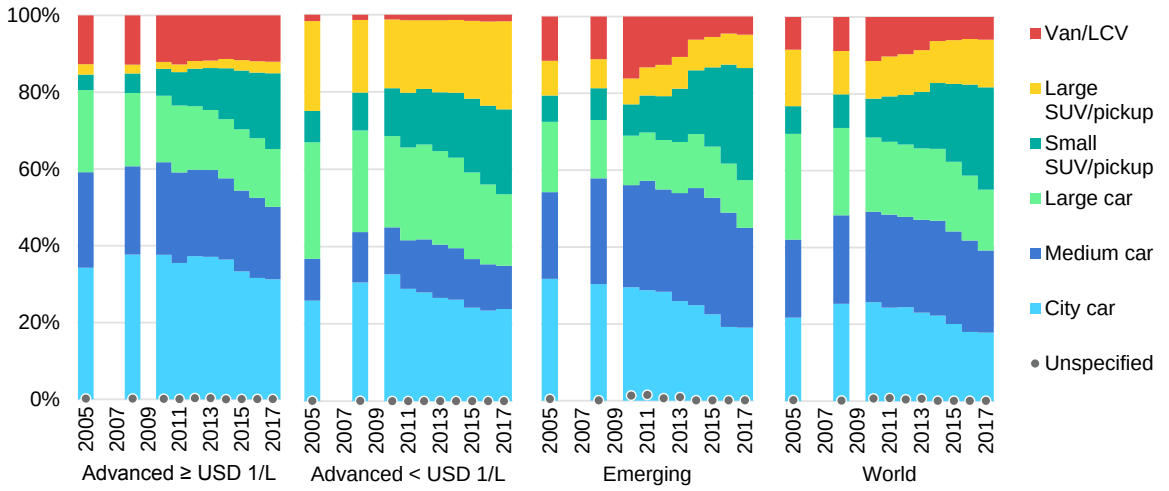
per 100 kilometres (L/100 km) in 2005 to 7.2 L/100 km in 2017, driven by standards that today cover around 85% of global car sales (IEA, 2019f). Policy played a big role in stimulating the development and commercialisation of technologies that made this possible. In recent years, however, improvements in fuel economy thanks to more efficient powertrains, lighter materials and other technical improvements have been partly offset by a shift to larger vehicles, including sport utility vehicles (SUVs), which motorists increasingly prefer (Figure 1.7). SUVs, which now account for around 15% of LDV sales worldwide compared with just 20% in 2010, consume a quarter more energy on average than medium-size cars.[3]

Figure 1.7 Light-duty vehicle market share by size segment, 2005-17



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Notes: LDV = light-duty vehicle; LCV = light commercial vehicle; pickup = pickup truck. Advanced < USD 1/L= advanced economies with gasoline prices below USD 1 per litre; Advanced > USD 1/L = advanced economies with gasoline prices above USD 1 per litre. Unspecified is the share of vehicles where there are no data on the size segment; the values are not included in the denominator to calculate market shares.

Source: IEA analysis based on IHS Markit (2018).

Small SUVs and pickup trucks have been gaining LDV market share over the last decade in advanced and emerging economies.

Electric cars have experienced a decade of rapid growth. Global sales increased by more than 60% every year since 2014 except for 2019, when growth slowed to 6% as the regulatory environment changed in China and passenger car sales contracted in major markets. Even so, electric vehicle sales reached 2.1 million in 2019, accounting for 2.6% of the global car market. Policy support has played a major role, with generous purchase subsidies in many countries helping to overcome cost barriers.

[3] www.iea.org/commentaries/growing-preference-for-suvs-challenges-emissions-reductions-in-passenger-car-market.

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Performance and cost improvements in lithium-ion batteries – the key technology today to enable road vehicle electrification – also have made an important contribution.

History teaches that energy transition takes a long time

What does this brief sweep through energy history reveal? It shows that large- scale energy transitions are possible and have been realised over the last century. Nevertheless it demonstrates that transformation may take decades to have a major impact on relative fuel shares. Energy demand – driven by rapidly growing populations and economies – was constantly rising, so that new fuels and technologies at the early stages of their deployment largely helped to meet additional demand rather than replacing existing technologies The sheer size of the global energy system means that, today more than ever, any new technology needs to be deployed rapidly and on a huge scale to make any dent in the shares of the existing ones. It took two to three decades to move from the first commercialisation of energy technologies to just 2.5-3% market share, and decades more to reach widespread deployment (Bento, Wilson and Anadon, 2018; Gross et al., 2015). The time needed to build large-scale infrastructure, and to see benefits for innovative technologies from learning and scale economies, have also constrained the pace of energy transitions, as has the reluctance to abandon sunk investments before the end of the useful life of the assets (Grubler, 2012; Smil, 2010).

Another important lesson is that clean energy technology progress has been most visible in energy supply, as well as electricity and other fuel transformation. In energy end use, progress has been made but there are few breakthroughs at the scale of solar PV and wind in power generation. Given the relative size of emissions stemming from the use of coal, oil and gas in the industry, transport and buildings sectors, technology progress will need to dramatically accelerate to meet environmental goals.

Covid-19: A threat or an opportunity to boost clean energy technologies?

For technologies that are currently at an early stage of adoption such as renewables and electric cars, indications suggest a degree of resilience in the face of the Covid pandemic and scope for progress to accelerate in the months ahead.

The current IEA forecast is that additions of renewable electricity capacity will decline by 13% in 2020 compared with 2019 due to delays in construction activity from supply chain disruptions, lockdown measures and social-distancing guidelines, as well as financing challenges. However, the majority of the delayed projects are expected to come online in 2021 and lead to a rebound in capacity additions to 2019 levels. At the same time, renewable electricity generation is expected to increase by

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nearly 7% and reach almost 30% of electricity supply globally, largely because of the low operating costs of renewables and preferential access in many power systems. In some countries, the share of variable renewables in overall electricity supply during the months of lockdown was particularly high, providing important operational insights for the future.

Electric car sales are likely to be resilient to the impacts from the Covid-19 crisis, particularly in Europe, where tougher CO_2 emissions performance standards for new passenger cars and vans came into effect at the start of 2020. Economic stimulus measures in many countries could speed up the transition to clean energy technologies in power generation and passenger transport compared to what would have been expected before the pandemic. IEA forecasts expect global sales of conventional car to drop by 15% in 2020 relative to the previous year, with electric cars sales coming in at about the same level as 2019, and perhaps even higher, depending on the pace of economic recovery, and the nature and extent of economic stimulus measures.

The impacts of the pandemic may vary for technologies that currently are at an earlier stage of deployment, in particular those at a demonstration or prototype stage or still in the laboratory. Key risks include pressures on public and private budgets, a riskier environment for clean energy venture capital and disrupted global supply chains. Public R&D is likely to hold up better than private R&D, and there is a reasonable chance that the governments of major economies will seek to boost innovation funding as a response to the crisis. Many companies face lower revenue and a lack of cash flow for capital investments to meet near-term growth targets, but there is currently little sign of backsliding on the part of those that have made commitments to reduce their emissions intensity and test new energy technologies. When the IEA surveyed industrial contacts in May 2020 for gauging the likely impacts of Covid-19 on their ability to support innovation to achieve longer term goals, responses indicated no change in long-term commitments and an expectation that their R&D budgets would be resilient, even though overall sentiment about the impact of the pandemic on the full range of innovation activities was gloomy (IEA, 2020b).

The months ahead present a unique opportunity to double down on progress on all clean energy technologies. While near-term responses to the Covid crisis have understandably focussed on mitigating health, employment and liquidity risks, attention is now turning to the speed of the recovery, creation of new jobs and the future shape of the economy. Economic stimulus plans being proposed in countries around the world offer a once-in-a-generation opportunity to boost clean energy technology progress. These plans may offer a supportive environment to new players with new ideas aiming to displace high-carbon producers and to scale-up quickly.

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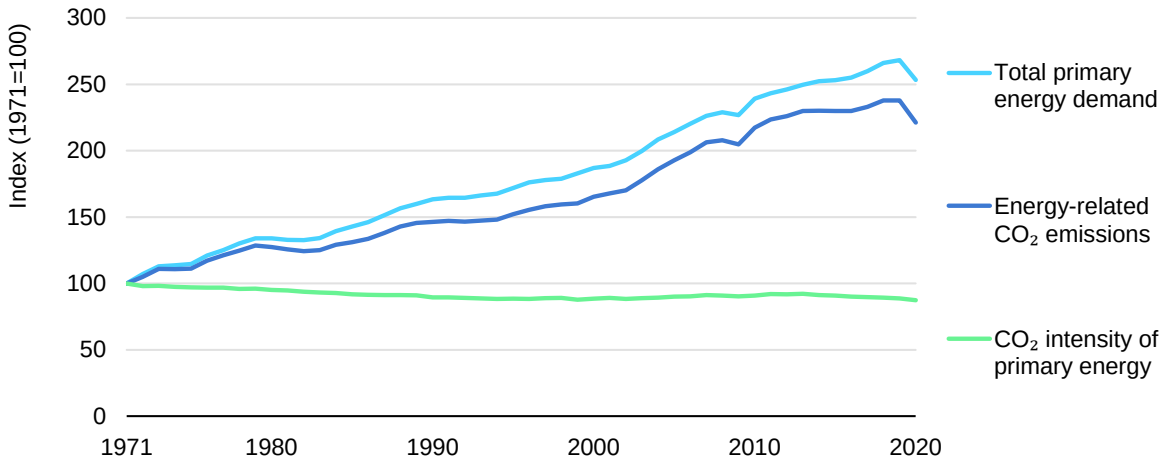
Implications for energy-related CO_2 emissions

The inexorable growth in energy demand and the continued heavy reliance on fossil fuels have led to large increases in global CO_2 emissions, despite major technology-driven improvements in energy efficiency and the rapid growth of renewables for power generation. Between the middle of the 20th century and the first decade of the 21st century, global energy-related CO_2 emissions – i.e. emissions from the combustion of fossil energy in transformation processes such as power generation and direct end uses – increased steadily, except during periods of major economic disruption, such as the oil crisis in 1973 and the global financial crisis in 2008-09 (Figure 1.8).

Figure 1.8 Global primary energy demand and energy-related CO_2 emissions, 1971-2020



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Energy-related CO_2 emissions generally have risen with energy demand since the 1970s; the Covid-19 is set to cause the largest decline in annual emissions over that period.

CO_2 emissions from fossil fuel combustion levelled off between 2014 and 2016 even in a period of robust economic growth as a result of a sudden slowdown in coal use in Asia (largely due to energy efficiency gains) and a surge in non-hydro renewables generation worldwide. But CO_2 emissions edged up in 2017 and held steady at around 33 Gt in 2018 and 2019. However, the Covid-19 pandemic has rocked this trend downward: it is expected to lead to the largest ever annual decline in energy-related CO_2 emissions in 2020 (Box 1.3).

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Box 1.3 What is the expected impact of Covid-19 on CO_2 emissions?

The outbreak of the Covid-19 pandemic led to a drastic curtailment worldwide of economic activity and mobility during the first half of 2020, pushing down global energy demand. IEA analysis suggests that if lockdowns last for many more months and economic recoveries are slow, global annual energy demand could drop by 6% in 2020, wiping out energy demand growth registered in the last five years. If efforts to curb the spread of the virus and restart economies are more successful, the decline in energy demand could be limited to under 4%. However a bumpier restart, disruption to global supply chains, and ongoing spread of Covid-19 second half of 2020 could suppress energy demand even further.

The expected impact on energy demand is generally largest for fossil fuels, and global CO_2 emissions are expected to fall to 30.6 Gt in 2020, almost 8% lower than in 2019. This would be the lowest level since 2010. Such a reduction would be six-times larger than the previous record reduction of 0.4 Gt in 2009 due to the financial crisis, and twice as large as the combined total of all previous reductions since the end of World War II.

Source: IEA (2020c).

Switching to gas and renewables has slowed the growth in CO_2 emissions

Coal remains by far the biggest contributor to global energy-related CO_2 emissions as it is the most carbon-intensive fossil fuel[4] and the second-largest energy source worldwide (Figure 1.9). Coal accounted for 45% of total CO_2 emissions in 2019, followed by oil (34%) and natural gas (22%). Apart from a brief hiatus in the 2000s, the share of coal in the global energy mix has been declining in recent decades, while that of oil has been broadly flat and that of gas has been rising steadily. The IEA calculates that coal has been the single leading cause of global warming: CO_2 emitted from coal combustion is responsible for more than 0.3°C of the 1°C increase in global average annual surface temperatures above pre-industrial levels.[5]

[4] The carbon intensity (or emission factor) measures the carbon content and, therefore, the amount of CO_2 emitted per energy content of fossil fuels. On average, the carbon intensity of coal is roughly three-quarters higher than that of natural gas and around one-third higher than oil. The precise factors vary according to the quality and category of each type of fuel.

[5] www.iea.org/reports/global-energy-and-co2-status-report-2019/emissions#abstract.

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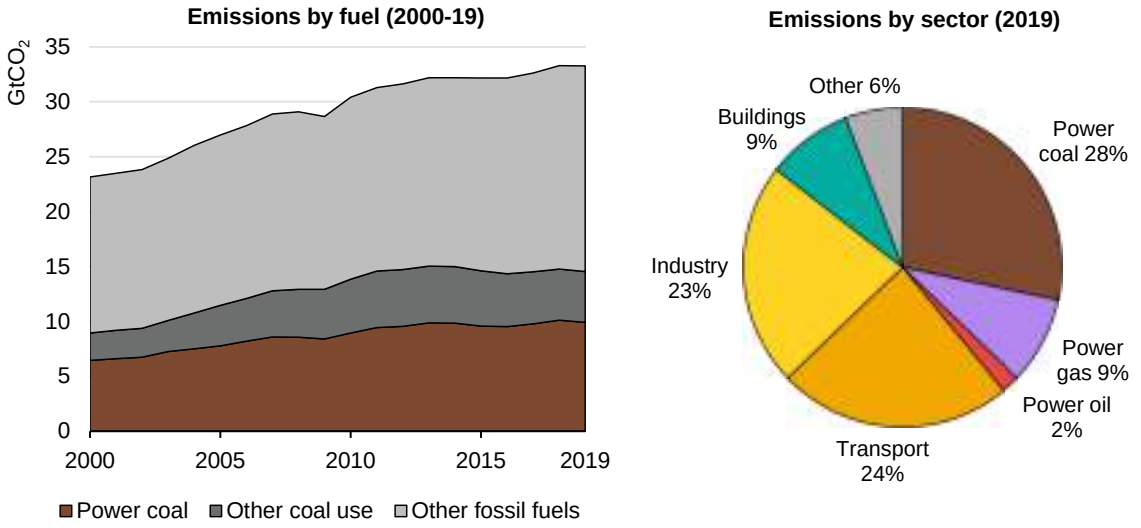
Figure 1.9 Global energy-related CO_2 emissions by fuel (left) and sector (right), 2000-19



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Power generation, where coal use is increasingly concentrated, is the biggest emitter of CO_2 worldwide, accounting for about 40% of total emissions.

The consumption of natural gas, which emits less CO_2 than coal and oil per unit of energy, has been rising more rapidly than coal consumption in recent years, which has lowered the average carbon intensity of global energy use. The increased use of renewables, mainly in power generation in China, Europe and United States, has further reduced the carbon intensity of energy as have the continuing use of nuclear power and gains in energy efficiency. In the power sector, the global average carbon intensity of electricity generated in 2019 was 470 grammes of CO_2/kWh – 12% lower than in 2000. Cumulative emissions savings related to increased contribution of renewables in power generation since 2000 are estimated at 16 Gt. The equivalent cumulative emissions savings figure related to nuclear power generation is 30 Gt. Emissions savings from the use of other prominent clean energy technologies such as electric vehicles (53 million tonnes [Mt] in 2019) or LEDs (100 Mt in 2019) have so far been limited in comparison. Energy efficiency gains in the power sector and in various end uses have also made a significant difference. For instance, efficiency improvements to coal-fired power plants in China since 2005 have resulted in cumulative CO_2 emissions savings of over 6 Gt.

Emission trends diverge across regions

There is considerable variation in CO_2 emission trends across countries and regions. Since 2000, increases in CO_2 emissions generally have slowed and, in some cases, started to decline in the advanced economies due to dampening of primary energy demand, a shift to clean energy sources and gains in energy efficiency. Between 2000 and 2019, CO_2 emissions from energy dropped by 18% in Europe, 17% in the

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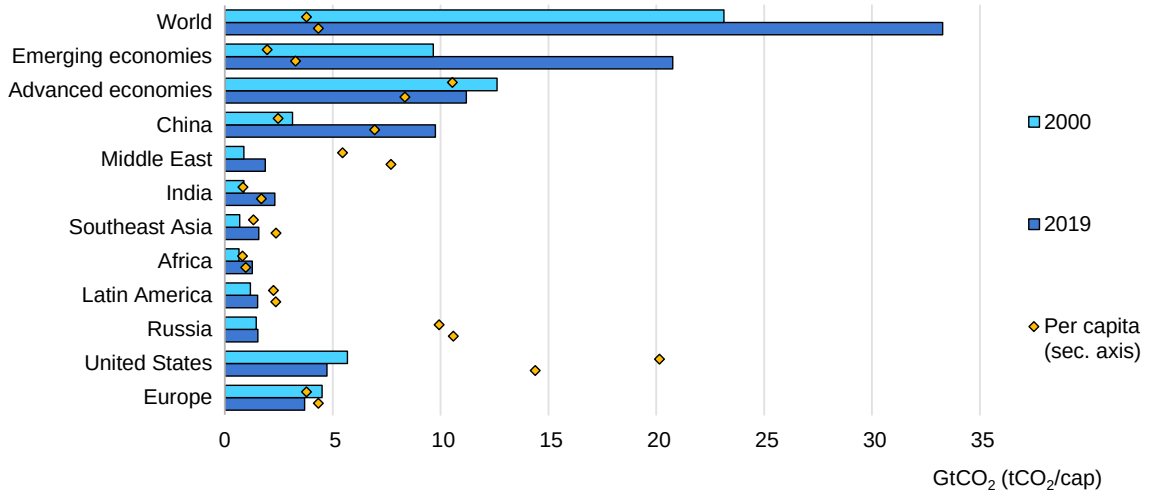
United States and 13% in Japan. By contrast, CO_2 emissions in the emerging economies have risen briskly, albeit at a slower pace in the last few years. Emissions between 2000 and 2019 tripled in China and more than doubled in other emerging economies in Asia. Per capita emissions in emerging economies however remain substantially lower than levels in advanced economies.

Emerging economies in Asia have been the principal driver of global CO_2 emissions growth for the past two decades (Figure 1.10). China alone contributed just under two-thirds of the increase in global emissions between 2000 and 2019: other emerging economies in Asia accounted for another 25%. China's emissions skyrocketed in the decade up to 2013 – the result of an unprecedented surge in power generation capacity and industrial output, largely powered by coal. With 9.8 Gt of emissions in 2019, China accounted for 30% of global CO_2 emissions – up from just 14% in 2000. However, there are signs of a slowdown in emissions growth as the Chinese economy matures, mirroring what happened in most advanced economies in the 2000s. China's CO_2 emissions fell between 2013 and 2016 due to lower emissions from industry and the power sector, though they rebounded thereafter.

Figure 1.10 Global energy-related CO_2 emissions by region



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Note: tCO_2/cap = tonnes of carbon dioxide per capita.

Emissions have started to fall in most advanced economies as a result of a slowdown in primary energy demand, a switch to clean energy and gains in efficiency, but they are still rising almost everywhere else.

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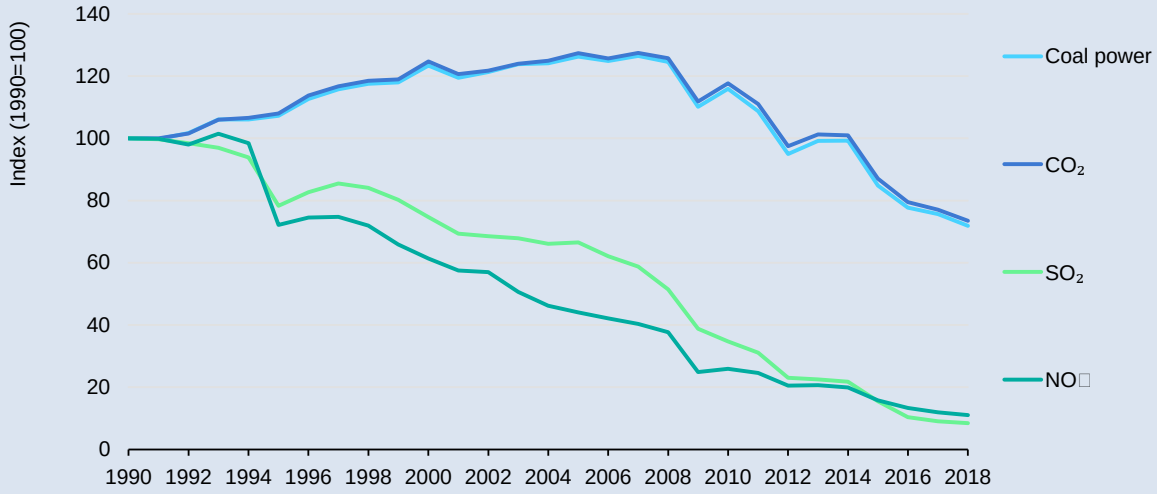
Box 1.4 How technology has cut air pollutant emissions from power plants: the US example

While the carbon intensity of US coal-fired power plants has barely changed over the past three decades, enormous progress has been made in reducing emissions of the main air pollutants from those plants, in large part thanks to the installation of pollution control equipment in response to stringent air quality regulations. Between 1990 and 2018, emissions of sulphur dioxide (SO_2) and nitrogen oxides (NOx) from coal-fired power plants plummeted by around 90% A reduction in the share of coal plants in total power generation over the last decade in favour of less-polluting gas plants as well as wind and solar power also helped to reduce overall air pollutant emissions.

Emissions from US coal-fired power plants, 1990-2018



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Source: US EIA (2020).

The implementation of environmental regulations under the Clean Air Act Amendments (CAAA) of 1990 gave the initial impetus to efforts to cut pollution from coal plants. The CAAA gave rise to several regulations to reduce pollution, notably the Mercury and Air Toxics Standards; the Acid Rain Program, which introduced a cap and trade programme for emissions of SO_2 and NOx from coal and fuel oil-fired power plants in phases between 1995-2010; and the Clean Air Interstate Rule (replaced by the Cross-State Air Pollution Rule in 2015), which required 27 states in the east to file implementation plans to reduce emissions further. The main approach adopted by generators to meet the requirements was to install pollution control equipment at existing plants, including flue-gas desulphurisation (scrubber) and dry sorbent injection equipment, low-NOx burners and selective catalytic reduction equipment. In some cases, generators switched to using lower sulphur coals or closed capacity where it was uneconomic to invest in pollution control facilities.

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Similar progress has been made in other advanced countries, notably in Europe and Japan. In China, where the surge in coal-fired generation in recent decades has led to severe air pollution, the government introduced Ultra-low Emissions Standards in 2014, requiring coal plants progressively to limit air pollutant emissions. As a result, emissions of SO_2, NOx and PM in China dropped by 65%, 60% and 72% respectively between 2014 and 2017, greatly improving air quality and its consequences for public health.[6]

What will happen to today's CO_2 emissions tomorrow?

So far, progress in deploying clean energy technologies has not been sufficient to bring about a peak in energy-related CO_2 emissions, even with the strong growth in renewables for power generation and the millions of electric vehicles on the road in the last decade. This is, in part, because of strong growth in energy demand, but also because of existing infrastructure and its emissions. Understanding the dynamics of the various sectors and technologies that comprise the existing infrastructure is important in the context of efforts to accelerate the use of clean energy technology.

Emissions from existing infrastructure

The amount and type of energy that is used worldwide reflects investments already made in the vast range of physical assets that produce, transport and consume energy. It is not possible to accurately predict the future energy consumption and subsequent emissions of these assets, as there is considerable scope for adjusting the quantities and types of energy carriers that they will consume and the span of their operational lives. Decisions about whether to cease, continue or extend operation of a given asset will be based predominantly on its operational cost relative to existing or emerging alternatives, and/or the ability to obtain a return in a given economic and regulatory context. However, examining the likely emissions trajectories of various sectors and equipment is a useful starting point in an attempt to understand the outlook for emissions in the coming decades, and to estimate the room for manoeuvre.

Absent investment in new fossil-fuelled assets, emissions from the global energy system would decline, but the decline would take time (Figure 1.11). If operated under the conditions typically observed in each sub-sector, existing energy infrastructure could lead to nearly 750 $GtCO_2$ in emissions between now and 2070, in line with other

[6] www.ucl.ac.uk/news/2019/oct/china-track-meet-its-ultra-low-emissions-goals-2020.

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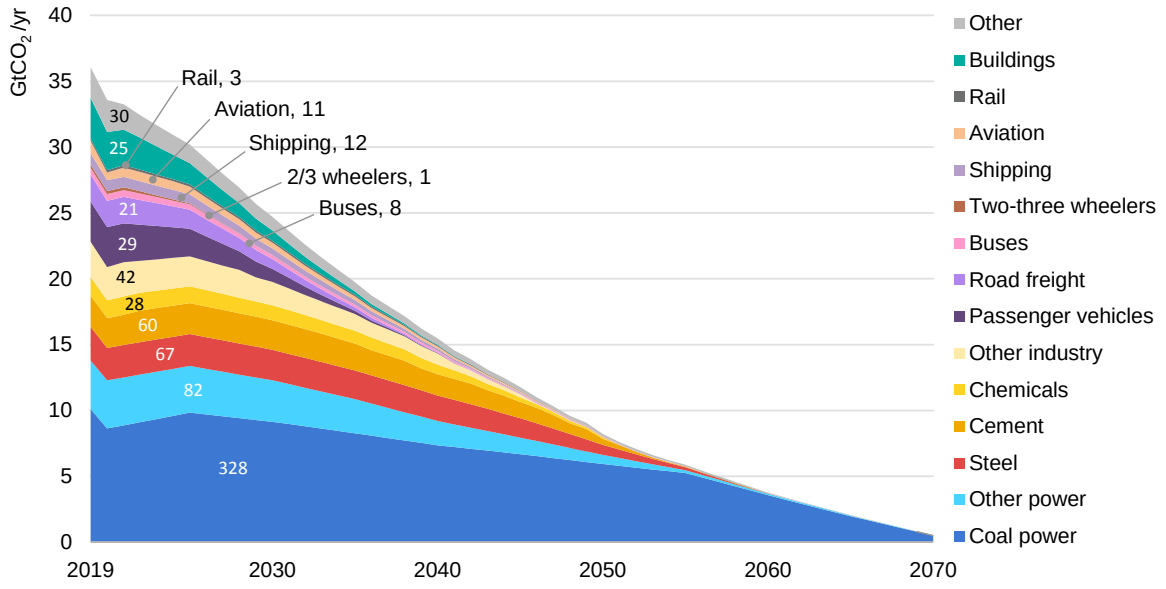
estimates (Tong et al., 2019). This would exhaust the bulk of the remaining CO_2 budget that the IPCC estimates is compatible with limiting the global temperature rise to "well below 2°C". There are likely to be additional emissions as well from new fossil fuel infrastructure during the next decade in the absence of sufficiently developed alternative technologies in certain sub-sectors. Clearly, the details of how we deal with existing infrastructure are critical to consider in any effort to meet global climate commitments.

Figure 1.11 Global CO_2 emissions from existing energy infrastructure by sub-sector, 2019-70



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Notes: Includes assets under construction in 2019, the base year of this analysis. Numeric area labels on the graph denote cumulative emissions quantities by sub-sector in $GtCO_2$. Analysis includes industrial process emissions, and emissions are accounted for on a direct basis. Annual operating hours over the remaining lifetime are based on the level in 2019.

Assuming typical lifetimes and operating regimes, cumulative emissions from existing energy infrastructure could reach nearly 750 $GtCO_2$ by 2070.

The bulk of cumulative emissions from existing infrastructure is expected to come from the power (55%) and heavy industry (26%) sectors, reflecting their large shares of emissions today and the long lifetimes their assets, e.g. power stations and manufacturing facilities (Figure 1.12). Transport accounts for around a further 11%, with two-thirds stemming from road transport, particularly road freight and passenger vehicles. While many households in advanced economies may replace their vehicles every 5-10 years, these cars can have lengthy "second lives", whether in the same market or after export to another country. Direct emissions from the buildings sector account for another 3%.

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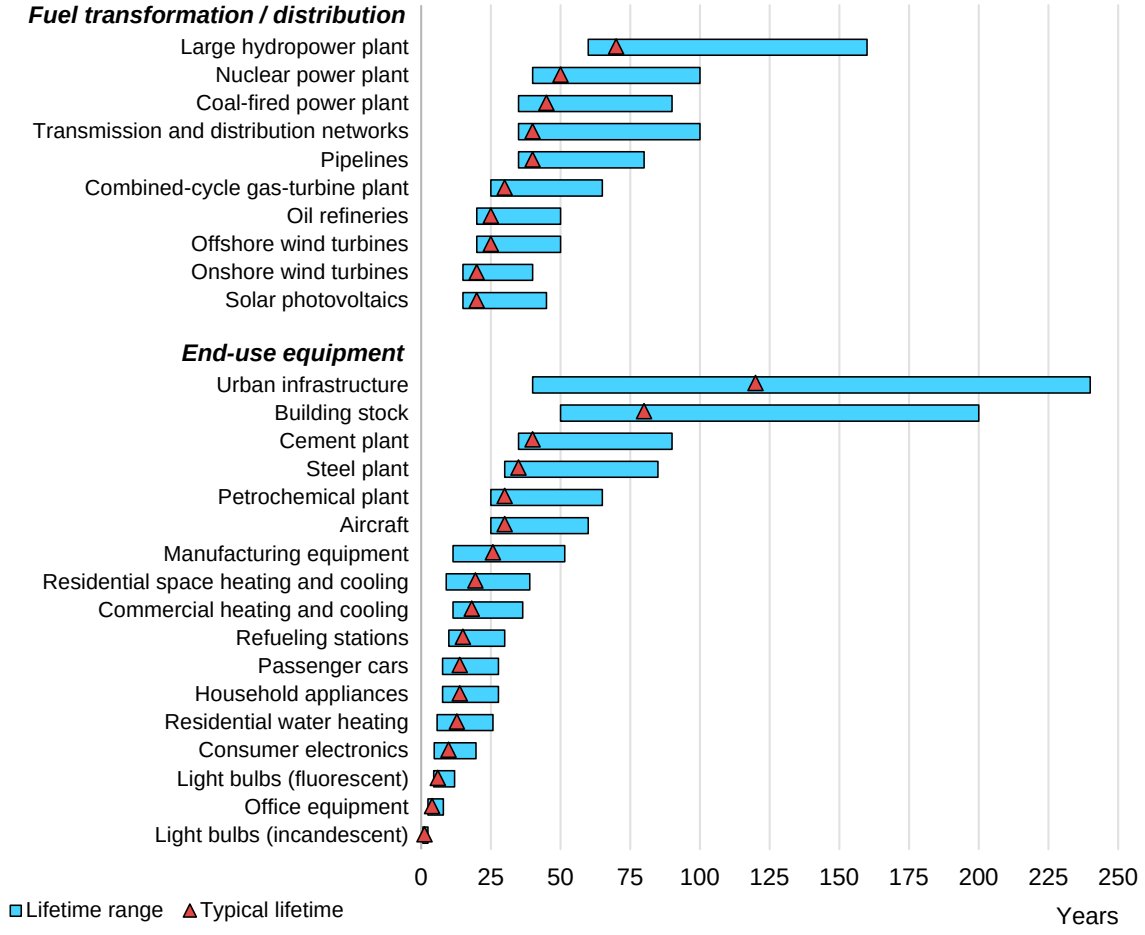
Figure 1.12 Typical lifetimes for key energy sector assets



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Notes: The red markers show expectations of average lifetimes while the blue bars show typical ranges of actual operation in years, irrespective of the need for interim retrofits, component replacement and refurbishments. "Buildings" refers to building structures, not the energy consuming equipment housed within. Examples of "urban infrastructure" assets include pavement, bridges and sewer systems.

The operating lifetime of some assets, especially those that produce materials or transform energy, can span several decades: this means that it could be a long time until they are replaced by cleaner and more efficient ones.

Around 80% of the expected cumulative emissions from the power sector are from coal plants. By 2050, annual emissions from existing coal plants would be 5.9 Gt – nearly 70% of current levels – absent early retirement or other emission reduction measures. Around 75% of cumulative power sector emissions through to 2070 are related to projects in Asia, with China alone accounting for almost 50% of all cumulative CO_2 emissions. More coal plants are still planned, although final investment decisions for new coal plants have fallen by about 80% over the past three years, from about 88 gigawatts (GW) in 2015 to around 17 GW in 2019 (IEA, 2020a).

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Industry is the other major contributor to emissions from existing infrastructure, due to the high energy intensity of the sector, the large share of fossil fuels in energy use and the relatively long operational lifetimes of production facilities. Of the expected 196 $GtCO_2$ of cumulative emissions from industry, absent early retirement or other measures, the steel and cement sub-sectors account for around 30% each, and the chemicals sub-sector for around 15%. A complex array of smaller sub-sectors and manufacturing industries account for the remaining 25%. In the iron and steel industry, emissions come primarily from the production of iron for primary steelmaking, and particularly blast furnaces. In the cement sector, the key emitting process unit is the kiln for producing clinker, which is the active ingredient in cement; in the chemicals sub-sector, ammonia accounts for close to 50% of the cumulative emissions, methanol and high- value chemicals[7] account for about a quarter each. Reducing emissions during the coming decades depends on finding ways to reduce process emissions (i.e. those that result from chemical reactions occurring in industrial processes rather than from the combustion of fuels); finding alternative ways to provide the high-temperature heat that is most easily provided by fossil fuels; and avoiding "carbon leakage" – the migration of energy-intensive industries to countries with less stringent policies to curb emissions.

The rate of turnover of the energy system's capital stock strongly influences the opportunities for adopting new energy technologies, including clean ones. That rate varies considerably across the various sectors and types of equipment. Many household appliances and office equipment such as computers may be replaced after a few years, while cars and trucks, heating and cooling systems, and industrial boilers generally last between one and two decades. But most existing buildings, roads, railways and airports and many power stations, oil refineries and pipeline systems are likely still to be in use several decades from now. Existing infrastructure certainly presents challenges for reducing emissions, but there are also technology opportunities to be seized (see Chapter 7 for strategies to deal with existing infrastructure).

Age and distribution of the current asset stock

The scope for replacing the existing energy-related capital stock is determined by the current age of the existing assets and their typical lifetimes. In key sectors, particularly power generation, the average age of energy assets is substantially lower in emerging economies than in advanced economies, reflecting the fact that much of the investment in these assets has been more recent as their economies were growing and industrialising rapidly. For example, around 50% of the installed fossil-fired power generation capacity in China was built within the last ten years, and 85% within the last 20 years. From the point of view of emissions, it is worth noting that

[7] High-value chemicals include ethylene, propylene, benzene, toluene and mixed xylenes.

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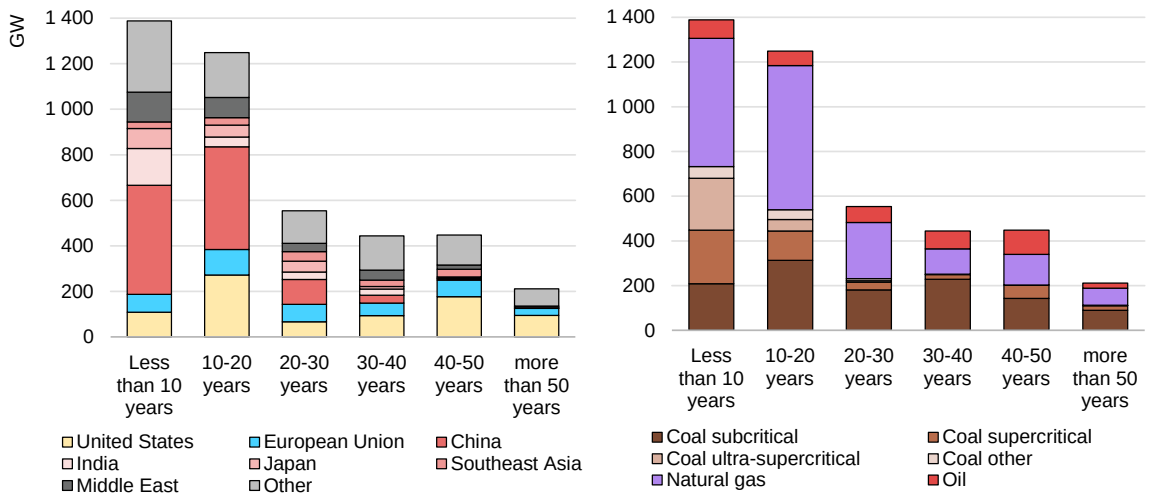
500 GW of subcritical coal plants – the least efficient coal technology – have been added in the last two decades, mainly in China and elsewhere in Asia. Such plants now account for a quarter of global installed coal-fired capacity.

The average age of fossil fuel-based power plants varies considerably around the world (Figure 1.13). The average age of coal plants is over 40 years in the United States and around 35 years in Europe, while it is below 20 years in most Asian countries, and just 13 years in China. Gas-fired power plants are generally younger: they are on average less than 20 years old in all major countries with the exception of Russia, Japan and United States, reflecting the fact that gas was only introduced as a fuel for power generation in many countries from the 1990s. Gas plants however have a shorter technical lifetime than coal plants. Of the 2 100 GW of coal-fired capacity in operation worldwide today and the 167 GW under construction, around 1 440 GW could still be operating in 2050 – 900 GW of it in China. Of the 1 800 GW of gas power plants in operation today and 110 GW under construction, only 350 GW are likely to still be opertional in 2050.

Figure 1.13 Age structure of existing fossil power capacity by region and technology



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Notes: Based on fossil fuel power plants in operation in 2018.
Source: Informed by Platts (2020a).

Around a third of existing coal-fired power capacity worldwide was added during the last decade, and almost a third of that new capacity uses inefficient subcritical technology.

In heavy industry sectors, China again takes centre stage (Figure 1.14). It accounts for nearly 60% of global capacity used to make iron from iron ore – the most energy-intensive step in primary steel production. It also accounts for just over half the world's kiln capacity in cement production and for around 30% of total production capacity for ammonia, methanol and high-value chemicals (HVCs) combined in the chemicals sub-sector. The majority of this capacity is at the younger end of the age

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range in each asset class, averaging between 10 and 15 years, compared with a typical lifetime of 30 years for chemical plants and 40 years for steel and cement plants. The range of ages of individual plants within the country varies considerably, but the output growth over the last 20 years in China's steel (more than sevenfold) and cement (nearly fourfold) sub-sectors shows the relatively short timeframe over which most of these installations have been added.

Our estimates for the steel industry's key assets (blast furnaces and direct reduced iron [DRI] furnaces) incorporate plant-level information on the years when plants were most recently refurbished. Taking this information into account implies that European blast furnaces are among the most recently renewed plants on average (a theme discussed in Chapter 7).

The chemical sub-sector has a more even distribution of capacity both regionally and in terms of age than cement and steel industries. Several chemical facilities have been built in recent years in advanced economies such as the United States as well as in the Middle East. Most of the investment in methanol and HVC capacity has taken place in regions with access to low cost petrochemical feedstocks, particularly North America, Middle East and China. The shale revolution has made US ethane (a compound present in natural gas and a key petrochemical feedstock) comparable in price to ethane in the Middle East, leading to a re-balancing in the geographical spread of chemical production capacity. Methanol and HVC plants are on average around ten years old. Ammonia output growth has been slower than that of HVCs and methanol, with emerging economies generally adding these facilities early in their development, in step with agricultural development. Ammonia plants are on average 15 years old, and around 16 years old in China.

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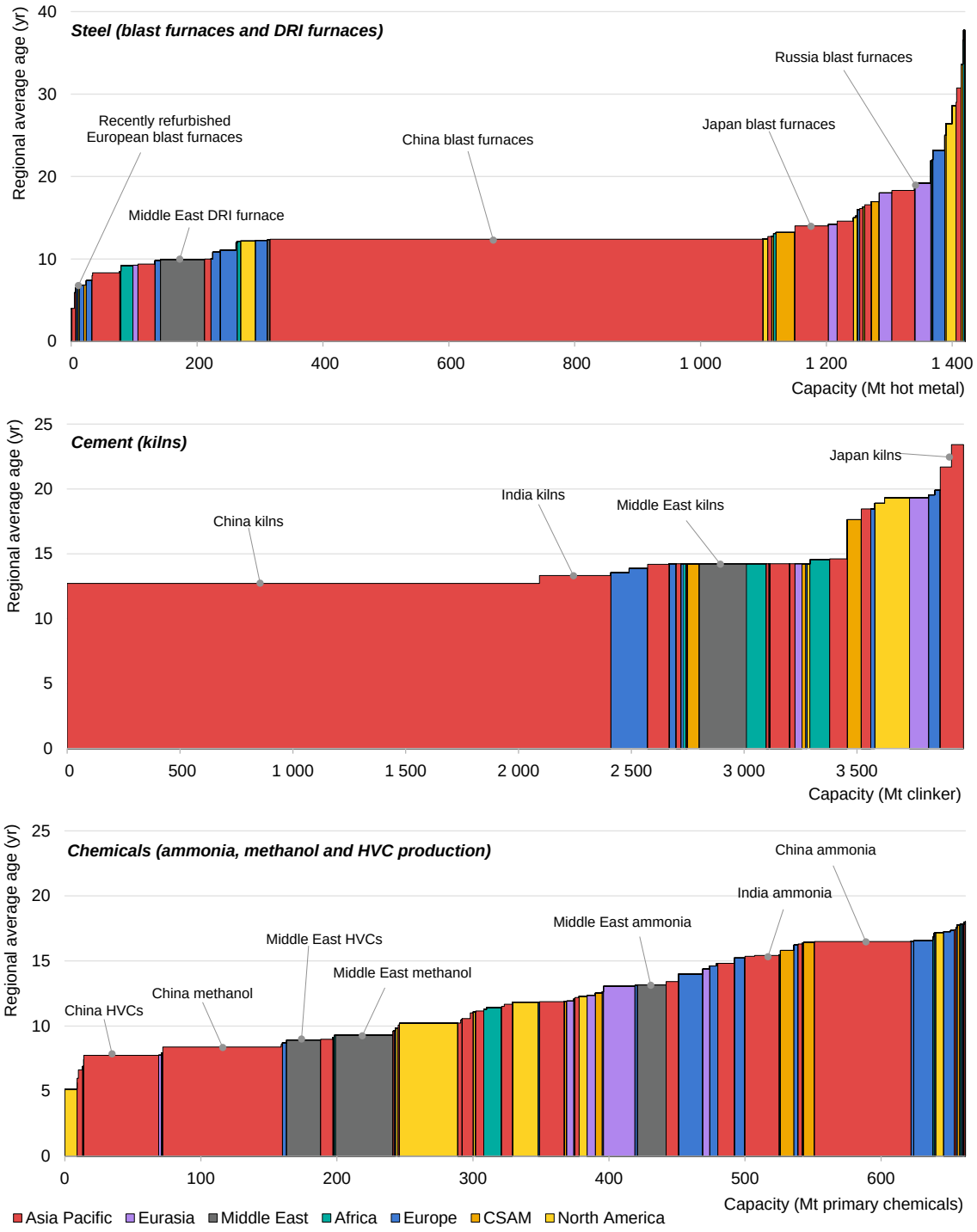
Figure 1.14 Age profile of global production capacity for key industrial sub-sectors



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Notes: CSAM = Central and South America. HVC = high-value chemicals. Average ages are calculated by region or country, depending on data availability, for 2019. Steel data are calculated based on plant-level data, while cement, ammonia, methanol and HVC calculations are based on historic data on capacity additions at the national level.

Sources: Informed by capacity and production data from Steel Institute (2018), Wood Mackenzie (2018), IFA (2020), Platts (2020b), and USGS (2020).

China's middling-to-young production capacity accounts for upwards of 50% of the global total in key industrial sub-sectors. India and the Middle East are also key regions.

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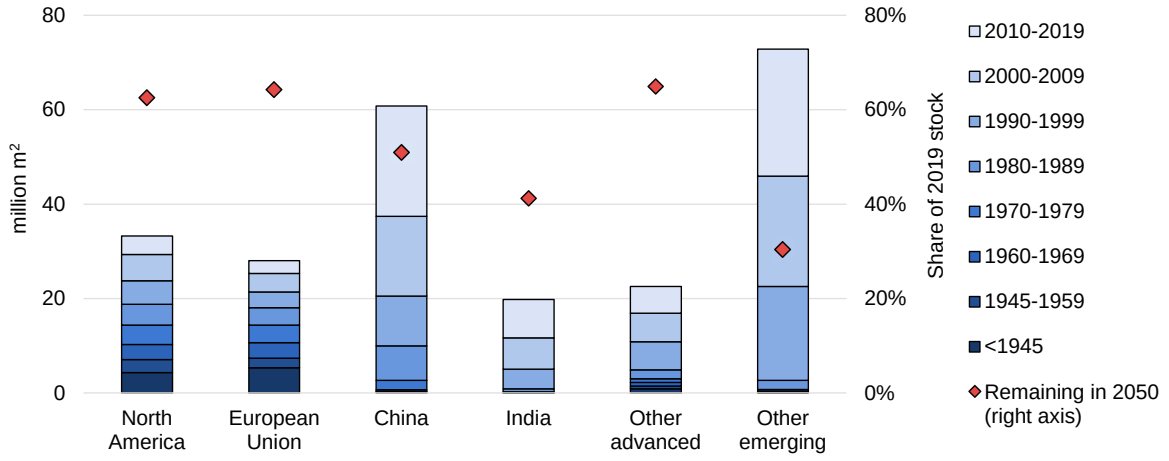
The energy conversion devices that lead to direct emissions in the buildings sector (e.g. natural gas combustion for space and water heating) have a short lifetime compared with power plants and industrial assets: they tend to last for around 15 years. However, the buildings in which they are housed will shape energy consumption and subsequent emissions from the sector for decades. The average age of the buildings stock is between 12 and 15 years for most emerging economies and 30 to 40 years for advanced economies. About half of today's buildings stock is likely to be in use in 2050 (Figure 1.15). The average lifetime of a building varies from 30-50 years for commercial buildings to 70-100 years for modern residential construction and 150 years or more for historic buildings, although low-quality construction can reduce the lifetime of residential buildings to 30 years or less, especially in rapidly emerging economies (IEA, 2019g).

Figure 1.15 Building stock by year of construction and share of stock that remains in 2050



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Note: Building floor area covers residential, commercial, services, education, health, hospitality, public and other non-residential sectors but excludes industrial premises.

Sources: Informed by NRCan (2020), RECS (2020), CBECS (2020), and EU Commission (2020), NBS China (2020).

Around half of today's buildings stock is likely still to be in use in 2050.

The age of a building tends to make a big difference to its heating and cooling needs. Buildings constructed before 1960 for example, can require three-times (or more) as much heat as those built in accordance with current building codes. Building energy codes increase efficiency and reduce energy needs, with the energy requirements of new buildings reducing by around 20% since 2000 globally and by more than 30% in the United States and the European Union[8] (IEA, 2019h). However, the long life of buildings and a relatively small number of renovations means that overall progress is

[8] The European Union in the analysis incorporates EU-27 and the United Kingdom.

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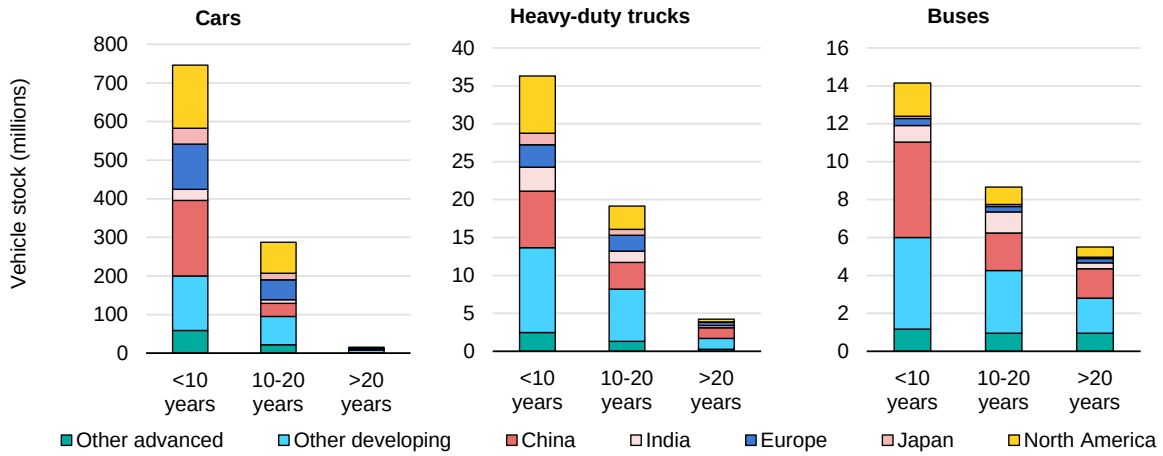
slow: around 60% of the global building stock in use today was erected when there were no code requirements regarding energy performance, and this rises to 85% or more in most emerging economies.

The global vehicle fleet is generally young, with about 70% of cars, trucks and buses being less than ten years old (Figure 1.16). The global passenger car fleet in 2019 reached about 1 billion vehicles. As cars age, many get exported from advanced economies to emerging economies where they may be driven for many more years. The lifetime of cars, trucks and buses is roughly comparable, but trucks in particular are used very intensively by their first owner over a period of three to five years, and as a result they are typically used infrequently for low-intensity operations by the time they reach a decade or more of age.

Figure 1.16 Age profile and geographic distribution of road transport vehicles



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The global car, bus and truck fleets are relatively young, with about 70% of the total being less than ten years old.

The past decade has seen a dramatic shift the location of where new cars are sold, with China surpassing the European and North American market in the early 2010s. Emerging economies have gone from accounting for less than one-quarter of new car sales in 2005 to making up about half of global sales today (IEA, 2019f). The result is that the car fleet in emerging economies is newer than in advanced ones. Around 85% of the cars on China's roads are less than a decade old; in Europe, Japan and North America, cars manufactured within the past ten years make up only about 70% of the fleet. The same general pattern is seen with trucks and buses, but the shifts in new sales of each of these modes are even starker: the majority of trucks sold in the

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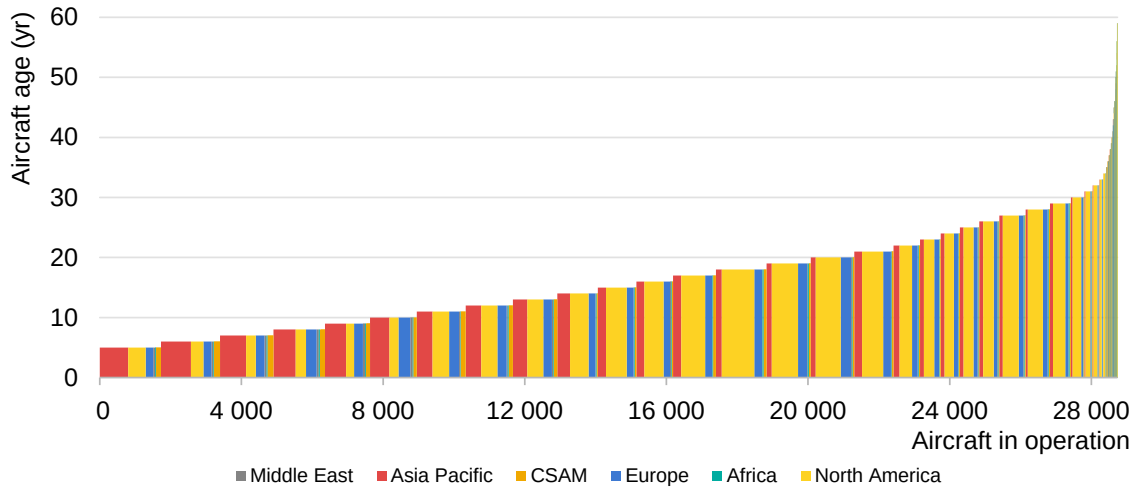
past decade are in emerging economies, as are two-thirds of the buses. With recent declines in car sales in China and India, global car sales may peak in the coming few years.

While about 70% of the global aircraft fleet operating in 2019 was built after 2000, aircraft may continue to operate for 50 years or more (Figure 1.17). The median age of the fleet is around 15 years. Newer aircraft predominantly are providing additional capacity to service rapidly growing demand in Asian Pacific commercial passenger aviation markets. Aircraft operating in Europe are roughly of median age on average, while aircraft servicing the North American market tend toward the older end of the distribution range.

Figure 1.17 Age profile and geographic distribution of aircraft



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Notes: CSAM = Central and South America.

Aircraft built in the past ten years are primarily being used to service rapidly growing demand for commercial passenger aviation in the Asia Pacific region.

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References

Bento, N., C. Wilson and L. Anadon (2018), Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies, Energy Policy, Vol. 119, 08/2018, pp. 282-293, https://doi.org/10.1016/j.enpol.2018.04.015.

CBECS (Commercial Buildings Energy Consumption Survey) (2020), https://www.eia.gov/consumption/commercial/data/2012/bc/cfm/b9.php.

European Commission (2020), EU Building Stock Observatory, https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings/eu-bso.

Gross, R. et al. (2018), How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end-use technology, Energy Policy, Vol. 123, pp. 682-699, https://doi.org/10.1016/j.enpol.2018.08.061.

Grubler, A. (2012), Energy transitions research: Insights and cautionary tales, Energy Policy, Vol. 50, 11/2012, pp. 8-16, https://www.sciencedirect.com/science/article/pii/S0301421512002054.

IAEA (International Atomic Energy Agency) (2020), Power Reactor Information System (PRIS) (database), https://pris.iaea.org/PRIS/home.aspx.

IEA (International Energy Agency) (2020a), Tracking Clean Energy Progress 2020, IEA, Paris, https://www.iea.org/topics/tracking-clean-energy-progress.

IEA (2020b), Clean Energy Innovation, IEA, Paris, https://www.iea.org/reports/clean-energy-innovation.

IEA (2020c), Global Energy Review 2020, https://www.iea.org/reports/global-energy-review-2020.

IEA (2019a), World Energy Outlook 2019, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2019.

IEA (2019b), World Energy Investment 2019, IEA, Paris, https://www.iea.org/reports/world-energy-investment-2019.

IEA (2019c), Nuclear Power in a Clean Energy System, IEA, Paris, https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system.

IEA (2019d), The Future of Hydrogen, IEA, Paris, https://www.iea.org/reports/the-future-of-hydrogen.

IEA (2019e), Energy Efficiency 2019, IEA, Paris, https://www.iea.org/reports/energy-efficiency-2019.

IEA (2019f), Fuel Economy in Major Car Markets: Technology and Policy Drivers 2005-2017, IEA, Paris, https://webstore.iea.org/fuel-economy-in-major-car-markets.

IEA (2019g), Global Status Report for Buildings and Construction 2019, IEA, Paris, https://webstore.iea.org/material-efficiency-in-clean-energy-transitions.

IEA. All rights reserved.

IEA (2019h), Material efficiency in clean energy transitions, IEA, Paris, https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

IFA (International Fertilizer Association) (2020), International Fertilizer Association Database, http://ifadata.fertilizer.org/ucSearch.aspx.

IHS Markit. (2018). Vehicle Registrations and Other Characteristics at Model Level (database), June 2018), IHS Markit, London, https://ihsmarkit.com/btp/polk.html.

IPCC (Intergovernmental Panel on Climate Change) (2018), Summary for Policymakers. In: Global Warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty, Masson-Delmotte, V., P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), World Meteorological Organization, Geneva, https://www.ipcc.ch/sr15/.

S&P Global Platts (2020a), World Electric Power Plant Database (purchased), April 2020, S&P Global Platts, London.

S&P Global Platts (2020b), Global Olefins Outlook 2019-2029, S&P Global Platts, London, https://www.spglobal.com/platts/en/products-services/petrochemicals/global-polyolefins-outlook.

NBS (National Bureau of Statistics of China) (2020), http://www.stats.gov.cn/english/Statisticaldata/AnnualData/.

NRCan (Natural Resources Canada) (2020), Statistics Canada, https://www150.statcan.gc.ca/n1/en/type/data?MM=1.

RECS (Residential Energy Consumption Survey) (2020), https://www.eia.gov/consumption/residential/data/2015/hc/php/hc2.3.php.

Smil, V. (2010), Energy Transitions: History, Requirements, Prospects, Praeger, https://products.abc-clio.com/abc-cliocorporate/product.aspx?pc=A2598C.

Steel Institute (2018), Steel Institute VDEh PLANTFACTS database (purchased), Stahl-Online, https://en.stahl-online.de/index.php/about-us/vdeh/.

Tong, D. et al. (2019), Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target, Nature 572, 373-377, https://doi.org/10.1038/s41586-019-1364-3.

United Nations Population Division (2019), 2019 Revision of World Population Prospects, UN, New York. https://population.un.org/wpp/.

US EIA (United States Energy Information Administration) (2020), Electricity, Detailed State Data, US EIA, Washington, DC, https://www.eia.gov/electricity/data/state/.

USGS (United States Geological Survey) (2020), Cement Statistics and Information, https://www.usgs.gov/centers/nmic/cement-statistics-and-information.

Wood Mackenzie (2018), Methanol Production and Supply Database (purchased), www.woodmac.com/research/products/chemicals-polymers-fibres/.

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Chapter 2. Technology needs for net-zero emissions

- An energy sector transition to net-zero CO_2 emissions by 2070 of the kind depicted in the Sustainable Development Scenario requires a radical technological transformation of the energy sector. Energy efficiency and renewables are central pillars, but additional technologies are needed to achieve net-zero emissions. Four technology value chains contribute about half of the cumulative CO_2 savings: technologies to widely electrify end-use sectors (such as advanced batteries); carbon capture, utilisation and storage (CCUS); hydrogen and hydrogen-related fuels; and bioenergy.
- Greater use of clean electricity is central for decarbonisation. The share of electricity in final energy demand grows from one-fifth today to nearly 50% in 2070 in the Sustainable Development Scenario, contributing almost a fifth of cumulative CO_2 savings. Electricity demand expands by 30 000 TWh, which means that each year to 2070 sees electricity demand equivalent to the current annual demand of Mexico and the United Kingdom combined be added to the world power system, pushing far more use of solar, wind and other renewables, as well as nuclear power.
- CCUS technologies can reduce the emissions of fossil-fired plants in power generation and industry, provide negative emissions, and in the longer term produce carbon-neutral CO_2 to produce fuels. In the Sustainable Development Scenario, bioenergy with carbon capture and direct air capture create in combination with storage 3 Gt of negative emissions in 2070 or are used to produce 5 mb/d of clean aviation fuels.
- Global hydrogen production grows by a factor of seven to 520 Mt in 2070. Hydrogen use expands to all sectors and reaches a share of 13% in final energy demand in 2070. The development of technologies at the demonstration and prototype stage today leads to hydrogen and hydrogen-based fuels becoming important for the decarbonisation of heavy trucks, aviation and shipping as well as for the production of chemicals and steel.
- The share of sustainable biomass in primary energy demand doubles to 20% in 2070, reflecting versatility and technology readiness of much of the related value chain. It is used to make transport biofuels and generate power and heat; in both cases, it is frequently coupled with CCUS. Bioenergy provides 12% of the cumulative emissions reductions in the Sustainable Development Scenario.

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Plotting a path to net-zero emissions

If the goal of the Paris Agreement of 2015 is to be met, the clean energy transition will need to bring about a rapid reduction in emissions of greenhouse gases to zero on a net basis over the coming decades.

The Paris Agreement set a goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". It also calls for greenhouse gas emissions to peak as soon as possible and for a rapid reduction thereafter in order to achieve net-zero emissions – in the second half of this century. Achieving net-zero emissions requires any remaining anthropogenic emissions to be entirely offset by anthropogenic carbon sinks such as changes in land-use systems or the removal of carbon dioxide (CO_2) through bioenergy with carbon capture and storage (BECCS) or direct air capture with storage.

The Paris Agreement goal does not correspond to a single pathway for energy sector CO_2 emissions or a specific date for achieving net-zero emissions. This is because that goal spans a range of outcomes and because the required energy trajectory depends on emissions from outside the energy sector, as well as emissions of other greenhouse gases and air pollutants that also have climate effects (Box 2.1). The precise timing of the need for overall net-zero greenhouse gas emissions worldwide also depends on how soon the peak in emissions is achieved and the rate at which emissions are subsequently reduced.

Net-zero CO_2 emissions for the energy sector mean that any remaining emissions in sectors where abatement is technically difficult or very costly would need to be fully offset by negative emissions through BECCS or direct air capture with storage in other parts of the energy sector. Similarly, any emissions persisting in particular countries or regions would need to be balanced by net-negative emissions in other countries. Assuming that emissions peaked in 2019 and that they decline in a steady, near-linear fashion from now on, as in the Sustainable Development Scenario, then current research suggests that achieving net-zero emissions from the energy sector globally by around 2070 would limit the global temperature rise to below 1.8°C by 2100, with a 66% probability if CO_2 emissions remain at net-zero after 2070 (IEA, 2019a). If CO_2 emissions were to fall below net-zero after 2070, then this could increase the possibility of reaching 1.5°C by the end of the century, depending on the level of carbon removal eventually reached. Removing carbon through negative emissions is a very common feature of the scenarios assessed by the

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Intergovernmental Panel on Climate Change (IPCC) in its special report: 88 out of the 90 scenarios in the IPCC's report assume some level of net-negative emissions.[1]

Box 2.1 Non-energy sector and non-CO_2 emissions

In *Energy Technology Perspectives 2020*, unless otherwise stated, historical and projected CO_2 emissions from the energy sector include those from fossil fuel combustion as well as from industrial processes, which are often closely linked to energy use. On this basis, CO_2 emissions from the energy sector account for 92% of all anthropogenic CO_2 emissions and for 70% of all greenhouse gas emissions. The combustion of bioenergy is considered to be carbon-neutral (following the Intergovernmental Panel on Climate Change's [IPCC] 2006 *Guidelines for National Greenhouse Gas Inventories*), with energy-related CO_2 emissions in the production of bioenergy feedstocks or the conversion of biofuels being accounted for within the agriculture and other energy transformation sectors. CO_2 emissions from non-energy activities predominately arise through agriculture, forestry and other land use, and accounted for 7% of all anthropogenic CO_2 emissions in 2017. These emissions will also need to be reduced in order to meet the goals of the Paris Agreement.

Emissions of greenhouse gases other than CO_2, such as methane (CH_4, which accounted for 16% of all greenhouse gas emissions in 2017), nitrous oxide (N_2O, 6%) and various chemical compounds used in aerosols (2%), originate mainly from non-energy sectors, notably agriculture and waste processing. Variations in the projections from these sectors affect the necessary rates of transformation of the energy sector. The IPCC *Fifth Assessment Report Scenario Database* contains projections of non-CO_2 emissions over the 21st century across a number of scenarios; it is thus possible to determine the residual CO_2-only budgets for particular temperature targets by using these IPCC projections of non-CO_2 emissions to 2100.

Energy transition scenarios

As with previous editions of *Energy Technology Perspectives* (ETP), this report adopts a scenario approach to exploring the outlook for clean energy technologies and, specifically, the energy transition that would be required to achieve climate and

[1] A critical parameter in the analyses of the temperature impact is the climate sensitivity, describing the temperature impact of doubling the CO_2 in the atmosphere. A recent study indicates that the uncertainty range for this parameter could be smaller than previously thought (Sherwood et al., 2020), which could imply that the Sustainable Development Scenario would at a 66% probability result in a slightly lower temperature increase than 1.8°C.

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broader energy sustainability goals. Projections for two main scenarios, which are also employed in the International Energy Agency's (IEA) flagship publication, the *World Energy Outlook*, are presented here. These two scenarios map out different energy technology pathways over the period to 2070, and are differentiated primarily by the assumptions they make about government policies.

Sustainable Development Scenario: This is the scenario which lies at the heart of *ETP-2020* and that is used to illustrate the technology needs for reaching net-zero emissions from the energy sector. It describes the broad evolution of the energy sector that would be required to reach the United Nations Sustainable Development Goals (SDGs) most closely related to energy: achieving universal access to energy (SDG 7), reducing the impacts of air pollution (SDG 3.9) and tackling climate change (SDG 13). It is designed to assess what is needed to meet these goals, including the Paris Agreement, in a realistic and cost-effective way. The trajectory for energy- and industry-related CO_2 emissions in the Sustainable Development Scenario is consistent with reaching global net-zero CO_2 emissions from the energy sector in 2070.[2]

Stated Policies Scenario: This scenario serves as a benchmark for the projections of the Sustainable Development Scenario. It assesses the evolution of the global energy system on the assumption that government policies and commitments that have already been adopted or announced with respect to energy and the environment are implemented, including commitments made in the nationally determined contributions under the Paris Agreement. Where commitments are aspirational, such as the goal of reaching net-zero emissions, a judgement is made as to the likelihood of those commitments being fully met based on an assessment of the impact of measures that have been agreed to date. This scenario does not assume any future changes to existing and announced policies and measures, although it does consider their impact on long-term technology evolution as a means to guide scenario expectations beyond the time horizon of current policy plans.

The scope of the projections in terms of the regional, sectoral and technology coverage is the same for each scenario, but the modelling approach differs. For the Stated Policies Scenario, the approach involves defining a set of starting conditions and then modelling where they lead the energy system, without aiming to achieve any particular outcome. The opposite approach is used for the Sustainable Development Scenario, which involves defining a set of future outcomes and

[2] An additional Faster Innovation Case, presented in Chapter 6, explores the technology needs for reaching net-zero emissions by 2050.

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modelling how they can be achieved in a least-cost manner through policy interventions, including targeted support for technology research, development, demonstration and deployment.

The projections for both scenarios are generated by the IEA's ETP Model, a large-scale energy systems model that comprises optimisation or simulation models (depending on the sector) and embodies a rich representation of current and future technology options across all sectors. The ETP Model has been developed over many years, using the latest data for energy demand and supply, costs, and prices.[3] It comprises four interlinked technology-rich models that cover the energy supply and transformation, buildings, industry, and transport sectors. One of the features of the framework is its technological richness, which is underpinned by a thorough assessment of technology readiness at all levels, from broad technology families and supply chains to individual technologies, sub-types and components; overall, the *ETP* comprises more than 800 technologies that are modelled individually, 230 of which are today not yet commercially deployed (see Box 2.6). Depending on the sector, the modelling framework includes 28-39 world regions or countries. *ETP-2020* covers the period to 2070, expanding the analysis beyond the 2060 timeframe of the last edition in 2017.

The projections for both scenarios build on those of the *World Energy Outlook 2019* (IEA, 2019b), which run to 2040 and are based on the IEA World Energy Model. They have, however, been updated with new GDP and energy price assumptions to take into account the macroeconomic impacts of the Covid-19 pandemic. Key assumptions and more detail on the modelling framework are presented in the online documentation of the ETP Model. Emerging near- and medium-term energy and emissions trends will be discussed in the forthcoming *World Energy Outlook 2020*.

The scenarios should not be considered as predictions, but rather as assessments of the impact of different policy approaches on energy and emissions trends as well as technology choices: their aim is to provide a quantitative framework in order to support decision making and policy making in the energy sector and to improve understanding of the need for technological innovation in energy supply and use. Any projection of energy supply or use 50 years ahead is bound to be speculative to some degree as we cannot know with certainty how technology will evolve. The further into the future we look, the greater the uncertainty about how technology will change, the types of new technology that will emerge and how quickly they will be deployed.

In recognition of these uncertainties, neither of the two scenarios assumes the emergence of technologies that are not already known. In the period to 2040, most of the technologies that are deployed are already commercially available or are on

[3] Full descriptions of the model and key assumptions can be found on line at: www.iea.org/reports/energy-technology-perspectives-2020/etp-model.

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the brink of large-scale commercialisation; beyond 2040, some other technologies that are already in the innovation pipeline (i.e. at a stage of development that makes commercial-scale deployment possible by 2070) are also deployed at greater scale. Given the enormous uncertainties surrounding whether and when such technologies will become commercial, only technologies for which there is sufficient technical and economic information for modelling purposes are considered, though others are identified as potentially having an impact before 2070. The rate of deployment of both the best available existing technologies and new technologies that will become available in the future is considerably faster in the Sustainable Development Scenario on the assumption of much more rigorous policy action. More than 400 individual technology designs and components across the whole energy system have been assessed in the new *ETP Clean Energy Technology Guide* for their potential contribution to achieving the goal of net-zero emissions.[4]

The path to net-zero emissions in the Sustainable Development Scenario

CO_2 emission trajectories

The significant gap in energy sector CO_2 emissions between the Stated Policies Scenario and the Sustainable Development Scenario over the projection period represents the size of the challenge the world faces in achieving sustainable development through the accelerated deployment of clean energy technologies. In the Stated Policies Scenario, global emissions return onto an upward trajectory after a decline in 2020 due to the macroeconomic impacts of the Covid-19 outbreak (Figure 2.1). By contrast, in the Sustainable Development Scenario, the measures taken for sustainable recovery in the wake of the pandemic and additional policy action mean that emissions peak in 2019 and fall to zero on a net basis by 2070.[5]

[4] The interactive *ETP Clean Energy Technology Guide* is available at: www.iea.org/articles/etp-clean-energy-technology-guide.

[5] Technology implications to reach net-zero emissions already by 2050 are discussed in a Faster Innovation Case in Chapter 6.

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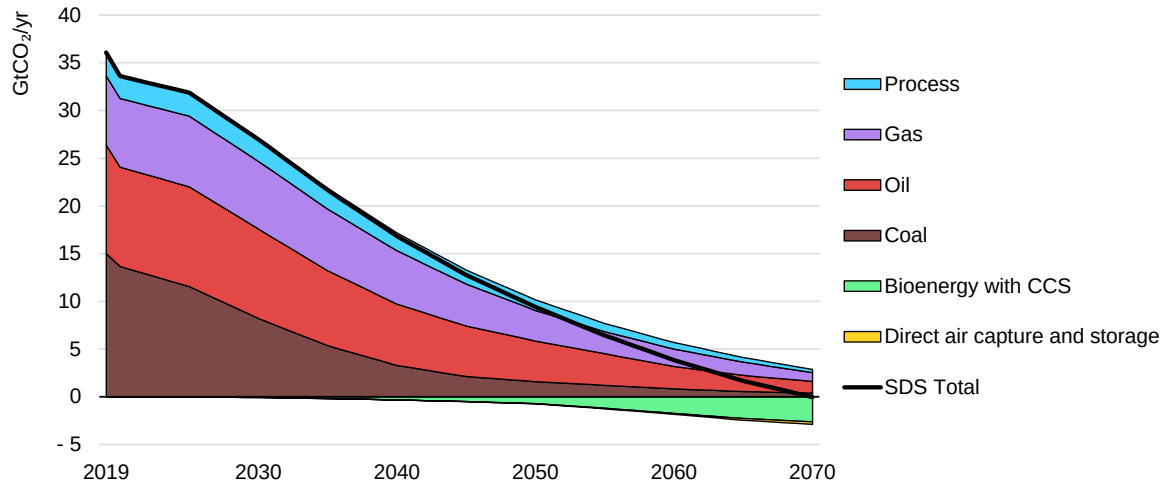
Figure 2.1 Global energy sector CO_2 emissions by fuel and technology in the Sustainable Development Scenario, 2019-70



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Notes: CCS = carbon capture and storage. SDS= Sustainable Development Scenario.

In the Sustainable Development Scenario, CO_2 emissions from fossil fuel combustion and industrial processes drop to 3 Gt in 2070; they are offset by negative emissions technologies, resulting in net-zero emissions.

Achieving net-zero CO_2 emissions requires a range of measures and a range of technological transitions (Figure 2.2). The immediate opportunities are in energy efficiency, in particular in industrial processes, space heating and cooling, and the fuel economy of vehicles, (Box 2.2) and energy from renewable sources, in particular wind and solar photovoltaic (PV). Over the next two decades, energy efficiency and renewables contribute between them around 70% of cumulative CO_2 emissions savings relative to the Stated Policies Scenario. Material efficiency reduces demand for energy services and is another immediate opportunity: it saves around 5% of cumulative emissions through to 2040 by reducing the need to produce materials (through designing for long life, lightweighting, reducing material losses during manufacturing and construction, amongst other actions: see also the section on "Focus on material efficiency: A blind spot?" below).

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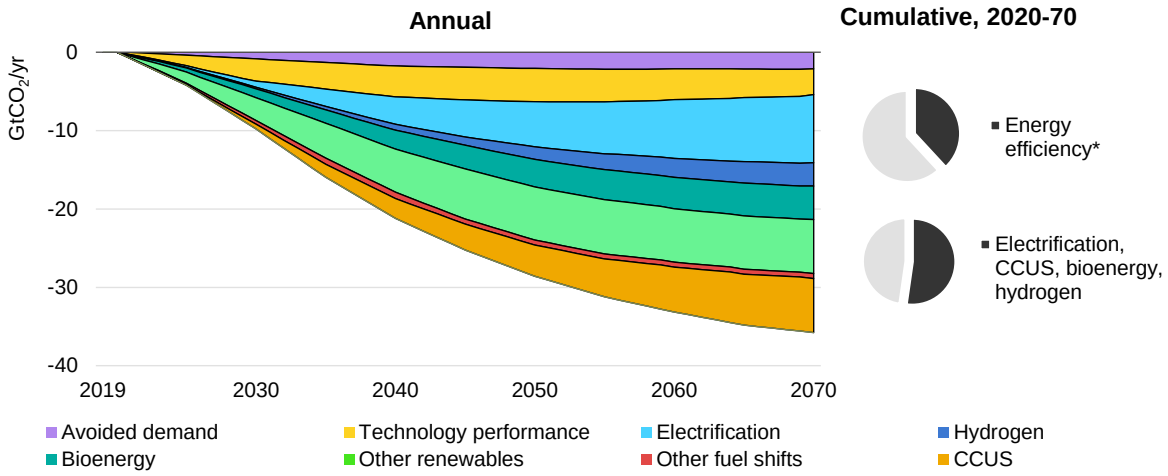
Figure 2.2 Global energy sector CO_2 emissions reductions by measure in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-70



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* Energy efficiency includes enhanced technology performance as well as shifts in end-use sectors from more energy-intensive to less energy-intensive products (including through fuel shifts).

Notes: CCUS = carbon capture, utilisation and storage. See ETP model documentation for the definition of each abatement measure. *Hydrogen* includes low-carbon hydrogen and hydrogen-derived fuels such as ammonia.

Electrification, CCUS, bioenergy and hydrogen-derived fuels contribute to more than half of cumulative emissions reductions from 2020 to 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario.

Box 2.2 Energy efficiency benefits in the Sustainable Development Scenario

Energy-efficient technologies and services contribute to about 40% of cumulative emissions reductions to 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario (Figure 2.2). Those stem from efficiency improvements and refurbishments to further enhance technology or process efficiency and from shifting towards low-carbon electric, renewable, or hydrogen end-use equipment that are more efficient than existing products. Avoided demand through material efficiency, public transportation, and active controls also contributes.

Energy efficiency contributes to lower CO_2 emissions in two ways:

- **Reducing total energy use:** total final energy demand is more than 30% lower in 2070 in the Sustainable Development Scenario than in the Stated Policies Scenario. Such savings are enabled by a strong decline of end-use energy intensity*, particularly in buildings and road transport (-50% to -65% relative to 2019). Short-term opportunities pair with electrification on the longer-run. In

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2070, the share of electricity in total final energy use is 20% higher than in the Stated Policies Scenario.

- **Placing downward pressure on upstream supply systems,** the pace of decarbonisation of which can be constrained by resource availability (e.g. biomass, rare earth), land-use (e.g. solar PV) and technology cost. For example, lower peak power capacity needs can reduce the cost of decarbonising electricity: high-efficiency cooling alone could save USD 1.2 trillion globally through to 2050 as avoided capital spending for power generation (IEA, 2018b).

Energy efficiency benefits however are much broader than reducing emissions and also contribute to policy priorities such as energy security, clean energy access, job creation, economic growth, productivity, public budgets, air quality or health and well-being (IEA, 2019d). To take full advantage, policy packages should aim at steering demand for high-efficiency products, integrating multiple components such as regulation (i.e. mandatory standards for vehicles, motors, appliances, etc.), incentives (i.e. creating a push effect with subsidies, rebates, etc.) and information (i.e. collecting data to monitor and disclose progress using labelling, certifications, digital visualisation tools, etc.). In parallel, R&D should aim at enhancing best available product performance while broadening their applicability to foster efficiency via fuel shifting (e.g. extending heat pump use to a broader range of industrial or building renovation applications).

* Energy intensity was assessed based on final energy use per square meter for buildings, final energy use per vehicle-kilometre for road transport, and final energy use per USD of industry value added at purchasing power parity for industry.

In the long run, four additional technology opportunities emerge as critical for the path to net-zero emissions:

- **Electrification of end-use sectors.** The contribution of electrification to emissions reductions increases as the power sector becomes fully decarbonised: electrification accounts for 20% of cumulative savings relative to the Stated Policies Scenario in 2070, making it the largest single contributor to CO_2 abatement.
- **CCUS.** The role of CCUS changes over the projection period: at first the focus is on decarbonising existing assets in the power sector and heavy industries, but over time it shifts towards the removal of carbon from the atmosphere, offsetting emissions in sectors where they are hard to abate (see Chapters 4 and 5). CCUS makes the fourth-largest contribution to cumulative emissions savings in 2070, accounting for 15% of the total.

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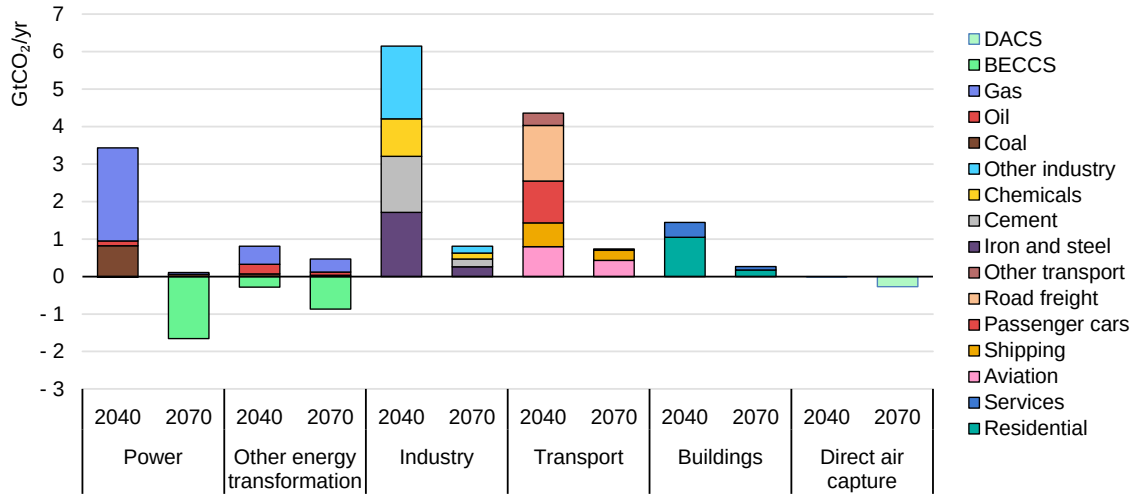
- **Low-carbon hydrogen and synthetic fuels** such as ammonia and synthetic hydrocarbon fuels. The use of these fuels increases over time across different sectors and contributes 6% of cumulative emissions savings by 2070, relative to the Stated Policies Scenario.
- **Sustainable bioenergy.** While sustainably grown bioenergy plays an important role in curbing emissions in the near term in the Sustainable Development Scenario, for example in transport, it has additional potential across different parts of the energy sector, such as in industrial applications. It contributes 12% of cumulative savings in 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario.

These four technology families are central to efforts to reduce emissions, especially in sectors where emissions are difficult to reduce, notably in industry and long-distance transport. Many parts of their value chains are, however, at an early stage of deployment, and they are less developed overall than renewables, nuclear for power generation and technologies to improve the efficiency of using fossil fuels (see below).

Figure 2.3 Global energy sector CO_2 emissions by sector and sub-sector/fuel in the Sustainable Development Scenario, 2040 and 2070



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Notes: BECCS = bioenergy with carbon capture and storage. DACS = direct air capture and storage. *Other energy transformation* includes coal mining, oil and gas extraction, oil refining, coal and gas transformation and liquefaction, production of hydrogen and hydrogen-based fuels, and biofuels production with and without CCS.

The emissions that remain in 2070 in the Sustainable Development Scenario are concentrated in sectors where emissions are hard to abate – essentially heavy industry and long-distance transport.

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Opportunities for reducing emissions in the next 20 years are greatest in those sectors where the current capital stock has the shortest remaining operational lifetimes (see Chapter 1), and where economically and technically viable clean energy technologies are already available. In the transport sector, this includes passenger cars (most of which are running on electricity by 2070), and in the buildings sector it includes hot water supply from heat pumps. But in other sectors, and in particular in heavy industry and long-distance transport, the remaining lifetime of existing assets is generally long and the availability of clean energy technology alternatives is limited. For this reason, global emissions are not projected to fall to zero in those sectors until after 2070 (Figure 2.3). The bulk of industrial emissions remaining in 2070 are in the iron and steel and cement sectors, where carbon-neutral technologies are today at demonstration or large prototype level; the bulk of transport emissions remaining in 2070 come from aviation, shipping and road freight.

Box 2.3 Reduced air pollution in the Sustainable Development Scenario

Clean energy technology is not just needed to deal with the climate crisis. The energy sector is also by far the largest source of air pollution from human activity: the three major air pollutants are NOx, SO_2 and particulate emissions, and the energy sector accounts for over 99% of the first two and over 85% of the third.

Air pollution comes primarily from the combustion of fossil fuels and traditional use of solid biomass, but also from fossil fuel extraction and other forms of mining and industrial activities, the processing/washing of coal, the transportation of coal and natural gas, and oil refining and charcoal production. Air pollution also comes from non-exhaust emissions from the transport sector (mainly tyre and brake wear, and road abrasion, but also fine dust particles of quartz sand and steel abrasion in rail transport). Fortunately, technologies are in place already today that can drastically reduce pollution: post-combustion control technologies are generally cheap, available and proven, so implementation is largely a matter of policy, monitoring and enforcement.

The decarbonisation of the energy system in the Sustainable Development Scenario also helps bring down the level of pollutant emissions. Outdoor air pollution is minimised mainly through a drastic reduction in the use of fossil fuels in power generation and industry and a shift towards low-carbon fuels in transport. The use of clean fuels for cooking also all but eliminates household air pollution from the use of traditional biomass for cooking. Global energy-related SO_2 emissions fall from 55 Mt in 2019 to 13 Mt in 2070, mainly through emissions reductions in the industry and power sector that stem from reduced use of coal. Global NOx emissions fall by over 80% to 16 Mt, mainly due to a reduction in emissions from transport and from

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industrial and power facilities. Global $PM_{2.5}$ emissions fall by 80% to 3 Mt largely thanks to a reduction in the use of polluting fuels for cooking, in particular the near total phase-out of the traditional use of biomass in the residential sector of emerging economies.

Although the Sustainable Development Scenario tackles many of the root causes of air pollution, reducing air pollutant emissions does not need to (and should not) wait for the decarbonisation of the energy sector, given the severity of its impacts on human health: technologies for post-combustion treatment are already proven and available. In the Sustainable Development Scenario, the widespread adoption of such technologies alongside measures for monitoring and enforcement mean that the majority of the decline in pollutant emissions (99% for SO_2, 87% for NO_x and 95% for $PM_{2.5}$) occurs prior to 2040.

Source: Based on IEA and International Institute for Applied Systems Analysis. For more information on methodology and data see e.g. IEA (2016) and IEA (2019a).

The extent of the challenge faced in reducing CO_2 emissions varies markedly across regions. The reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario are largest in absolute terms in regions where the energy sector is emissions-intensive today and where emissions are projected to be large on the basis of current policy plans (Figure 2.4). The proportion of cumulative emissions in the Sustainable Development Scenario expected to come from current infrastructure is highest in the People's Republic of China (hereafter "China") due to its young fleet of power stations, industrial and other capital stock, highlighting the critical importance of efficiency and CCUS retrofits there.

While low-carbon technologies mitigate CO_2 emissions, they can also help to reduce air pollution and their negative health impacts. Actually, the need to tackle air pollution has been in some cases a major driver for the deployment of clean technologies, such as support measures for electric vehicles or public transport in some heavily polluted cities (Box 2.3).

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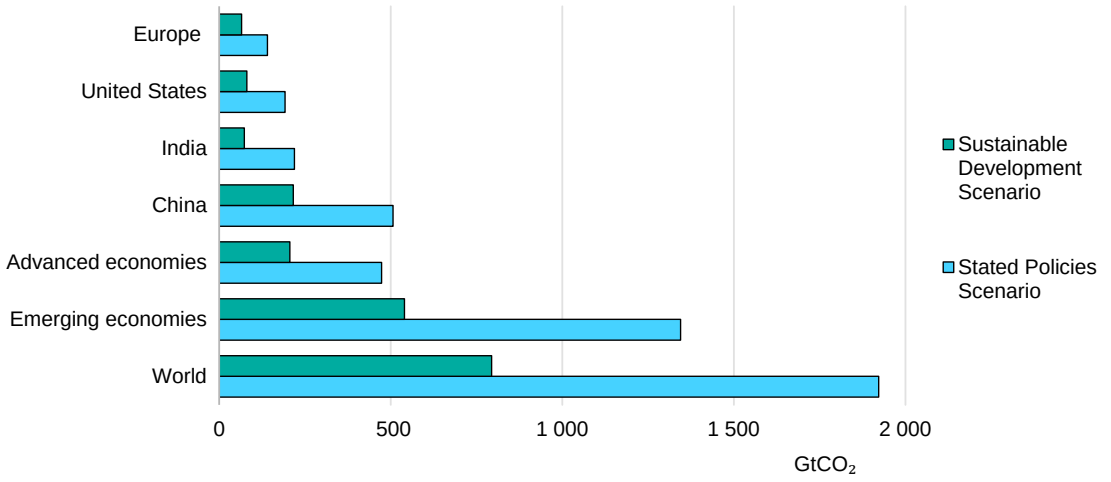
Figure 2.4 Cumulative energy sector CO_2 emissions by region and scenario, 2019-70



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The emissions reductions required in the Sustainable Development Scenario are greatest in countries with an emissions-intensive capital stock.

Energy implications

Trends in primary energy demand

World primary energy demand[6] increases only modestly between 2019 and 2070 in the Sustainable Development Scenario, by which time the global population is 35% more than it is today and the economy about 3.5 times larger (Table 2.1). This compares with an increase of nearly 40% in global primary energy demand in the Stated Policies Scenario, and the extent of the decoupling of economic growth and energy demand represents a significant break with past trends.

[6] Primary energy refers to energy in its initial form before being subjected to any human-engineered conversion process. Some energy is converted in power stations, refineries, heat plants and other transformation processes. Final consumption refers to energy and feedstock use in final end-use sectors net of losses in transformation and distribution.

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Table 2.1 Primary energy demand by fuel and scenario (Mtoe)

		Sustainable Development Scenario		Stated Policies Scenario
	2019	2040	2070	2070
Coal	3 783	1 309	696	3 188
Oil	4 523	3 000	1 156	4 778
Natural gas	3 336	3 056	2 048	4 786
Nuclear	728	1 140	1 472	1 101
Renewables	2 220	5 325	9 905	6 013
Hydro	371	585	840	716
Modern bioenergy	935	2 365	2 948	2 252
Traditional use of biomass	588	0	0	287
Solar	118	1 156	3 414	1 283
Wind	123	759	1 564	845
Other renewables	86	461	1 140	630
Total	**14 590**	**13 830**	**15 278**	**19 865**
Net CO_2 emissions ($MtCO_2$)	*36 064*	*16 834*	*0*	*35 737*

Notes: Primary energy demand includes conversion losses from biofuel production. *Modern bioenergy* includes biomass processed/pre-treated for electricity generation, industrial applications and biofuel production. *Traditional use of biomass* refers to burning locally sourced biomass for household cooking and heating, using basic technology such as an open fire pit.

The much slower increase in energy demand in the Sustainable Development Scenario is largely the result of big gains in energy and material efficiency: these help keep demand at roughly current levels through to the early 2050s, when it slowly begins to rise again because most of the potential for efficiency gains from currently available technologies has been exploited. Energy intensity – the amount of energy consumed per dollar of GDP – falls by two-thirds between 2019 and 2070, corresponding to a decline of the energy intensity of 2.2% per year, more than a third higher than the rate of 1.6% per year observed over the period 1990-2019.

The Sustainable Development Scenario sees a dramatic rise in the use of clean energy sources through to 2070. They account for 20% of global energy demand today: this doubles to around 40% in the Stated Policies Scenario, but it goes up much further to some 75% in the Sustainable Development Scenario (Figure 2.5).

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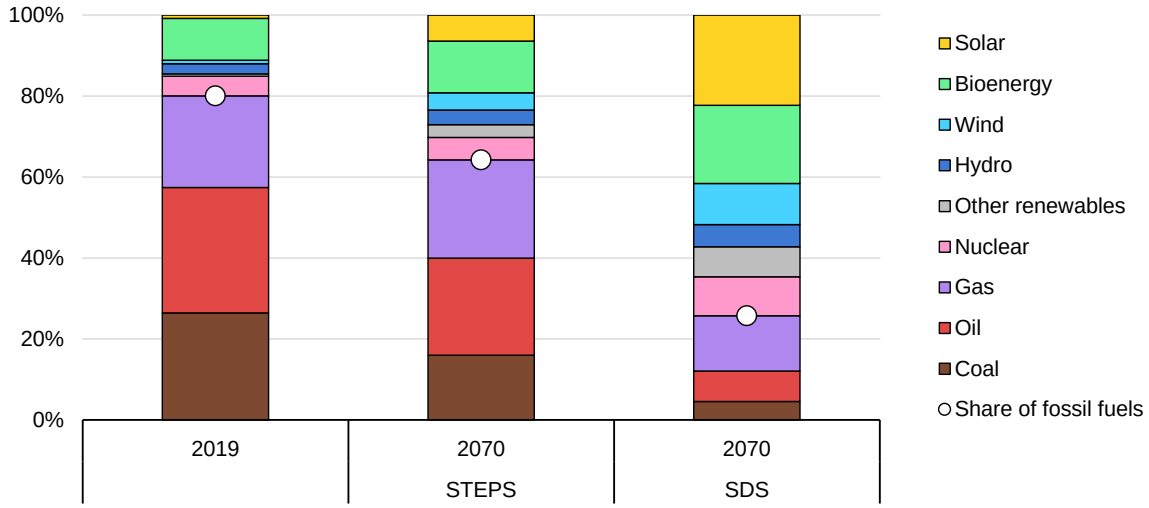
Figure 2.5 Global primary energy demand by fuel share and scenario, 2019 and 2070



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. *Bioenergy* includes traditional biomass use and modern bioenergy as well as the conversion losses from biofuel production. *Other renewables* include geothermal and ocean energy.

With fossil fuel use falling rapidly, renewables rise from 15% in 2019 to more than 60% in 2070 in the Sustainable Development Scenario, and solar energy becomes the largest primary energy source.

The use of fossil fuels falls rapidly over the projection period, and most of those fuels that are still used in 2070 do not produce emissions thanks to the widespread deployment of CCUS at both new and existing power stations and industrial plants. Coal consumption all but disappears, with remaining coal use in 2070 being dominated by iron and steel production. Oil demand falls by 75% below today's level to around 20 mb/d; nearly 65% of oil demand in 2070 is for non-emitting feedstocks and most of the remainder is for transport (aviation and shipping). Gas demand peaks during the 2020s and falls nearly 40% below today's levels by 2070. It is primarily used in 2070 as a feedstock in the chemicals industry, as a fuel in power generation mostly equipped with carbon capture (to provide electricity-system flexibility), and as a fuel and feedstock in hydrogen production, again mostly equipped with carbon capture.

As for non-fossil fuels, nuclear primary energy use more than doubles between 2019 and 2070, with emerging economies in Asia accounting for around 75% of the growth in capacity. The share of renewables, including hydropower and solid biomass, jumps from around 15% in 2019 to more than 60% in 2070. Solar energy, which is used for power generation and for heating purposes in buildings and industry, becomes by 2070 the largest primary energy resource, accounting for more than 20% of global primary energy demand. Sustainable bioenergy reaches an almost similar level in the

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global primary energy mix, in part because its versatile nature means that it can be used to provide power and heat for buildings and industry or converted into liquid fuels for transport.

The growth in the global use of renewables – largely solar PV, wind power and bioenergy – in the Sustainable Development Scenario represents an acceleration of current trends, and is driven by stronger policies to tackle climate change, enhance energy security and improve air quality: these policies spur faster improvements in technology and cost reductions and encourage faster deployment. The integration of much higher shares of variable renewables into electricity systems requires far greater use of flexibility mechanisms, such as energy storage, to ensure electricity security. Greater electrification of end uses facilitates this integration by increasing the potential of demand response (e.g. flexible electric vehicle charging).

Energy needs in the Sustainable Development Scenario fall fastest in the advanced industrialised countries, where economic and demographic growth rates are lower. Primary demand is around 25% lower in 2070 than in 2019 in Europe and North America, where there is greater potential for efficiency gains (Table 2.2). In India and most other emerging economies, notably in Africa and the Middle East, demand increases through to 2070, though at a much lower rate than in the Stated Policies Scenario. Demand in China falls by nearly one-fifth, as efficiency measures compound a slowdown in the rate of economic growth. Developing regions account for most of the remaining consumption of fossil fuels in 2070, reflecting their large and relatively young industrial sectors, where eliminating direct and process emissions is hardest.

Table 2.2 Primary energy demand by region and scenario (Mtoe)

			Sustainable Development Scenario		Stated Policies Scenario
	2000	2019	2040	2070	2070
Americas	3 127	3 500	2 911	2 950	3 646
Europe	2 027	1 934	1 474	1 423	1 632
Africa and the Middle East	843	1 691	1 991	3 327	3 857
Eurasia	741	898	775	735	1 156
Asia Pacific	3 012	6 158	6 229	6 330	8 653
International bunkers	273	408	450	510	921
World	**10 023**	**14 590**	**13 830**	**15 278**	**19 865**

Notes: Primary energy demand conversion losses from biofuel production. *International bunkers* refers to fuel demand in international aviation and shipping.

Trends in final energy demand

Total global final energy consumption in the Sustainable Development Scenario levels off in the early 2020s and then falls steadily through the projection period. By 2070, it is at a level close to 10% below that in 2019, and more than 30% below the

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demand in the Stated Policies Scenario, thanks to major gains in energy and material efficiency – especially in the period to 2040 (Table 2.3). Oil and gas demand see the sharpest decline in relative terms in the Sustainable Development Scenario, each falling by more than 70% between 2019 and 2070, although the decline in oil demand is larger in absolute terms. Space heat demand in buildings and process heat demand in industry also fall as a result of more efficient use of technologies such as heat pumps. Electricity consumption increases the most in absolute terms, more than doubling by 2070, followed by hydrogen, which emerges as a fuel in the 2020s and is primarily used in the transport and industry sectors. Liquid synthetic hydrocarbon fuels, derived from hydrogen produced from electricity and CO_2, begin to be used in road freight trucks and aircraft in the second half of the 2020s: by 2070, the amount of synthetic fuel use is equivalent to 5 mb/d, and it meets around 40% of aviation fuel demand.

Table 2.3 Final energy consumption by sector, fuel and scenario (Mtoe)

			Sustainable Development Scenario		Stated Policies Scenario
	2000	2019	2040	2070	2070
Industry	2 054	3 278	3 162	3 077	4 513
Transport	1 961	2 865	2 537	2 461	3 923
Buildings	2 345	3 087	2 648	2 868	4 193
Other	950	1 153	1 310	1 081	1 639
Total	**7 310**	**10 384**	**9 657**	**9 486**	**14 269**
Coal	732	1 327	824	398	1 326
Oil	3 292	4 048	2 823	1 099	4 561
Natural gas	1 104	1 659	1 357	426	2 362
Electricity	1 076	1 943	2 909	4 507	4 004
Heat	240	312	272	187	356
Hydrogen	0	0	98	539	91
Ammonia	0	0	18	133	9
Bioenergy	859	1 035	1 035	1 315	1 285
Synfuels	0	0	32	254	0
Other renewables	7	60	290	629	275
Total	**7 310**	**10 384**	**9 657**	**9 486**	**14 269**
Hydrogen-related demand		*94*	*290*	*1 199*	*229*

Notes: Deviating from IEA Energy Balances, final energy demand for industry includes here and in the following energy use for blast furnaces and coke ovens. *Synfuels* refer to synthetic hydrocarbon fuels produced from hydrogen and CO_2. *Heat* refers to heat from combined heat and power plants or heat plants being sold to third parties, e.g. district heat use in buildings. *Bioenergy* refers to both traditional biomass use and modern bioenergy. *Other* refers to the final energy consumption in agriculture and fuels used for chemical feedstocks and non-energy products. *Hydrogen-related final energy demand* includes in addition to the final energy demand of hydrogen, ammonia and synfuels, the onsite hydrogen production in the industry sector and the final electricity produced from hydrogen.

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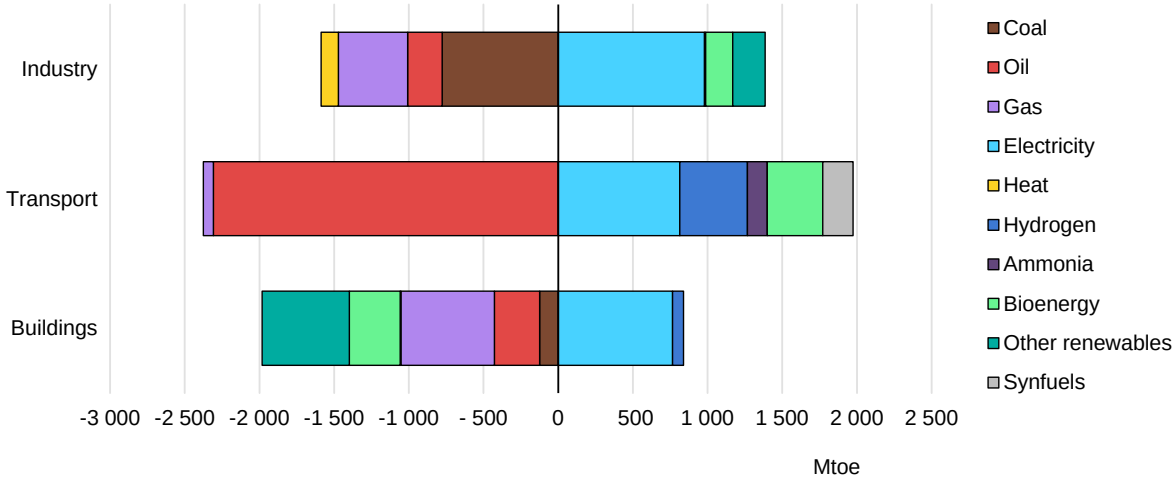
The decline in fossil fuel use is largest in the transport sector (mostly oil), but usage also falls in the industry and buildings sectors. In all three sectors, electricity emerges as the leading source of energy (Figure 2.6). In the transport sector, all hydrogen-based fuels combined (hydrogen, ammonia, synthetic hydrocarbon fuels) cover one-third of all energy needs in 2070, almost on a par with electricity.

Figure 2.6 Change in global final energy demand by fuel and sector in the Sustainable Development Scenario, 2019-70



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Notes: In the industry sector, heat and hydrogen can be produced onsite at industrial plants, i.e. not being purchased from third parties. In these cases, the final energy demand for the industry sector includes the corresponding fuel input being consumed to produce heat or hydrogen. *Synfuels* refer to synthetic hydrocarbon fuels produced from hydrogen and CO_2. *Other renewables* include solar and geothermal energy.

Electricity, bioenergy, hydrogen and hydrogen-based fuels replace the vast majority of fossil fuels in a net-zero emissions world.

The Sustainable Development Scenario brings energy intensity improvements in a range of end-use sectors. In industry, the global average thermal energy intensity of producing clinker (the main ingredient of cement) falls by 15% between 2019 and 2070 as a result of energy efficiency improvements associated with the adoption of state-of-the-art technology when existing assets are replaced by new capacity. These improvements are partly offset by additional energy requirements related to the use of other carbon mitigation measures, for instance the installation of carbon capture equipment. In transport, improved efficiency yields large energy intensity improvements in the coming decades in international shipping and in light-duty vehicles; for both vehicle categories, energy intensity is cut nearly in half between 2019 and 2040. The improvements in light-duty vehicles come from cars, light

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commercial vehicles and minibuses exploiting efficiency gains from improved engines and powertrains (including hybridisation), improvements in design and materials, and a shift to electric drive.

Improving energy efficiency is crucial to global energy transitions. It has played an important role in the slowing of global CO_2 emissions growth in past years and has the potential to play a leading role in the future, especially in the near term. The scale of improvement in energy efficiency in the Sustainable Development Scenario requires early policy action to accelerate the adoption of the most efficient technologies so as to avoid locking-in inefficient energy use in the long term: the bulk of the energy and emissions savings come in the first two decades of the projection period.

While an accelerated deployment of clean and efficient energy technologies are needed to reduce the emission impacts of transport, buildings and industry, these efforts can be complemented by consumer behaviour and lifestyles changes and enable some of these technology efforts (Box 2.4).

Box 2.4 The role of consumer behaviour in the clean energy transition

Consumers will be directly involved in the Sustainable Development Scenario's change of technology landscape, including through:

- **Greater end-user engagement.** New electricity technologies allow consumers to play a role in electricity generation and balancing. In 2070, around 3 600 GW of distributed rooftop solar PV is integrated into the fabric of buildings – on the roof and walls, or in windows. Greater electrification also enables households to participate directly in demand-side response, with electric vehicles and heat pumps potentially unlocking hundreds of gigawatts of flexibility, for example.
- **The emergence of energy communities.** Interactions among end users play a role in the use of distributed energy resources through peer-to-peer energy trading. Citizens also have a key role in promoting the deployment of infrastructure supporting clean energy technologies, such as district energy systems, mini-grids, publicly available vehicle chargers and virtual power plants.
- **Consumer acceptance of change.** A number of changes rely on behavioural shifts on the part of consumers. Urban planning, for example, encourages greater use of less emissions-intensive modes of transport such as buses, trains and bicycles, while the success of the circular economy relies on people being willing to renovate rather than replace old buildings, and to do more to reuse and recycle goods (see Chapter 3).

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- **Interaction with energy service providers.** Energy service companies, whose revenues approached USD 30 billion in 2018, currently mostly operate in China and the United States and in the services and industrial sector (IEA, 2018). The Sustainable Development Scenario broadens their market potential, and they play a part in the retrofitting of the existing buildings stock and in improving access to clean energy in emerging economies.

Focus on material efficiency: A blind spot?

The potential for material efficiency improvements to reduce emissions is often overlooked. Material efficiency covers a broad suite of measures that lower energy needs through more efficient use and management of materials. Collectively these measures account for about 5% of the cumulative CO_2 emissions reductions in the Sustainable Development Scenario compared to the Stated Policies Scenario in 2070 – an amount equal to 1.5 times the current total annual emissions. Different material efficiency measures can be applied at each stage of the supply chain for each type of good or service (Box 2.5). Some reduce material demand, while others may increase demand for particular materials while enabling CO_2 emissions benefits at other stages of the supply chain. Some involve a shift to using lower emission materials or production routes. Material efficiency measures, such as lightweighting or recycling, can interact with each other, leading to synergies in some cases and counterbalancing effects in others (for additional details on material efficiency strategies, see IEA [2019c]). Measures include:

- **Design stage:** Good design can factor in optimisation measures such as lightweighting – the use of less or lighter material in the production or construction process so as to reduce the quantity or weight needed to produce the same good or provide the same service. 3D printing has emerged as a promising technology for lightweighting. The full lifecycle should be considered at the design stage. For example, in some cases, the optimal solution may be to design a more durable product, which may increase the initial demand for materials but yield offsetting emissions savings over their lifetime by reducing the frequency of the need to replace them.
- **Production stage:** There may be scope to reduce waste and overuse of material inputs or replace materials with ones that involve lower lifecycle emissions in manufacturing and construction.
- **Use stage:** Using a product or building more intensively or extending its lifetime through repair and refurbishment can reduce the need for materials to produce new products.

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- **End of life:** Reusing or recycling materials at the end of product lifetimes can reduce the need to produce new materials or, in the case of recycling, can make possible lower emission secondary production routes.

Measures to extend the lifetime of buildings account for some of the largest reductions in demand for materials within the wide portfolio of material efficiency strategies – they account for 40% of cumulative reductions for steel and nearly 70% for cement over the period 2019-70 compared with the Stated Policies Scenario (Figure 2.7). Improved buildings design and construction contribute about one-fifth of cumulative reductions in demand for steel and one-third for cement (see Chapter 4 for further discussion of material efficiency in buildings). Reduced material losses also play an important role.

For metals, potential exists to improve yields at two stages: semi-manufacturing (the process of converting crude metal into finished metal products like bars and sheets) and product manufacturing (the process of converting finished metal products into final end-user products like cars and appliances). Reducing scrap generated during car manufacturing when the chassis is cut from metal sheets is an example of materials improvement at the product manufacturing stage, and digitalised production may play a key role in reducing such scrap and other production losses. Between them, semi-manufacturing and product manufacturing material improvements contribute to a reduction in demand for steel in the Sustainable Development Scenario of 25% by 2070, compared with demand in the Stated Policies Scenario. Direct reuse of metals (without remelting) for various applications such as steel beams or ship plates also helps to cut materials demand, and this contributes to a reduction in demand for steel on the same basis of 18% by 2070.

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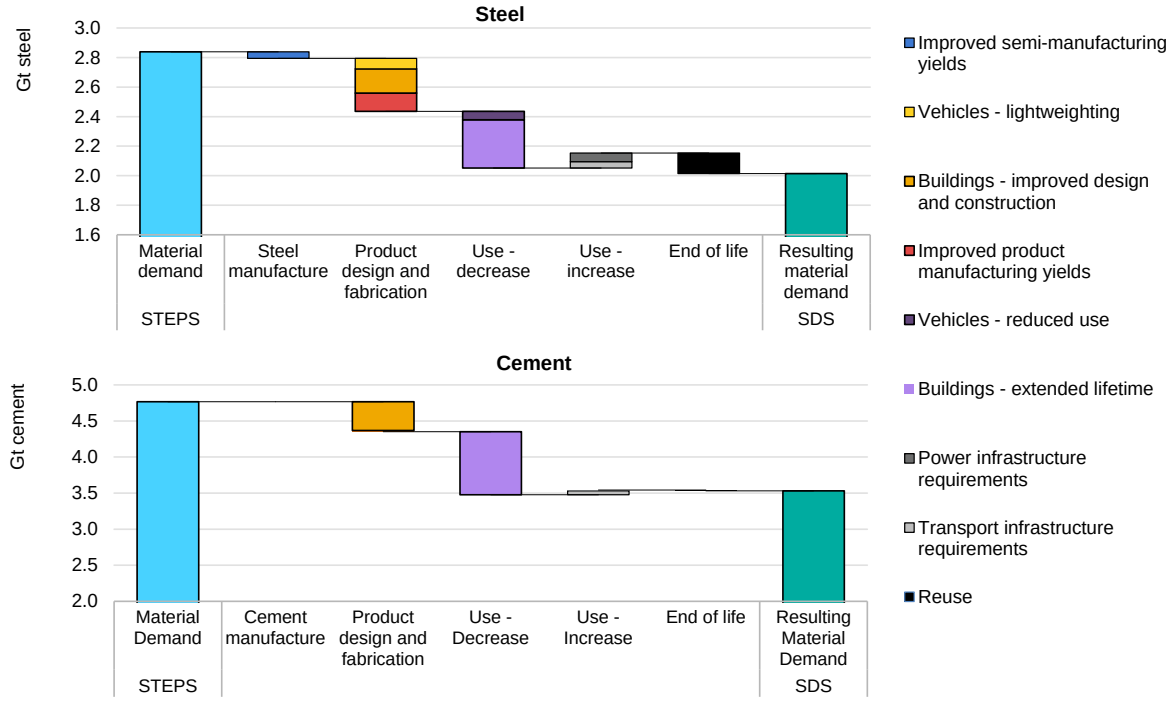
Figure 2.7 Reduction in global steel and cement demand through material efficiency gains by stage in the supply chain in the Sustainable Development Scenario relative to the Stated Policies Scenario in 2070



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario.

The biggest potential for material efficiency gains that reduce the need for steel and cement lies in improved designs and a more intensive use of buildings and vehicles, notably through extended lifetimes in tandem with energy efficiency retrofits.

Recycling is also an important aspect of material efficiency. It does not directly impact total demand for materials, but rather enables increased secondary production, which is considerably less energy- and CO_2-intensive than primary production. Steel recycling, which depends on available volumes and qualities of scrap, is already widely used: scrap currently accounts for 32% of total output, reaching 50% by 2070 in the Sustainable Development Scenario (see Chapter 4). Various innovation efforts are underway to improve metal and plastic sorting and recycling. Recycling of cement is more limited, given that a large portion of cement reacts with water (hydrates) during concrete hardening, and that this process cannot easily be reversed. However, innovation efforts are underway to recycle concrete fines – which are small particles from the process of crushing concrete for recycling that contain calcium oxide and that could be used in cement production in place of calcium carbonate, thus reducing process emissions – and to recover unreacted cement from end-of-life concrete.

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The potential for lightweighting to lower CO_2 emissions in transport is particularly large, not just through its impact on material efficiency, but also through its ability to improve fuel economy. For passenger light-duty vehicles, lightweighting contributes approximately 2 Gt of cumulative CO_2 emissions reductions by 2070 relative to the Stated Policies Scenario from use of the vehicle, on top of almost 1 Gt of net reductions from materials production. The absolute amount of savings decreases over the course of the scenario period as vehicles increasingly shift to electricity and other low-emission fuels, thus reducing the potential for lightweighting also to lower emissions. Lightweighting can also bring benefits other than direct CO_2 emission savings. In the next few years, when battery costs are likely to remain high, lightweighting could boost driving range, thereby facilitating faster uptake of battery-electric vehicles. Later on, the pressure on increasingly scarce or expensive materials needed to produce batteries may be reduced if lighter vehicles can achieve the same performance, including range, with smaller batteries.

Box 2.5 3D printing as an enabler of lightweighting and reduced material use

As industries continue to digitalise, 3D printing has emerged as one of the most visible of the process technologies that could transform certain industrial operations (Cotteller and Joyce, 2014). 3D printing can produce both plastic and metal parts in layer-by-layer fashion, on demand and directly from digital 3D files, and has several advantages compared with conventional manufacturing. It reduces lead times, scrap material, inventory costs, manufacturing complexity and floor space, while providing the ability to produce goods using fewer parts and so increasing the durability of the final product (Huang, 2016). It can yield significant energy and material savings under the right conditions. As an electricity-driven process, it also promotes the electrification of thermal forming processes such as metal casting and forging, which reduces CO_2 emissions to the extent that power generation is decarbonised. It could, in addition, lead to the production of new objects with different or novel shapes, which improve the function of final products and lead to energy savings beyond the industrial sector.

3D printing is already being used in the production of lightweight aircraft components by some aircraft manufacturers to reduce fuel consumption (Airbus, 2016). Quantifying the net energy and resource savings that can be achieved by 3D printing in any given case requires a life-cycle assessment approach. One recent study quantified the energy and resource impacts of selected lightweight metallic additive manufacturing components in the US aircraft fleet under different adoption scenarios to 2050 (Huang et al., 2016). A life-cycle assessment found that 9-17% of total typical aircraft mass in the US fleet could be replaced by lighter 3D printed components in

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the near term. This could deliver two environmental benefits. First, the reduced materials intensity of these alternative components could avoid nearly 20 kt/yr of metal demand in 2050. Second, reduced aircraft mass could reduce the overall fuel use of the US aircraft fleet by up to 6.4% in 2050 if those components were fully adopted.

3D printing markets have grown rapidly in recent years. In 2016, the industry grew by 17.4% to USD 6.1 billion and its turnover has continued to rise rapidly (Wohlers Associates, 2017). However, the technology faces barriers that may limit widespread adoption, including high production costs, low throughput rates and difficulties in meeting the technical requirements for certain products (Huang, 2016; Huang et al., 2016). For these reasons, its use so far has been limited mainly to high-value applications in the aerospace, medical and transport industries.

The overall potential for material efficiency is exploited much more fully in the Sustainable Development Scenario than in the Stated Policies Scenario thanks to stronger government policies and regulations. Some directly incentivise material efficiency in order to increase emissions savings – for example, building codes that cover embodied emissions from a life-cycle perspective and include incentives for materials reuse. Others incentivise materials efficiency indirectly – for example, requirements for industry to reduce emissions lead to somewhat higher prices for steel, cement and other materials, which provide an incentive for construction companies and other industries to use them more efficiently. Policy-driven changes occurring in other sectors also contribute to lower material demand, for example by encouraging the renovation rather than the replacement of old buildings.

Exploiting the full potential of material efficiency will, however, not be easy or cheap. Real and perceived risks, time constraints, the high cost of labour relative to materials in many cases, fragmented supply chains, regulatory restrictions and lack of awareness are among the many barriers to greater uptake of material efficiency measures. Moreover, although estimates suggest that most material efficiency strategies are no higher than EUR 100/tCO_2 abated (Material Economics, 2018), improving material efficiency will in many cases incur additional upfront costs. But the message is clear: much stronger policies are needed to drive efforts from all stakeholders to realise the full benefits of material efficiency.

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Prospects and readiness of critical low-carbon technology value chains

Developing a new technology and successfully bringing it to market is typically a long drawn-out process (see Chapter 6). Technologies go through a journey in which they evolve from a concept to a prototype, are demonstrated at scale and, if successful, are adopted and commercialised more widely. One way to assess where a technology is in its journey from bench to market is to use the technology readiness level (TRL) scale (Box 2.6). As technologies pass through each stage, the level of risk associated with technology performance is successively reduced: however, capital expenditure grows throughout the process as scale increases, and this creates new risks.

Support schemes need to be tailored to the different stages of the innovation value chain to help mitigate the different risks that arise so that, for example, they address investment risks when a technology moves to large-scale demonstration plants. However, innovation is rarely a linear progression. Not all technology designs make it to market or get deployed at sizeable levels. Stages of development can accelerate or slow down, depending on technical or economic factors, and might reach a dead end that results in a return to square one. Moreover, a given technology can be at different stages of this process in different markets and applications, with each phase taking different amounts of time. As the development of a technology generates new ideas for improvements, alternative configurations and potentially better components can appear at different stages of the innovation process, even once a given technology configuration has become competitive. Stages overlap and run concurrently, feeding on one another.

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Box 2.6 Assessing technology readiness: The *ETP Clean Energy Technology Guide*

One way to assess where a technology is on its journey from initial idea to market is to use the technology readiness level (TRL) scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many US government agencies since the 1990s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale (Mankins, 1995). The US Department of Defense has been using the TRL scale since the early 2000s for procurement, while the European Space Agency adopted it in 2008. In 2014, the TRL was applied for the first time outside the aerospace industry to assess EU funded projects as part of the Horizon 2020 framework programme. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes.

The scale provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology then enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), through to testing in the conditions it which it will be deployed (TRL 5-6). The technology next moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn may require further development of the technology itself. For this reason, the IEA has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

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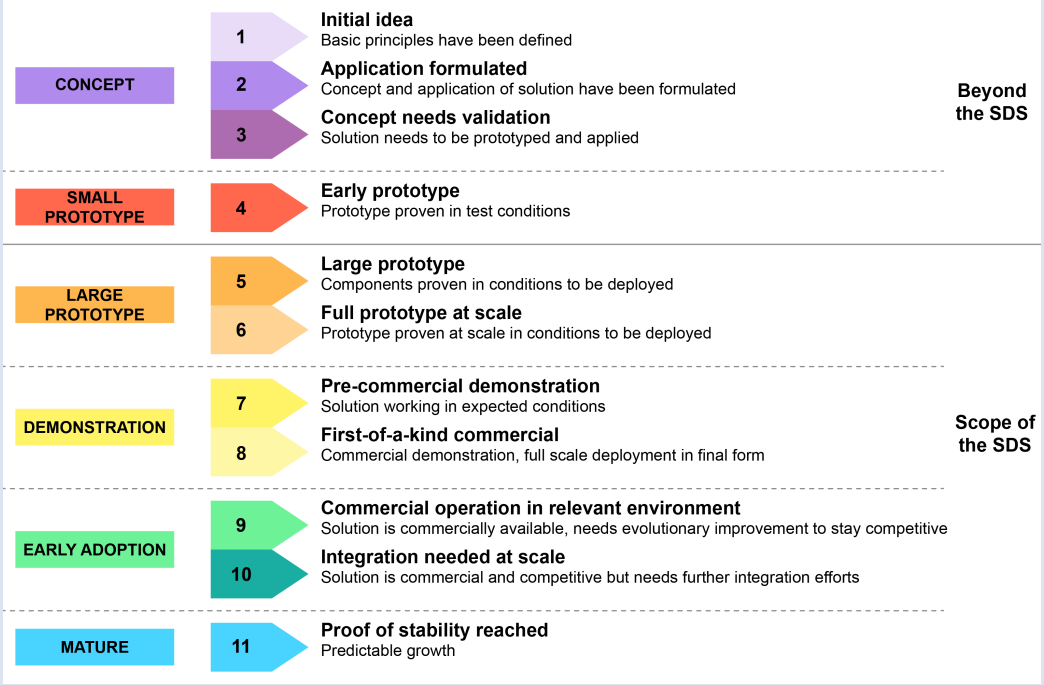
Technology readiness level scale applied by the IEA



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Note: SDS = Sustainable Development Scenario.

To inform this analysis, we have analysed the technology readiness of almost 400 individual technology designs and components, and have structured them hierarchically alongside others delivering the same service in what we refer to as the *ETP Clean Energy Technology Guide.** This is an interactive framework that includes information on the level of maturity of different technology designs and components, as well as a compilation of cost and performance improvement targets and leading players in the field. Sixty per cent of the technology designs and components analysed are not commercially available today, and 35% are at the early adoption phase, meaning that they are still significantly dependent on innovation to improve performance and reduce costs. Of the mature technology designs assessed, 65% relate to the buildings and power generation sectors: a higher proportion of the technologies in industry, transport and fuels transformation have lower TRLs.

In this report we refer to four broader readiness categories, each of which comprises different ranges of specific readiness levels from the full TRL scale: mature, early adoption, demonstration and prototype. Each technology type is assigned to one of these higher level categories based on the granular levels of maturity of individual technology designs or components today associated with that technology. In some cases, we distinguish between large and small prototypes; we also refer to some technologies as being at the concept stage, which means that they are not yet ready for the readiness categories.

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"Mature" for commercial technology types that have reached sizeable deployment and for which only incremental innovations are expected. Technology types in this category have all designs and underlying components at TRL 11. Hydropower and electric trains are examples.

"Early adoption" for technology types for which some designs have reached market and require policy support for scale-up, but where there are competing designs being validated at the demonstration and prototype stage. Technology types in this category have at least an underlying design at TRL ≥ 9 and others at lower TRLs. Offshore wind, electric batteries and heat pumps are examples.

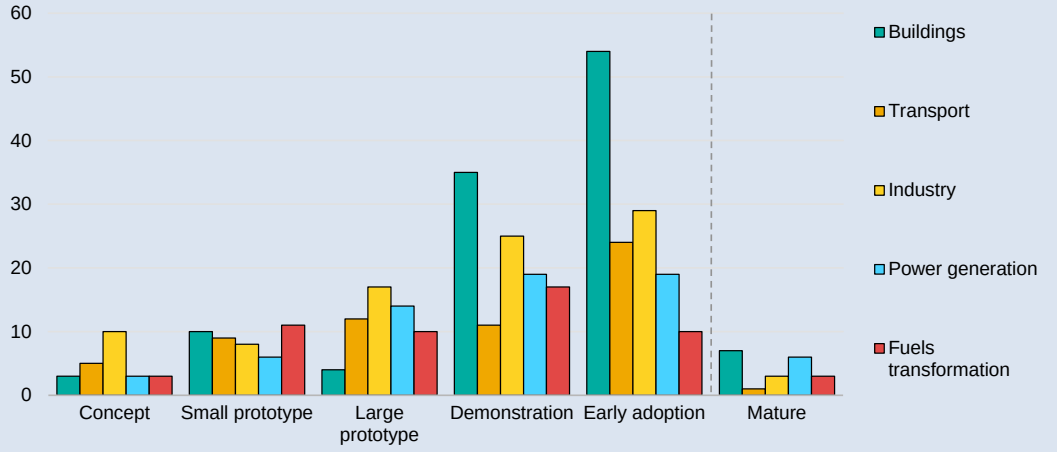
"Demonstration" for technology types for which designs are at demonstration stage or below, meaning no underlying design at TRL ≥ 9, but with at least one design at TRL 7 or 8. Carbon capture in cement kilns, electrolytic hydrogen-based ammonia and methanol, and large long-distance battery-electric ships are examples.

"Large prototype" for technology types for which designs are at prototype stage of a certain scale, meaning no underlying design at TRL 7 or 8, but with at least one design at TRL 5. Ammonia powered vessels, electrolytic hydrogen-based steel production and direct air capture are examples.

"Small prototype" for technology types for which designs are at early prototype stage, meaning no underlying design at TRL 5, but with at least one design at TRL 4. Battery-electric aircraft and direct electrification of primary steelmaking are examples.

"Concept" for applications that have just been formulated but need to be validated. Lithium-air batteries and electrifying a steam cracker for olefins production are examples.

Number of clean energy technology designs and components analysed in the *ETP Clean Energy Technology Guide*



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* For more information, see: www.iea.org/articles/etp-clean-energy-technology-guide.

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The Sustainable Development Scenario identifies four key decarbonisation strategies: 1) the electrification of the transport, industry and buildings sectors; 2) the deployment of CCUS systems; 3) the shift towards hydrogen and hydrogen-derived synthetic fuels (using low-carbon hydrogen and sustainable carbon sources); and 4) the use of more sustainable alternative fuels and feedstock such as bioenergy. For these decarbonisation strategies to be rolled out, innovation is needed to bring new technologies to market and to improve emerging ones along all the different steps of the involved value chains.

Electrification

A central pillar of the clean energy transition in the Sustainable Development Scenario is the acceleration of the electrification of the world economy. The share of electricity in final energy uses has been growing steadily for decades. In the period 1990-2019, global annual electricity demand grew on average by 3.0%, an average annual increase roughly equivalent to the total amount of electricity generated annually in Italy and Sweden combined. This trend continues in the Sustainable Development Scenario, driven by growing demand for electrical appliances and also by an expansion of electricity into new sectors, which reflects the environmental and practical advantages of electricity over other forms of energy in final applications. Final electricity demand expands by around 30 000 TWh through to 2070, which is around 6 000 TWh (or 25%) more than in the Stated Policies Scenario, and equivalent to around 135% of current consumption. The share of electricity in the global final energy demand grows from 19% today to 47% in 2070, compared with just 28% in the Stated Policies Scenario (Figure 2.8).

Electricity becomes the main energy carrier in all end-use sectors in the Sustainable Development Scenario, but trends vary significantly. The buildings sector is the largest user of electricity today, and demand in 2070 increases by 75%, or almost 9 000 TWh, driven mostly by conventional uses in electric appliances. But the scope for the buildings sector to use more electricity is generally lower in the Sustainable Development Scenario than for other sectors, as demand growth is held back by stringent efficiency measures (demand grows by 110% over the period 2019-2070 in the Stated Policies Scenario, in which efficiency improves less).

Electricity demand in industry and transport grows by 11 500 TWh and 9 500 TWh respectively. Electricity is already an important fuel for the industry sector today, meeting around one-quarter of total demand. In the Sustainable Development Scenario, demand growth between 2019 and 2070 is about 135% higher than in the Stated Policies Scenario, driven in particular by the chemicals and the iron and steel sectors. Transport relies predominantly on oil today: electricity is largely confined to the rail sector, and meets just 1% of total transport energy demand. The change in the transport sector is the biggest of all in the Sustainable Development Scenario:

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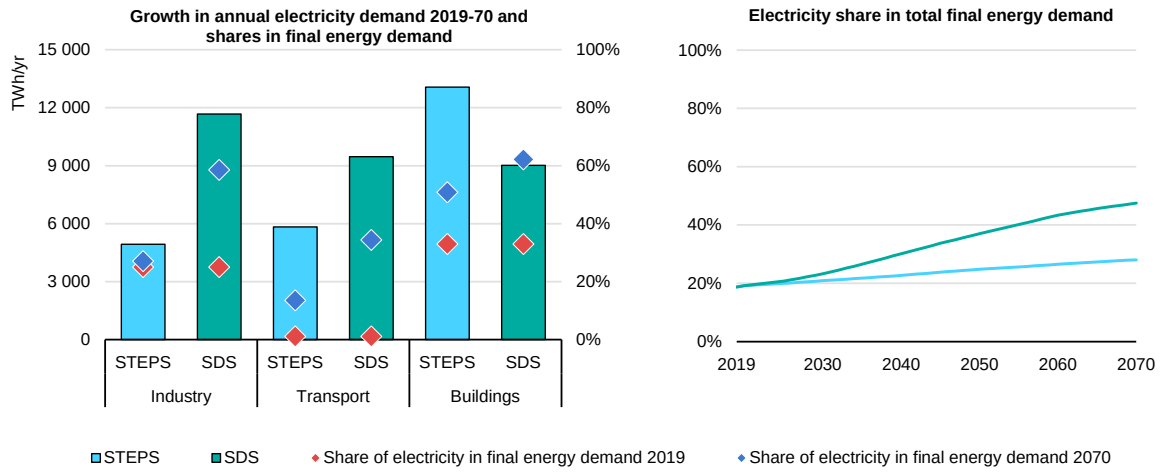
electricity overtakes oil by 2060 to become the main form of energy for transport, and more than one-third of transport energy demand (and half of road transport demand) is met by electricity by 2070, with electric vehicles dominating the passenger car fleet. Many trucks also convert to electric powertrains, though their adoption lags that of cars by more than a decade (see Chapter 5).

Figure 2.8 **Growth in global electricity consumption by sector and scenario and electricity share in total final consumption in the Sustainable Development Scenario**



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario.

Electricity accounts for almost half of all final energy demand by 2070 in the Sustainable Development Scenario: its growth is driven by increased demand in industrial motors, electric vehicles and appliances in buildings.

Increased electrification of end-use sectors accounts for almost 30% of the annual CO_2 reductions in 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario (or about one-fifth on a cumulative basis over the period) because it replaces fossil fuels with low-carbon electricity. A major part of these reductions come from the transport sector, particularly through the uptake of electric vehicles, first in light-duty vehicles (cars and commercial vehicles) and urban buses, and later in medium- and heavy-duty buses and trucks. Significant CO_2 reductions from electrification occur also in the industry sector, led by the continued electrification of low-temperature heat needs through industrial heat pumps (Figure 2.9).

Electricity systems need to become more flexible in the face of increasing electrification. With the expansion of electric vehicle (EV) fleets, EV charging could increase the peak of daily loads, unless steps are taken to spread the load. Similarly, growth in the use of electricity for space heating or cooling via heat pumps in

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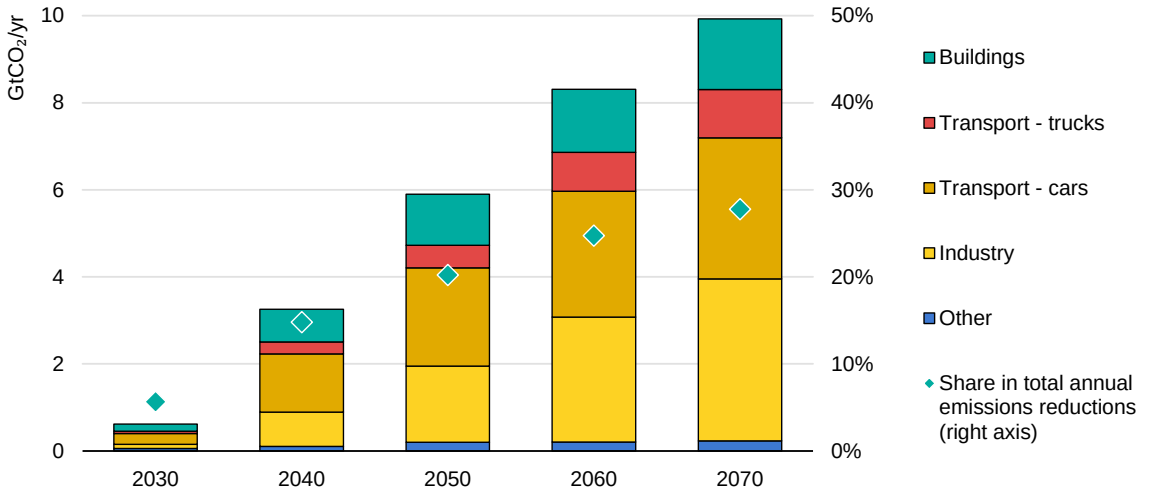
buildings could raise peak loads, especially in countries with cold winters, even with the much higher efficiency of electric heat pumps that is projected in the Sustainable Development Scenario (IEA, 2020a).

Figure 2.9 **Global CO_2 emissions reductions from electrification by sector in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2030-70**



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Electrification accounts for almost 30% of the annual CO_2 emissions savings in the Sustainable Development Scenario in 2070, with industry and transport making the biggest contributions.

At the same time, the much greater reliance on solar PV and wind power that is projected would increase the need for system flexibility to deal with the natural daily and seasonal variability of these sources of generation. That flexibility could come from additional dispatchable generation and stronger electricity networks, alongside enhanced interconnections with neighbouring systems that would take advantage of larger geographical areas to help smooth out variations. Long-distance high-voltage direct current transmission lines could also facilitate energy transfers between regions (east-west for short-term energy shift, and north-south for seasonal energy shift). Demand response is another solution: for example, smart electric vehicle recharging infrastructure that takes account of the operational aspects of the electricity system could manage the timing of recharging in response to real-time price signals to balance load with available output, allowing a higher share of variable renewable capacity (Box 2.7). Electric vehicle batteries could provide additional short-term storage, subject to the development of vehicle-to-grid inverters. Large amounts of additional short-term storage (minutes to hours) and long-term electricity storage (hours to days or weeks) would also be needed, whether in the form of grid-

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scale batteries, pumped hydro, hydrogen storage or some alternative to these. Reducing the cost of storage technologies is a major challenge for global energy transitions.

In the Sustainable Development Scenario, low-carbon heating systems in buildings based on biomethane and hydrogen ease the need to use electricity directly for space heating or cooling in buildings and for process heat in industry, as do district heat and cooling from low-carbon combined heat and power generation District heating, bioenergy and hydrogen account on average for almost 60% of global space heating demand in 2070, compared with around 20% from electricity. Both hydrogen and district heating could, however, stem indirectly from electricity, and the indirect electrification that comes from the conversion of electricity into hydrogen, hydrogen-based fuels (ammonia, synthetic hydrocarbon fuels) and heat expands the use of electricity in industry, transport and buildings. When this is taken into account, the overall share of electricity in global final energy demand in the Sustainable Development Scenario increases to 55% in 2070 (compared with 48% with direct electrification only), with the transport sector accounting for more than 60% of the difference.

Box 2.7 The opportunity of cooling storage and electric vehicles in China

Two emerging trends in China will pose either a challenge or an opportunity in balancing electricity demand and supply: the growth of electricity use and the rise of variable renewables.

An additional 900 million air conditioners will be sold over the next ten years in China, equivalent to almost 2.5 times the number of air conditioners operating today in the United States. The battery capacity of on-board electric vehicles (light-duty and heavy-duty vehicles, buses, and two to three wheelers) will also grow about 10-fold. Many people are likely to run their air conditioner or charge their vehicle at roughly the same time of day. In the Sustainable Development Scenario, for example, residential space cooling represents only 4% of total electricity demand in China in 2030 but is responsible for 30-40% of the peak load (figure below).

At the same time, the falling costs of renewables mean that the contribution of wind and solar to total power capacity will jump from 20% today to around 50% in 2030 in the Sustainable Development Scenario. As supply and demand patterns may not coincide, total electricity capacity could end up increasing three times faster than annual electricity generation growth in order to ensure that demand can be met. Assuming electricity storage and flexible generation technologies but no demand-side response capacity, China's total installed capacity will have to increase

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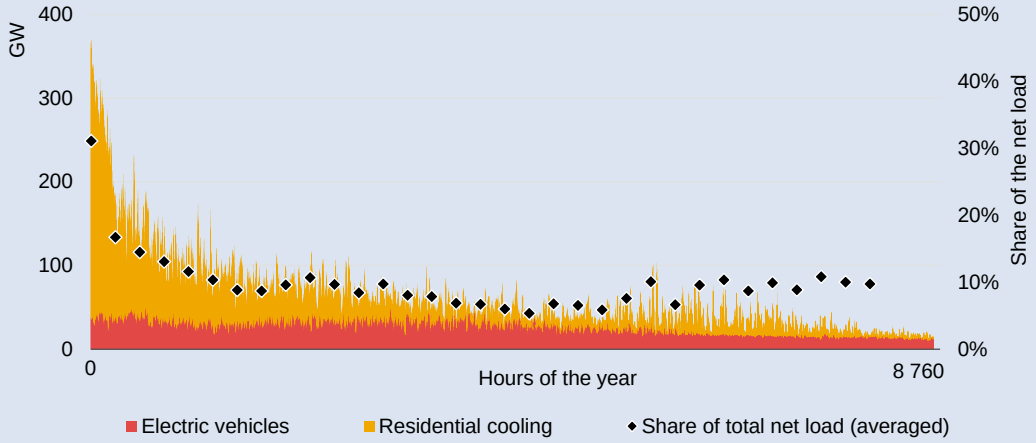
to 3 250 GW by 2030 (including 1 650 GW of variable renewables, covering less than a third of annual electricity generation).

Contribution of residential cooling and electric vehicles to net electricity load in China in the Sustainable Development Scenario, 2030



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Notes: Hours of the year are ranked based on non-variable renewable electrical capacity needs (from left to right). The increase in capacity needed to meet cooling demand on the left of the chart shows that cooling is a main driver of peak demand in China in 2030 in the absence of demand-side response.

Opportunities do, however, exist to trim the 300-450 GW of residential cooling peak demand. Domestic ice and chilled water storage and district cooling networks offer significant potential to reduce annual peak demand by displacing charging to off-peak hours over a day (for domestic applications) or seasonally (with geothermal systems). Avoiding the charging of electric vehicle batteries during peak times could save up to 40 GW and even enable batteries to supply electricity by means of vehicle-to-grid technologies, potentially providing up to 300 GW of additional capacity (IEA, 2020a). Some measures require changes in regulatory frameworks, upfront investments (e.g. in cooling storage systems, controls) and consumer active participation, but they could avoid the need to build hundreds of underutilised peak generation plants.

While electrification of end-uses reduces reliance on fossil fuels, with energy security benefits for countries that today rely heavily on fossil energy imports, it increases the demand for the metals and minerals needed to produce the infrastructure and equipment associated with wider deployment of low-carbon electricity. Copper, lithium, cobalt and platinum are at the core of the energy transition: copper is needed for transmission and distribution lines; lithium and cobalt for the currently prevailing lithium-ion battery designs; and platinum in fuel cells. The material with the most

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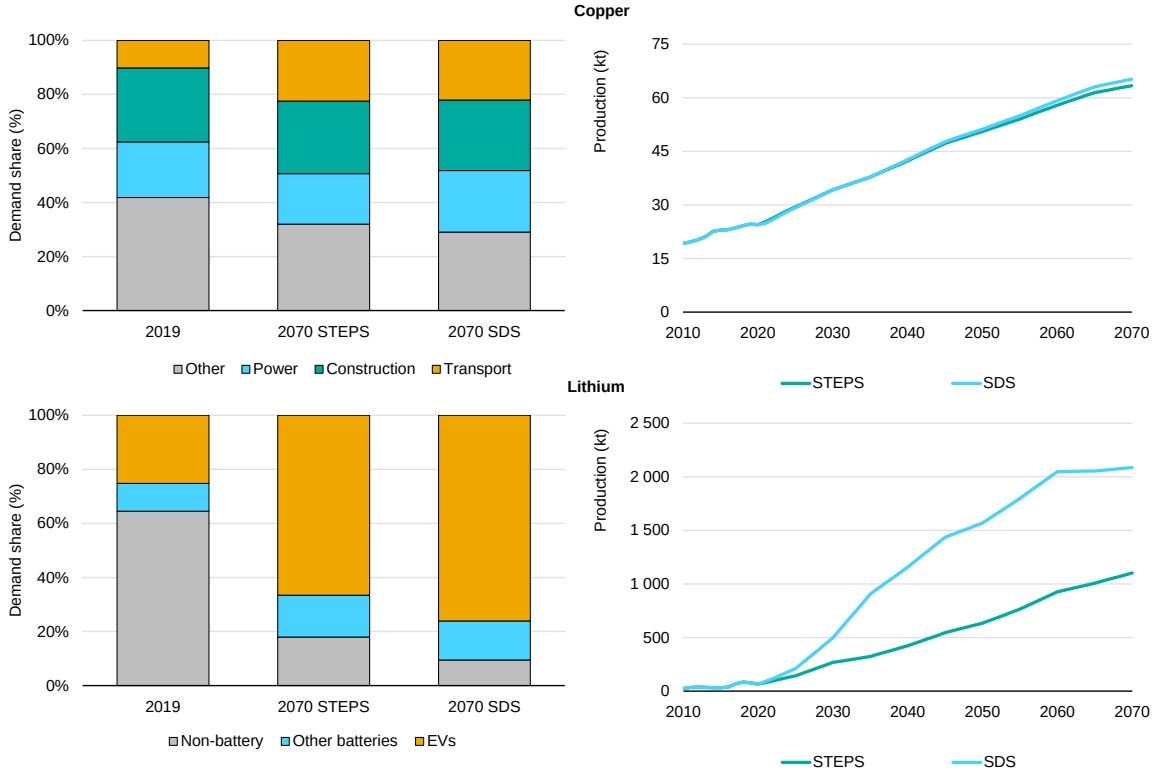
fragile supply chain is cobalt, which has highly geographically concentrated mining and processing facilities. The supply chain risks were made clear by a very sharp price hike in 2018, which provided a strong incentive for battery producers to reduce the cobalt content of battery chemistries: several chemistries are now being developed that do not require cobalt, although their timescales are uncertain. Lithium currently has a more stable supply chain, but it is likely to keep its status as a critical material because its physical properties make it nearly non-substitutable in the production of high energy density batteries.[7]

Figure 2.10 Global copper and lithium demand by sector and scenario



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. EVs = electric vehicles. *Other uses* of copper are mainly for electronics and consumer products. Non-battery use of lithium is varied: ceramics, lubricants, metallurgy, polymers, air purification or even pharmaceutical. The lifespan of batteries for electric vehicles is assumed to be the same as vehicles (between 14 and 17 years for light-duty vehicles). Electric trucks and buses are assumed to use two sets of batteries during their lifetime.

Demand for lithium, mainly for making batteries, increases twice as quickly in the Sustainable Development Scenario as it does in the Stated Policies Scenario, as a result of the faster penetration of electric vehicles and increased use of batteries in the power sector.

[7] There are two categoris of battery chemistries that avoid the use of lithium: sodium-ion batteries and multivalent-ion batteries, with the latter being at a comparatively earlier stage of development. See Chapter 6 for a discussion of advanced battery chemistries.

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Demand for copper, 60% of which is used today in construction, vehicles manufacturing and power systems, is projected to grow only slightly faster in the Sustainable Development Scenario than in the Stated Policies Scenario: in the Stated Policies Scenario, faster electrification is largely offset by reduced demand for copper in transport due to modal shifts and to more efficient use of materials in vehicles manufacturing and construction. By contrast, demand for lithium, which is used for making Li-ion batteries, increases much faster in the Sustainable Development Scenario due to the more rapid penetration of electric vehicles and to a greater need for batteries in the power sector (Figure 2.10).[8]

Box 2.8 Impact of the Covid-19 crisis on electricity-based technologies

Electricity demand fell by 20% or more in countries with full lockdown measures, though it is recovering quickly in countries where measures have been eased. Over the year as a whole, global electricity demand is currently expected to be around 5% lower than it was 2019 (IEA, 2020b).

Manufacturers of electricity-based technologies were affected to a varying extent by plant closures and supply chain disruptions. While heat pump manufacturing outputs, for example, quickly returned to pre-pandemic levels in China and Europe, a number of factories are still closed in India (as of June 2020). Daikin, accounting for an estimated third of the global heat pump market, plans to maintain its R&D spending in 2020 relative to 2019 (Daikin, 2020). Some governments are seizing the opportunity to include heat pumping technology in Covid-19 stimulus packages: for example, the Italian "Super Eco-bonus" provides a 110% fiscal incentive for A-class heating and cooling systems (up to EUR 30 000), on top of other renovation measures (Gazzetta Ufficiale, 2020). In transport, the Covid-19 pandemic brought about contrasting impacts on electric car sales, but overall they are proving more resilient than conventional car sales. In China, the decline was the largest in February, with electric car sales falling by around 60% from the same month in 2019 before rebounding in April and May to around 75-80% of the level of the previous year. In the United States, electric car sales in April more than halved compared with the previous year. In the largest European car markets combined (France, Germany, Italy and the United Kingdom), however, sales of electric cars in the first 5 months of 2020 were about 80% higher than in the same period the previous year as a result of recently revitalised incentive schemes.

[8] See Chapter 6 for analysis on implications on lithium demand of rolling out advanced batteries post Li-ion.

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Technology readiness of the low-carbon electricity value chain

The accelerated electrification of end-use sectors and the decarbonisation of power generation are essential to achieving net-zero CO_2 emissions. In the low-carbon electricity value chain, several technologies have reached maturity, such as hydropower and electric trains. In end-use sectors, some technologies such as electric vehicles and heat pumps are commercially available, but innovation remains an important issue: their ability to expand their markets depends on further technology innovation to improve performance and reduce costs.

But there is still a long way to go for others (Figure 2.11). This is particularly true in demand areas such as heavy industry and long-distance transport that are proving difficult to electrify: some key technologies in these areas are today still at small prototype stage or below. In primary steelmaking, the use of electricity to convert iron ore via electrolysis into steel is being explored in research projects and plans for pilot plants. In aviation, prototypes of electric planes are currently being developed and tested by several companies, but the use of electricity for aviation is likely to be limited to short-haul flights given the technical limitations associated with the low energy density of on-board batteries.

The need for further development applies to other areas of the low-carbon electricity value chain too. Innovation to develop effective integration measures that provide greater flexibility to lower carbon electricity grids is becoming increasingly important: relevant technologies today are, however, generally between the early adoption and large prototype stages.

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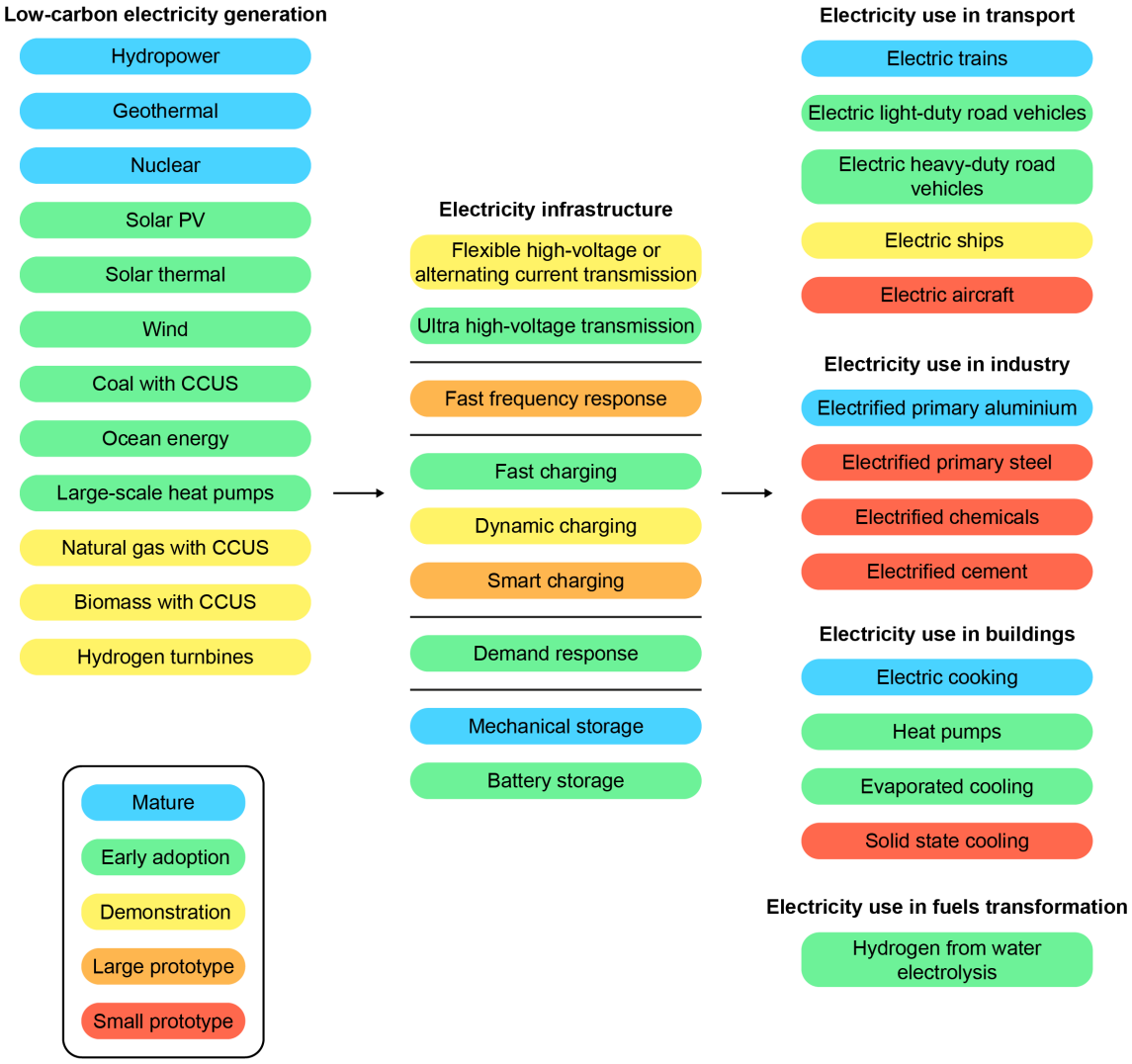
Figure 2.11 Technology readiness level of technologies along the low-carbon electricity value chain



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Notes: CCUS = carbon capture, utilisation and storage. Each technology is assigned the highest technology readiness level of the underlying technology designs. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, see: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all parts of the low-carbon electricity value chain are at commercial scale today; some technologies in end-use sectors and in electricity infrastructure are at demonstration or large prototype stage.

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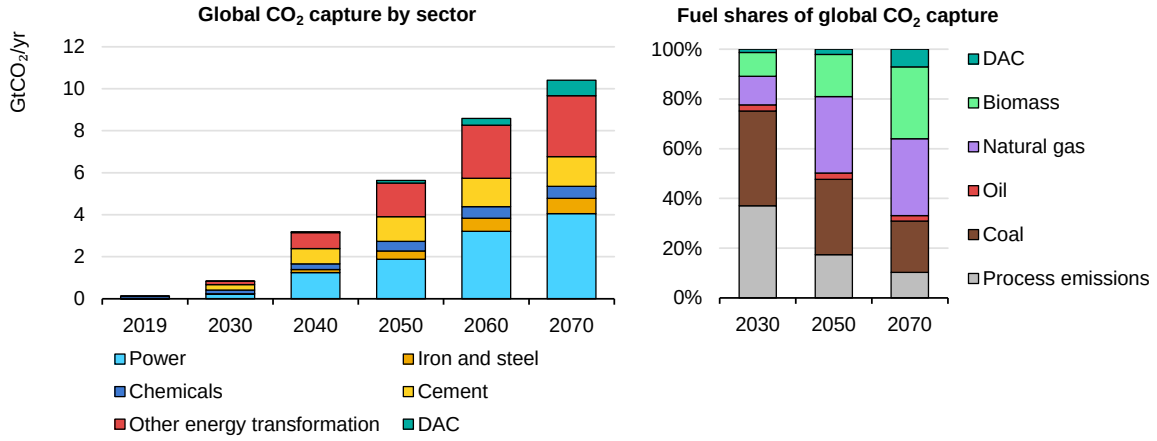
Carbon capture, utilisation and storage

In the Sustainable Development Scenario, CCUS plays a substantial and varied role in the transition to a net-zero global energy system.[9] CO_2 is captured for permanent geological storage or use from industrial processes, fuel production and transformation as well as power generation. CCUS also produces negative emissions (CO_2 removal) through BECCS and direct air capture and storage. In total, CCUS contributes almost 15% of the cumulative reduction in CO_2 emissions worldwide compared with the Stated Policies Scenario, with the role and contribution of CCUS growing over time.

Net-zero emissions are reached in the Sustainable Development Scenario in 2070, and around 10 Gt of CO_2 are captured in that year (Figure 2.12). The power sector accounts for less than 40% of the total CO_2 emissions captured, of which around half are from fossil power plants, allowing the continued operation of existing plants after CO_2 capture retrofits and lifetime extensions. The other half is captured at biomass-fired power plants, resulting in negative emissions to offset remaining emissions in heavy industry and transport.

Figure 2.12 Growth in global CO_2 capture by sector and fuel in the Sustainable Development Scenario, 2019-70



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Note: DAC = direct air capture.

In the Sustainable Development Scenario, the role of CO_2 capture shifts from managing the emissions from existing assets towards capture from biomass and air to enable carbon removal at scale.

[9] The IEA will release an ETP-2020 Special Report on CCUS with more detailed analysis of the role of CCUS in clean energy transitions to net-zero emissions.

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CCUS is particularly important in enabling the industry sector to capture process emissions in the production of cement, chemical feedstocks and steel. Overall, industry produces a quarter of the total CO_2 captured globally in 2070 in the Sustainable Development Scenario (see also Chapter 4). Around 30% (or 2.9 $GtCO_2$) of the global CO_2 captured in 2070 is linked to the production of other fuels, with 40% of global hydrogen production in 2070 being in combination with CCUS, while BECCS applied to biofuel production creates negative emissions of around 900 $MtCO_2$ in the same year. CO_2 is also used in combination with hydrogen to produce synthetic hydrocarbon fuels for the transport sector, in particular for the aviation sector, where few alternative decarbonisation options are available (see also Chapter 5). CO_2 is captured from the air and stored for carbon removal or used in combination with hydrogen for the production of clean fuels, and it accounts for around 7% of the CO_2 captured in the Sustainable Development Scenario.

CCUS goes through three phases in the Sustainable Development Scenario on the pathway towards net zero in 2070. Until 2030, the focus is on managing emissions from existing infrastructure and assets: over 80% of all CO_2 emissions captured in this decade are linked to fossil fuel and feedstock use in retrofitted coal-fired power units, chemical production (mainly for fertilisers), cement, and iron and steel facilities. During the second phase, from 2030 to 2050, the focus of carbon capture in power generation gradually shifts to natural gas, supporting the integration of variable renewables, while natural gas with CCS is also used to cover the growing demand for hydrogen. The scale of BECCS in power generation and biofuel production increases significantly and is responsible for around 15% of CO_2 captured in 2050. The final phase from 2050 to 2070 marks an important shift in the role of CCUS in the energy sector: the emphasis moves away from reducing emissions from existing infrastructure and fossil fuel use towards CCUS for carbon removal and CO_2 use for fuel production. In 2070, over one-third of all CO_2 emissions captured are from BECCS or direct air capture for generating negative emissions of carbon-neutral fuels.

Of the 10 Gt of CO_2 captured globally in 2070 in the Sustainable Development Scenario, more than 90% are stored. Nearly 3 Gt of the stored CO_2 comes from BECCS or direct air capture, which is more than a quarter of all CO_2 captured. The almost 1 Gt of the CO_2 captured in 2070 that is used rather than stored goes principally to produce fuels and feedstocks (Figure 2.13), and in particular to the production of synthetic hydrocarbon fuels, primarily for the aviation sector. Around 250 Mtoe of aviation fuels are produced in 2070 in combination with low-carbon hydrogen. With the CO_2 being sourced from the atmosphere (55% of all CO_2 used in 2070) or captured at biomass power or biofuel production plants (45%), the aviation fuel produced is carbon-neutral, and it helps to decarbonise the global aviation sector by meeting around 40% of its energy demand in 2070. Besides CO_2, which requires electricity to source CO_2 from the atmosphere through direct air capture,

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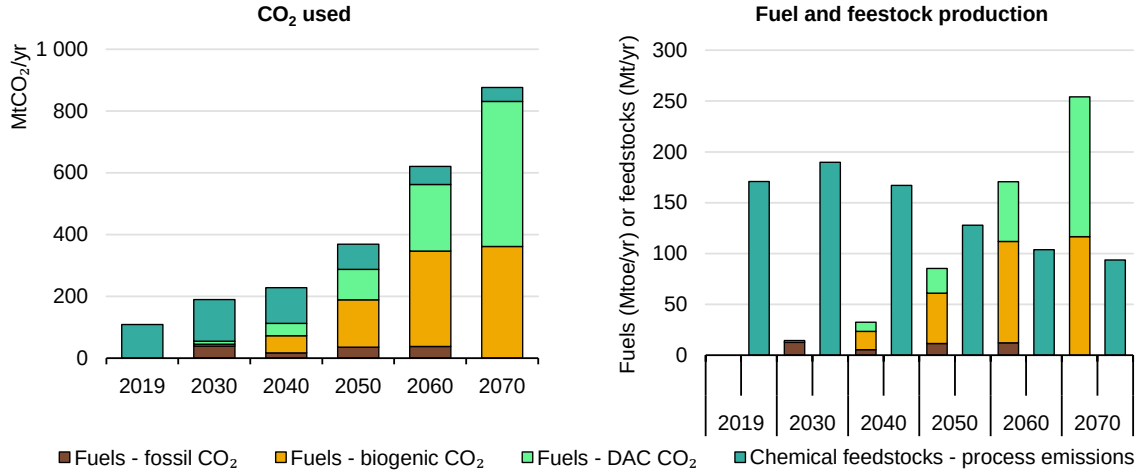
the production of this 250 Mtoe of synthetic kerosene requires around 120 MtH_2 (350 Mtoe) of electrolytic hydrogen, meaning that in total it requires 5 500 TWh of electricity, or around 8% of all the electricity produced worldwide in 2070 in the Sustainable Development Scenario.

Figure 2.13 Global CO_2 use for fuel and feedstock production in the Sustainable Development Scenario, 2019-70



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Notes: DAC = direct air capture. Feedstocks refer to the production of methanol and urea.

Almost 1 Gt of CO_2 captured from biomass or the air is used to produce clean fuels in the Sustainable Development Scenario, supporting in particular the decarbonisation of the aviation sector.

Trends by sector

In the Sustainable Development Scenario, cumulative CO_2 capture through to 2070 is largest in the power sector at 88 Gt: this represents about 15% of the CO_2 reduction in this sector. In industry, the cumulative CO_2 captured through to 2070 is 77 Gt, representing more than 20% of its CO_2 reduction. Negative emissions provided in combination with biofuel production in the other energy transformation sector and from direct air capture provide around 2% of the cumulative emissions reduction.

Power

Although there are a wide range of low-carbon alternatives available for decarbonising power generation, CCUS has an important role to play, in particular through CCUS retrofits to the existing fleet of fossil fuel power plants. In the Sustainable Development Scenario, over 190 GW of coal-fired capacity and almost 160 GW of gas-fired capacity is retrofitted. CCUS power plants also offer one option for facilitating the integration of growing shares of renewables into the power system

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by providing system balancing services and flexibility over different timescales, while the combination of CCUS and sustainable biomass (BECCS) in the power sector enables it to become net-negative after 2050, and to provide net-negative emissions of around 1.5 $GtCO_2$ in 2070. As a result, carbon capture contributes some 20% to the cumulative decarbonisation efforts of the power sector over the period to 2070. By 2070, a total of 1 100 GW of generating capacity is equipped with CCUS, producing around 6 000 TWh of electricity (or 8% of global power generation). All of the remaining coal-fired and gas-fired electricity generation, and about 50% of biomass-fired generation are linked to CCUS.

Industry

CCUS accounts for around 45% of the total reduction in cumulative emissions from cement, iron and steel, and chemicals production in the period to 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario. In the period to 2030, CO_2 emissions captured in industry increase by a factor of 4, and by a factor of 24 through to 2070. The amount of CO_2 captured is largest in the cement industry, followed by iron and steel and chemicals. By 2070, about 90% of all the CO_2 emitted globally in cement and around 75% in chemicals and iron and steel is captured. For this to happen, an average of almost 40 cement plants, over 15 chemicals plants and over 10 steel plants operating with CO_2 capture need to be built every single year through to 2070.

Other energy transformation sector

The other energy transformation sector today accounts for annual emissions of 1 400 $MtCO_2$, or around 4% of total energy sector emissions, mostly from refineries and oil and gas production. In the Sustainable Development Scenario, the other energy transformation sector helps to support the target of reaching net-zero emissions through the deployment of CCUS technologies. CCUS plays an important role in facilitating the production and use of low-carbon hydrogen from fossil fuels, which offers a way to decarbonise a range of energy sectors, in particular long-haul transport. For example, almost 100 Mtoe of ammonia for fuelling ships are produced from natural gas with CCUS, covering around 30% of fuel demand for shipping. CCUS is also a source of CO_2 for clean synthetic hydrocarbon fuels, and enables the capture and storage of biogenic CO_2. In the Sustainable Development Scenario, the total amount of biofuel production grows to more than 830 Mtoe in 2070, of which 35% is combined with CCUS, yielding to nearly 1 $GtCO_2$ of negative emissions.

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Box 2.9 Impact of the Covid-19 crisis on CCUS technologies

For CCUS, short-term uncertainty has been tempered by recent project and funding announcements. In March 2020, the United Kingdom confirmed its pledge to invest GBP 800 million (USD 995 million) in CCUS infrastructure. In Europe, the EUR 10 billion Innovation Fund will be available to support CCUS projects (and other clean energy technologies) from 2020, while in Australia, the government announced in May plans to make CCUS eligible for existing funding programmes. Direct air capture research also received a boost in March 2020 when the US Department of Energy earmarked USD 22 million in research and development grants (US DOE, 2020a). Recent industry commitments to CCUS include investments in the United States and Europe.

Technology readiness of CCUS value chain

The capture, transport and utilisation or storage of CO_2 emissions as a successful decarbonisation strategy hinges on the commercial availability of technologies at each stage of the process as well as on the development and expansion of CO_2 transport and storage networks on a sizeable scale.

Capture: While CO_2 has been captured for decades in certain industrial and fuel transformation processes such as ammonia production and natural gas processing, it has just commercially emerged or is still being demonstrated at a large scale in many of the other possible applications (Figure 2.14). In each of these potential new applications, which range from power generation and fuels transformation to cement and iron and steel production, a wide range of CO_2 separation techniques need to be tailored to the particular conditions of each individual process. Chemical absorption is the CO_2 separation technique for which there is the most operational experience, and it is currently used in commercial capture facilities and embedded in demonstration plants for most applications across different sectors. Chemical absorption is therefore the CO_2 separation technique the most widely used over the next two decades in the Sustainable Development Scenario.

Use: CO_2 is used commercially today in a few industries; it is, for instance, used in the production of urea (the main precursor of nitrogen-based fertilisers) and of carbonated drinks. In both applications, CO_2 is only stored temporarily and is ultimately released to the atmosphere. Other potential uses of CO_2 are emerging: they include building materials (which would provide long-term but not permanent

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CO_2 storage) and feedstock for synthetic fuels (which would prevent the CO_2 from being released into the atmosphere only temporarily).[10]

Storage: CO_2 has been used for enhanced-oil recovery for more than five decades; this counts as a form of storage because the vast majority of the CO_2 is retained in the reservoir. Most of the CO_2 used is sourced from natural reservoirs, but an increasing amount comes from CO_2 captured from industrial sources. There is relatively limited experience in operating other geological storage options at scale, although there are 5 large-scale facilities currently storing more than 7 $MtCO_2$/year in saline formations, one of which has been operating since 1995 (the Sleipner CCS project). CO_2 storage in depleted oil and gas wells has been limited to pilot demonstrations, but there are plans to develop commercial facilities.

Negative emissions: Biomass-based CO_2 emissions capture and storage and direct air capture both have the ability to yield negative emissions, and therefore have considerable potential long-term importance. With a few exceptions, however, neither technology has yet reached markets at a large scale.[11] Some demonstration plants and pilots have been completed, and in some cases they have been maintained in operation, particularly when a suitable commercial use for the captured CO_2 was found nearby. Several small pilot-scale direct air capture plants are currently operating around the world: they incorporate commercial facilities that sell the captured CO_2.

[10] Even if released again, the use of fossil CO_2 can contribute to CO_2 reduction as, in principle, each carbon molecule is being used twice: the carbon contained in a fossil fuel is used to produce energy or in an industrial production process; then the resulting CO_2 is used in combination with hydrogen to produce a synthetic hydrocarbon fuel.

[11] An ethanol plant in Illinois (United States) captures and stores 1 $MtCO_2$ per year.

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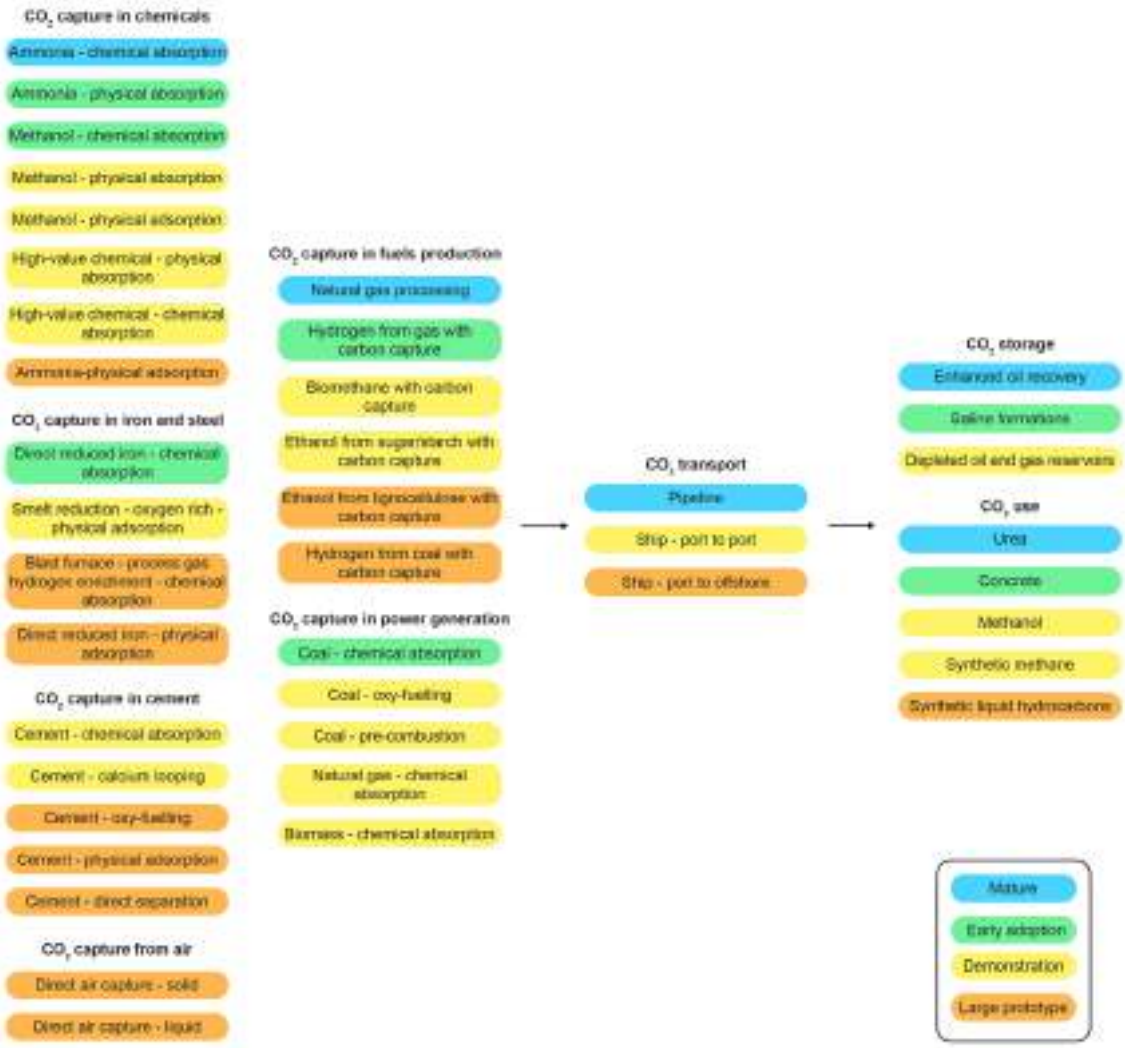
Figure 2.14 Technology readiness level of technologies along the CO_2 value chain



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Notes: Technologies included are at large prototype or at a more advanced stage. Each technology is assigned the highest technology readiness level of the underlying technology designs. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, see: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all parts of the CO_2 value chain are operating at commercial scale today: many of the relevant technologies are still at the demonstration and the large prototype stage.

Hydrogen and hydrogen-based fuels

Hydrogen holds great promise for the transition to a clean energy system. It can be an option to decarbonise sectors where few alternative mitigation solutions exist, such as long-distance transport, chemicals, and iron and steel production. With increasing shares of variable renewables in the electricity generation mix, it is one of the very few technology options for storing large amounts of electricity over days, weeks or even months. Hydrogen or hydrogen-based fuels can also be a means to transport renewable energy from regions with abundant renewable resources over

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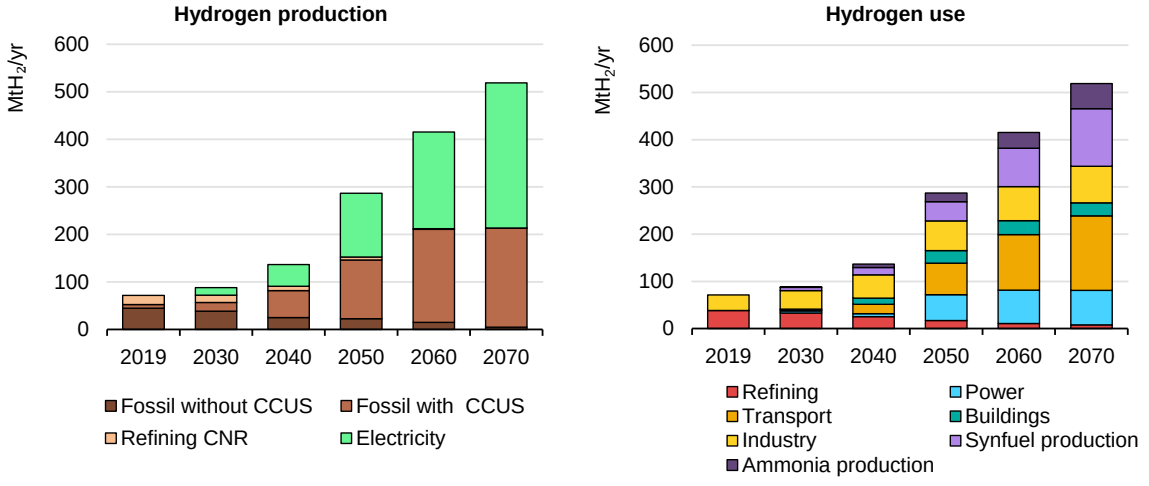
thousands of kilometres to regions and cities with growing energy needs. Hydrogen is a very versatile energy carrier; it can be produced from a variety of energy resources, including natural gas, coal, oil, renewables and nuclear energy. Hydrogen can also be converted into feedstocks for the chemical industry or, in combination with CO_2, into synthetic hydrocarbon fuels for the transport sector.

Despite these opportunities, hydrogen use today in the energy sector is largely limited to the refining sector and the production of ammonia and methanol in the chemical industry. Global hydrogen demand in 2019 stood at 75 MtH_2 (or 215 Mtoe): the hydrogen was mainly produced from fossil fuels without CCUS, and in particular from natural gas. In the Sustainable Development Scenario, this situation changes, with global hydrogen demand increasing sevenfold to 520 Mt by 2070 (Figure 2.15). The direct use of hydrogen in the transport sector for cars, trucks and ships accounts for 30% of hydrogen use in 2070, while around 20% of hydrogen is used in the production of synthetic kerosene from hydrogen and CO_2 for the aviation sector, and a further 10% is converted into ammonia as a fuel for the shipping sector, meeting almost half of all shipping fuel demand in 2070. Industry accounts for 15% of hydrogen use in 2070, mostly for chemicals and iron and steel; the power sector accounts for almost 15%, which supports flexible electricity generation; and the buildings sector accounts for 5%, which is used for space and water heating, 5% in the form of hydrogen blended together with natural gas and biomethane in the gas grid, and 95% in the form of pure hydrogen transported in new pipelines or in converted natural gas pipelines.

Figure 2.15 Global hydrogen production by fuel and hydrogen demand by sector in the Sustainable Development Scenario, 2019-70



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Notes: CCUS = carbon capture, utilisation and storage. *Refining CNR* refers to the production of hydrogen as a by-product of catalytic naphtha reforming in refineries. *Ammonia production* refers to the fuel production for the shipping sector. Hydrogen use for industrial ammonia production is included within the industry use.

Global hydrogen production and use grows sevenfold by 2070 compared to today in the Sustainable Development Scenario, with demand growth almost completely met by low-carbon hydrogen.

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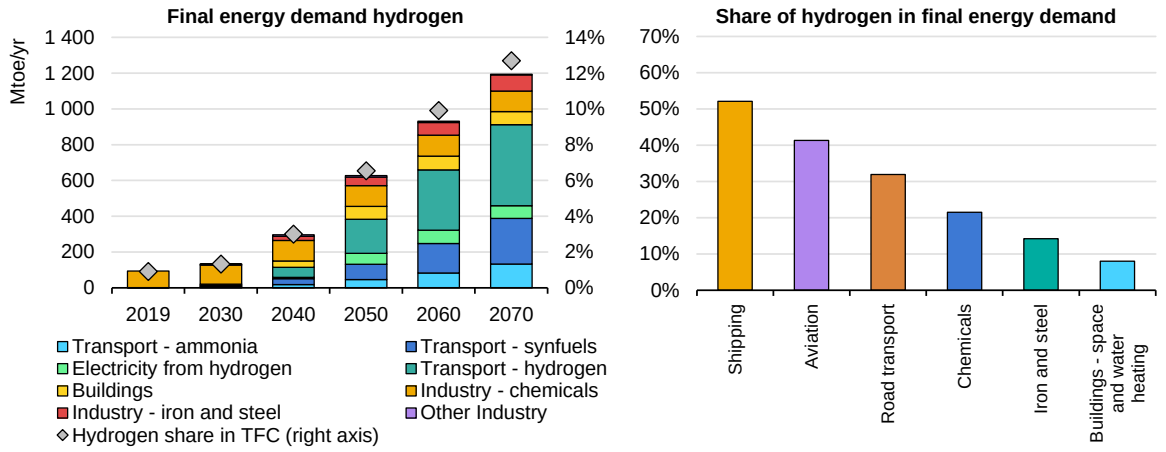
In the Sustainable Development Scenario, hydrogen and hydrogen-based fuels account in 2070 for 13% of all final energy needs, compared to around 1% in 2019 (Figure 2.16), with most of these fuels being used in transport and industry:

- **Transport** accounts for 70% of the use of these fuels in 2070, which meet significant shares of the final energy demand for different transport modes: 52% for shipping, 40% for aviation and a third and road transport. Within road transport, hydrogen and fuel cells become important for decarbonising trucks. Almost a quarter of all medium-freight trucks on the road in the Sustainable Development Scenario in 2070 use hydrogen and fuel cells, as do around 50% of all heavy-freight trucks (see Chapter 5).
- **Industry** accounts for approaching 20% of the use of these fuels in 2070, with the introduction of hydrogen as a reducing agent in steel production being the main driver for growth in industrial hydrogen demand. Almost 15% of final energy demand in the iron and steel sector is linked to hydrogen use, and more than a quarter of global primary steel production in 2070 is based on the electrolytic hydrogen-based direct reduction technology route. Hydrogen remains also an important feedstock in the chemical industry for the production of ammonia and methanol, accounting for a fifth of the energy demand in this industry (see Chapter 4).

Figure 2.16 Global final energy demand for hydrogen by sector and share of hydrogen in selected sectors in the Sustainable Development Scenario



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Notes: TFC = total final consumption. *Synfuels* refer to synthetic hydrocarbon fuels produced from hydrogen and CO_2. Shares of hydrogen in the final energy demand include for transport modes ammonia and synthetic hydrocarbon fuels.

Hydrogen and hydrogen-based fuels account for 13% of global final energy demand by 2070 in the Sustainable Development Scenario, and are mostly used in transport and industry.

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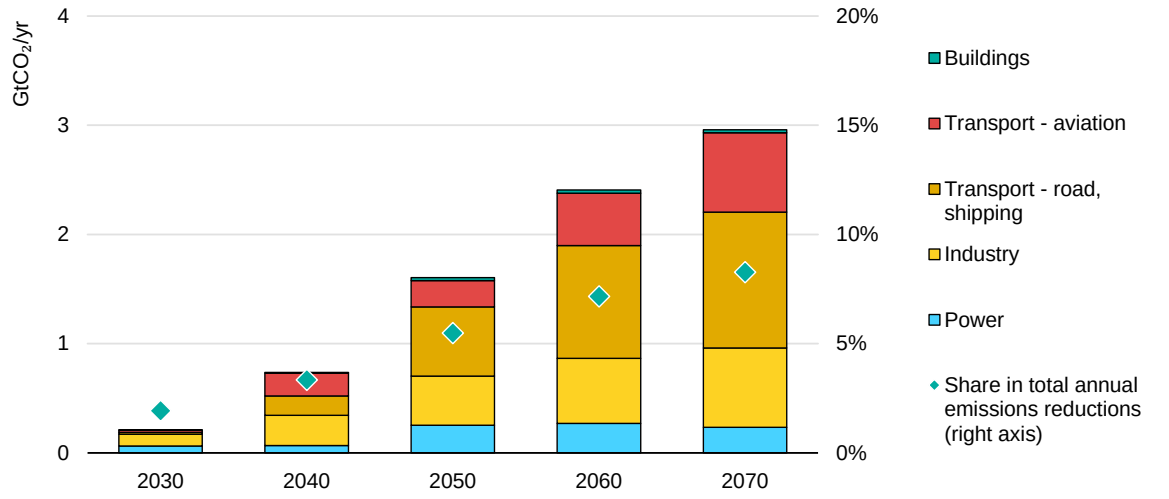
On the production side, almost all hydrogen today comes from fossil fuels, with natural gas accounting for around three-quarters of pure hydrogen production, coal for almost a quarter (mainly in China), and oil and electricity for the remainder. As a consequence, hydrogen production was responsible in 2019 for CO_2 emissions of more than 800 $MtCO_2$, around 2% of global CO_2 emissions from the energy sector. In the Sustainable Development Scenario, this situation changes as the focus switches to Low-carbon hydrogen (hydrogen produced from fossil fuels in combination with CO_2 capture and storage or through water electrolysis from low-carbon electricity). Low-carbon hydrogen totals 513 MtH_2 in 2070 and accounts for 99% of global production. More than half of this is produced through electrolysis, and requires 13 750 TWh of electricity to produce, or 19% of global electricity generation in 2070 – equivalent to around half of today's total generation. The rest of the low-carbon hydrogen produced – some 40% – comes from fossil fuels with CCUS, and results in the capture of 1 900 $MtCO_2$. The use of low-carbon hydrogen and hydrogen-based fuel provides 8% of the CO_2 reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario in 2070 (or 6% of the cumulative emission reductions over the period 2019-70) (Figure 2.17). Hydrogen use in the transport sector accounts for 6% of the overall CO_2 reductions, and industry for 2%.

Figure 2.17 Global CO_2 emissions reductions from hydrogen by sector in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2030-70



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Hydrogen and hydrogen-based fuels account for 8% of the annual CO_2 emissions savings in the Sustainable Development Scenario in 2070, with transport making the biggest contributions.

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Box 2.10 Impact of the Covid-19 crisis on hydrogen technologies

The economic crisis resulting from the Covid-19 outbreak brought risks for hydrogen-related projects. Hydrogen Europe initially estimated that up to EUR 130 billion of investments in low-carbon hydrogen production projects might be at risk in Europe alone (Hydrogen Europe, 2020). However, a number of governments and companies have responded in ways that show a strong continuing commitment to maintaining the momentum of hydrogen.

On the government side, several countries (including Germany, Norway and Portugal) have adopted ambitious national strategies, while the European Commission (EC) announced a new Hydrogen Strategy in July which set a target of at least 6 GW of renewable hydrogen electrolysers by 2024 and 40 GW by 2030 (EC, 2020). The EC also announced the creation of the European Clean Hydrogen Alliance to help deliver on the strategy and build up an investment pipeline for scaled-up low-carbon hydrogen production. In China, Beijing released its municipal "New Infrastructure Action Plan (2020-2022)" in June 2020, showing that it plans to become the demonstration city in China for hydrogen fuel cell vehicles, including by establishing national-leading manufacturing centres for hydrogen technologies (Beijing Municipality, 2020).

On the industry side, several big companies have announced plans to accelerate the development of hydrogen technologies. Volvo and Daimler announced in April a joint venture to work on hydrogen fuel cells for trucks, and Bosch announced plans to manufacture fuel cells for mobile and stationary applications (Kahn, 2020; Daimler, 2020). The consortium behind the development of iron ore reduction for steelmaking based on electrolytic hydrogen has confirmed its commitment to commence the construction of an industrial scale demonstration plant in 2023 with the objective of producing commercial fossil-free steel by 2026 (Hybrit, 2020). The production of low-carbon hydrogen-derived products has also received a significant boost: Air Products, ACWA and NEOM signed an agreement for a USD 5 billion project to produce 1.2 million tonnes per year of green ammonia, and a consortium of 6 Danish companies announced a joint effort to develop hydrogen-based fuels for long-distance transport and heavy industry, with the first projects starting operations in 2023 (Air Products, 2020; Financial Times, 2020).

Technology readiness of the hydrogen value chain

The value chain for low-carbon hydrogen is not completely developed at commercial scale today. It comprises many technologies that are necessary to produce, transport, store and consume low-carbon hydrogen, each of them at a different stage of maturity and facing specific technical challenges (Figure 2.18).

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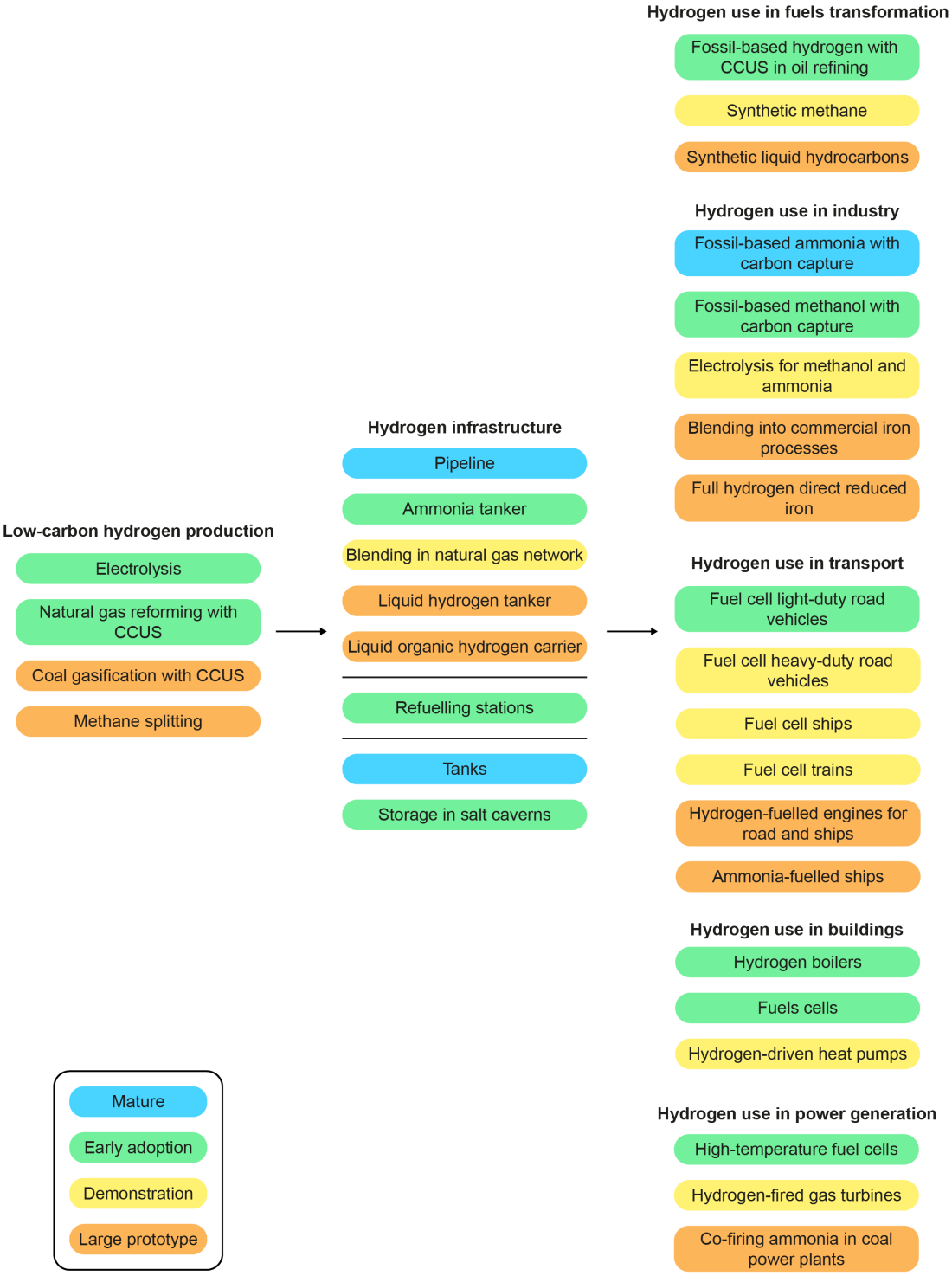
Figure 2.18 Technology readiness level of technologies along the low-carbon hydrogen value chain



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Notes: CCUS = carbon capture, utilisation and storage. Technologies included are at large prototype or at a more advanced stage. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, see: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all steps of the low-carbon hydrogen value chain are operating at commercial scale today: the majority of demand technologies are only at the demonstration or prototype stage.

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Among the low-carbon hydrogen production routes that are commercially available today, the decline in the costs of renewable electricity is creating renewed interest in water electrolysis, with scaling up of deployment and manufacturing capacities seen as critical to bring down costs. Natural gas reforming with CCUS is an alternative commercially available option for hydrogen production.

Setting to one side its long-standing use in oil refining and chemical production, hydrogen use today is limited by current commercially viable technologies to light-duty vehicles, space heating, and electricity generation in buildings and distributed electricity systems.[12] The use of electrolytic hydrogen in heavy industrial processes is at the demonstration stage today, whereas the use of natural gas with CCUS is already in operation at several facilities. Large portions of the full potential demand for hydrogen will remain untapped until technologies are developed to use hydrogen in iron and steel and heavy-duty transport, and until fuels derived from low-carbon hydrogen (for example, synthetic hydrocarbon fuels and ammonia), are demonstrated at commercial scale and then deployed. Technologies for transporting and distributing hydrogen will also be critical for its wider deployment. Infrastructure technologies such as hydrogen pipelines and hydrogen refuelling stations are already mature or at an early adoption stage today, but others, such as long-distance transport of hydrogen by ships or blending of hydrogen in natural gas grids, are still being tested as large prototypes or are at commercial demonstration scale.

Bioenergy

Bioenergy has a central role to play in reducing carbon emissions from the energy sector. In the Sustainable Development Scenario, bioenergy becomes the second-largest primary energy source worldwide after solar, its share in total energy demand almost doubling from today's level to nearly 20% in 2070 (Figure 2.19). In absolute terms, primary bioenergy demand increases by 1 430 Mtoe (60 EJ), reaching a level of 3 000 Mtoe (125 EJ) in 2070 in the Sustainable Development Scenario. Ensuring that this growth in bioenergy demand can be realised in a sustainable way, avoiding adverse social, environmental or economic impacts, will be critical (Box 2.11).

Around 60% of final bioenergy use (and 40% of primary bioenergy use) is today in the form of the traditional use of solid biomass for cooking in emerging economies, which has negative impacts on human health through indoor air pollution and harmful social, economic and environmental consequences. The provision of clean cooking fuels by 2030 is one of the United Nations' Sustainable Development Goals. Meeting this goal entails a reduction in traditional use of solid biomass by almost 90% over the next 10 years, which requires a steady increase in the efficient use of

[12] Stationary fuel cells deployed today mostly rely on natural gas as fuel, although they are capable of using hydrogen.

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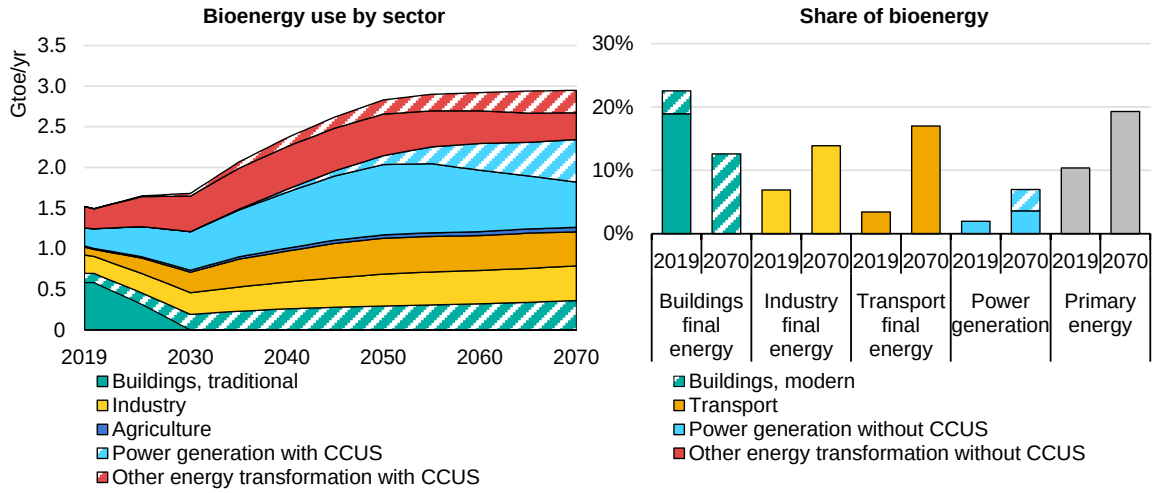
biomass in solid, liquid or gaseous forms (e.g. modern cooking stoves, space heating boilers): in the Sustainable Development Scenario, the efficient use of biomass accounts for 13% of total buildings energy needs in 2070.

The bulk of bioenergy use in 2070 is for making transport biofuels and for power and heat generation – in both cases much of it with CCUS. The combination of bioenergy with CO_2 capture and storage removes CO_2 from the natural carbon cycle, creating negative emissions: in the Sustainable Development Scenario, these negative emissions enable the goal of net-zero emissions to be reached in 2070.

The contribution of bioenergy to reducing CO_2 emissions is particularly important where direct electrification is difficult. An important advantage of bioenergy is that it can be converted into energy forms that are compatible with existing energy technologies that rely on the combustion of fossil fuels: it can be used as feedstock in the chemicals industry and it can be used in existing vehicle fuelling networks and gas pipelines, for example in the form of biomass-to-liquid (BTL) thermochemically produced fuels, hydrotreated vegetable oil or biomethane.

Figure 2.19 Global bioenergy demand by sector and share of bioenergy use in key sectors in the Sustainable Development Scenario, 2019-70



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Notes: CCUS = carbon capture, utilisation and storage. *Other energy transformation* includes coal mining, oil and gas extraction, oil refining, coal and gas transformation and liquefaction, production of hydrogen and hydrogen-based fuels, and biofuels production with and without CCUS.

Maximising the potential of bioenergy depends on mobilising supply chains for abundant and untapped waste and residue resources: the use of energy crops requires careful consideration of land-use competition.

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Box 2.11 How much bioenergy is sustainably available?

For bioenergy to play the expanded role envisioned in the Sustainable Development Scenario, it will need to be produced in a sustainable way to avoid depleting carbon sinks or causing other types of environmental, social or economic impacts (IPCC, 2019). For this reason, bioenergy support policies need to integrate sustainability criteria, ideally with third-party certification, to ensure that only truly beneficial bioenergy is supported. Increased competition for arable land, which would drive up food prices and potentially reduce biodiversity, is a potential concern.

Scientific studies have yielded a wide range of estimates of the availability of sustainable biomass for energy purposes, from close to zero to levels well in excess of the amount of primary energy the world uses today. Nonetheless, there appears to be a consensus that up to 2 400 Mtoe per year (100 EJ), or roughly twice current consumption, could be produced sustainably without serious difficulties, while estimates going up to as much as 5 000 Mtoe (200 EJ) are still considered reasonable (IPCC, 2014, 2019; IEA, 2017a). At 3 000 Mtoe (125 EJ) in 2070, the amount of feedstock supply needed in the Sustainable Development Scenario is well within the range.

The amount of feedstock supply needed in the Sustainable Development Scenario in 2070 is well within the range of what seems reasonable. However, securing this amount of bioenergy would require significant contributions from agricultural wastes and residues, as well as from energy crops. In the Sustainable Development Scenario, energy crops provide with 840 Mtoe (37 EJ) around 30% of all the bioenergy needs, which results in a land requirement in the range of 0.9-2.1 million km^2, depending on future energy crop yields.* Far-reaching measures would be needed to mobilise these resources in a sustainable manner, including by improving crop yields, sequential cropping, reducing waste in food supply, utilising abandoned and degraded lands, and mobilising supply chains for dispersed wastes and residues. Developing new biomass resources such as micro-algae for making biofuels (see Chapter 6) will also have a role to play.

* Calculation of areas is based on energy crop yields of dry matter in the range of 10-23 tonnes per hectare and year and a lower heating value of 18 GJ per tonne of dry matter.

In the Sustainable Development Scenario, liquid biofuels help to reduce emissions in cars and (in particular) trucks with internal combustion engine technologies in the period up to the 2040s. Thereafter, the increasingly widespread use of electricity and hydrogen as fuels for road transport leads to a decline in biofuel demand. Available biofuel production is then diverted towards other transport modes: up to the 2050s, it helps meet biofuel demand in the shipping sector, before the uptake of alternative

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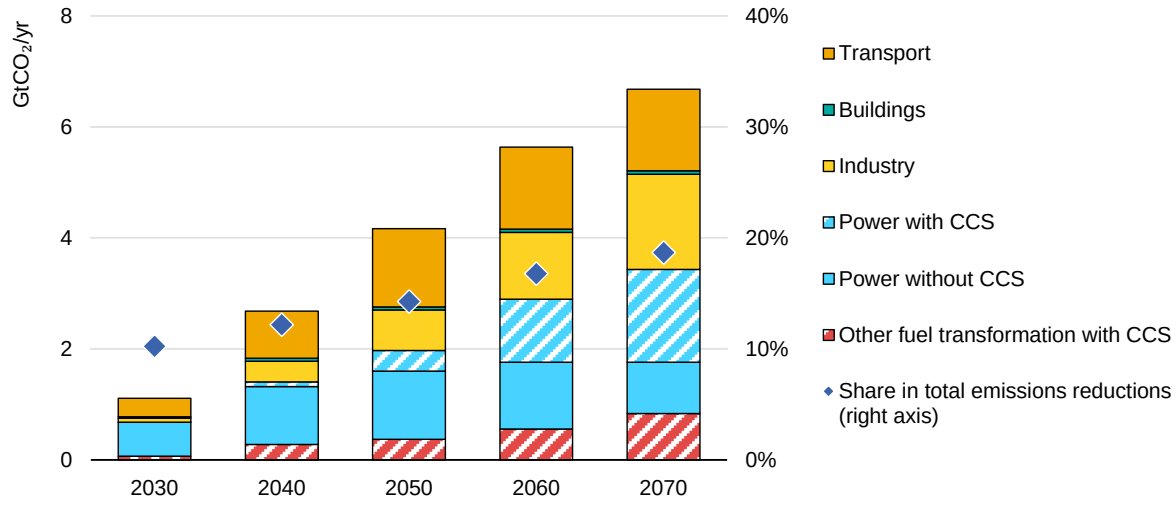
fuels (hydrogen and ammonia) limits biofuel demand growth there too. Towards 2070, it increasingly goes toward meeting the growing demand for biofuels in aviation. Road transport accounts in 2040 for around 60% of biofuel demand in the transport sector, but its share drops to one-third in 2070, with aviation and shipping together accounting for the other two-thirds: the share of total energy demand in aviation and shipping which is met by biofuels rises from less than 0.1% today to 30% by 2070.

Figure 2.20 Global CO_2 reductions from bioenergy use in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2030-70



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Notes: CCS = carbon capture and storage.

Bioenergy contributes one-fifth of the total annual CO_2 reductions in 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario, with the reductions mostly occurring in power, followed by transport and industry.

The use of biomass as a clean fuel and feedstock in industry doubles from today's levels to 14% in 2070 in the Sustainable Development Scenario. Biomethane can be blended up to any share into natural gas grids, reducing the carbon intensity of heating in buildings while making use of existing gas infrastructure. In the Sustainable Development Scenario, the global average blending share of biomethane reaches 16% in 2070, though regional blending shares can be much higher, such as 50% in the European Union and 67% in China in 2070. The share of bioenergy in the global power mix more than triples, from 2% to 7% in 2070, with biomass playing a vital role as a renewable and dispatchable source of electricity generation to support the integration of more variable renewables into the power system and, in combination with BECCS, to produce negative emissions. The use of BECCS in power generation and for biofuel production makes up 22% of primary bioenergy use in the Sustainable Development Scenario by 2070, resulting in negative emissions of 2.5 $GtCO_2$. Overall, the increased use of bioenergy in the

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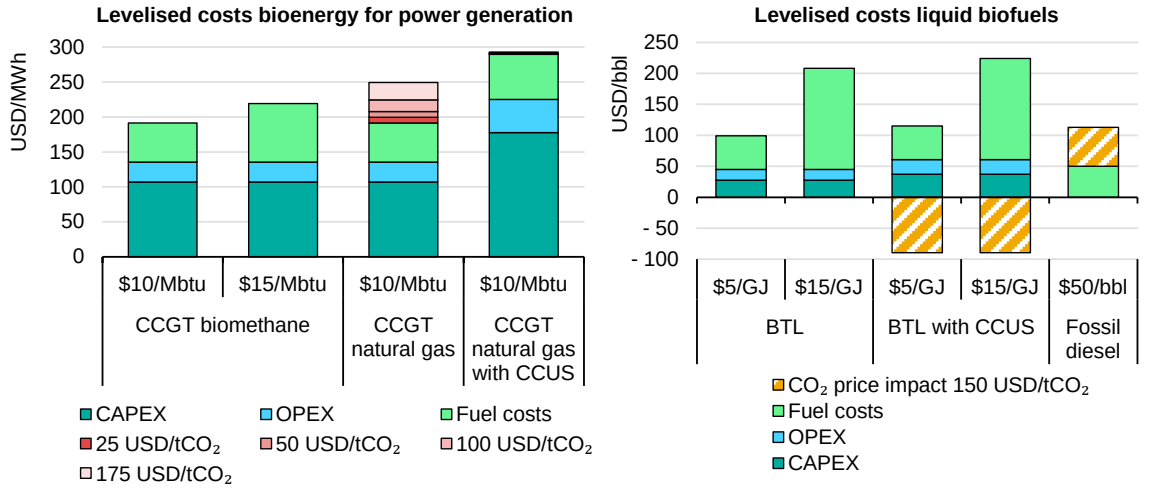
Sustainable Development Scenario – with and without CCS – provides one-fifth of global annual CO_2 reductions relative to the Stated Policies Scenario in 2070 (Figure 2.20).[13]

Bioenergy technologies generally struggle to compete with existing fossil fuel-based ones because of the higher costs involved, although the extent of the cost gap depends critically on the availability of biomass feedstock and its cost (Figure 2.21). Their uptake in the Sustainable Development Scenario therefore requires carbon pricing and/or other regulatory measures, such as clean fuel standards in the transport sector or blending mandates. For example, biomethane becomes competitive with natural gas in gas turbines and combined-cycle power plants as a flexible generation option at a CO_2 price of around USD 100/tonne in regions with cheap biomethane and high natural gas prices, while advanced biofuels produced from lignocellulosic feedstock become an increasingly cost-effective alternative to fossil diesel as the CO_2 price rises, especially in regions with low feedstock costs.

Figure 2.21 Competitiveness of bioenergy for power generation and biofuels, 2050



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Notes: CAPEX = capital expenditure. OPEX = operating expenditure. CCGT = combined-cycle gas turbine; BTL = biomass-to-liquids. Bbl =barrel. MBtu = million British thermal unit.

CCGT: load factor: 10%; CAPEX: USD 1 000/kW without CCUS and USD 1 660/kW with CCUS; OPEX: 2.5% of CAPEX; gas price: USD 10-15/MBtu; net efficiencies: 61% without CCUS and 53% with CCUS; technical lifetime: 25 years; representative discount rate: 8%.

BTL: load factor: 90%; CAPEX without CCUS: USD 46/(GJ/yr); OPEX without CCUS: USD 3/(GJ/a); conversion efficiency without CCUS: 52%; CAPEX with CCUS: USD 63/(GJ/yr); OPEX with CCUS: USD 4/(GJ/yr); biomass feedstock price: USD 5-15/GJ; conversion efficiency without CCUS: 52%; capture rate with CCUS: 90%; technical lifetime: 25 years ; representative discount rate: 8%..

The cost-competitiveness of biomass for the production of electricity and biofuels depends on bioenergy feedstock costs, competing fossil energy prices and CO_2 prices.

[13] Following the 2006 IPCC *Guidelines for National Greenhouse Gas Inventories*, no CO_2 emissions have been assigned to the combustion of bioenergy; instead, these emissions are reported under agriculture, forestry and other land use (AFOLU). AFOLU CO_2 emissions are accounted for within the agriculture sector if they are caused by energy use within this sector.

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Bioenergy resources are unevenly distributed globally and are not always located close to demand centres, so they need to be traded internationally. This is particularly the case for transport biofuels. Today around 0.3 mb/d of biodiesel and ethanol are traded between major world regions – equivalent to less than 1% of total trade in oil. In the Sustainable Development Scenario, trade reaches close to 3 mb/d in 2070, with emerging economies in the Asia Pacific region becoming major importers, supplied principally by producers in South America, Eastern Europe and the Russian Federation.

Box 2.12 Impact of the Covid-19 crisis on bioenergy technologies

Biofuels is the bioenergy subsector hit the hardest by the Covid-19 crisis. Reduced fuel demand from decreased travel coupled with falling oil prices has led to reduced liquid biofuels production and some plant closures (World Bioenergy Association, 2020). Though demand for solid biomass has generally remained steady, many pellet producers in Europe have experienced reduced demand and disrupted supply chains (ENplus 2020; Voegele, 2020).

A number of positive steps have, however, been taken to support bioenergy across the value chain. The United Kingdom's Department of Business, Energy and Industrial Strategy extended the Renewable Heat Initiative's deadline to complete non-domestic projects by 14 months (UK BEIS, 2020), for example, and the United States Department of Energy has announced USD 68 million of funding for projects to improve the productivity and resiliency on bioenergy crops and USD 97 million for projects to improve bioenergy conversion technologies (US DOE 2020b; 2020c). The oil and gas industry has meanwhile announced new partnerships with biomethane producers in Europe and the United States, with Shell signing a significant long-term offtake agreement with Nature Energy, and Chevron teaming up with Clean Energy to provide biomethane fuelling stations near ports for truck drivers (Nature Energy, 2020; Bioenergy Insights, 2020), while retail giant Amazon has acquired 6 million gallons of sustainable aviation fuel in the form of renewable diesel (an advanced biodiesel) from Shell Aviation and World Energy for its air cargo operations (Biofuels International, 2020).

Technology readiness of bioenergy value chain

Overall, the bioenergy value chain is on the threshold of achieving early commercialisation. Many bioenergy conversion technologies, such as conventional biofuels and biomass-fired power plants, are at least at an early market adoption

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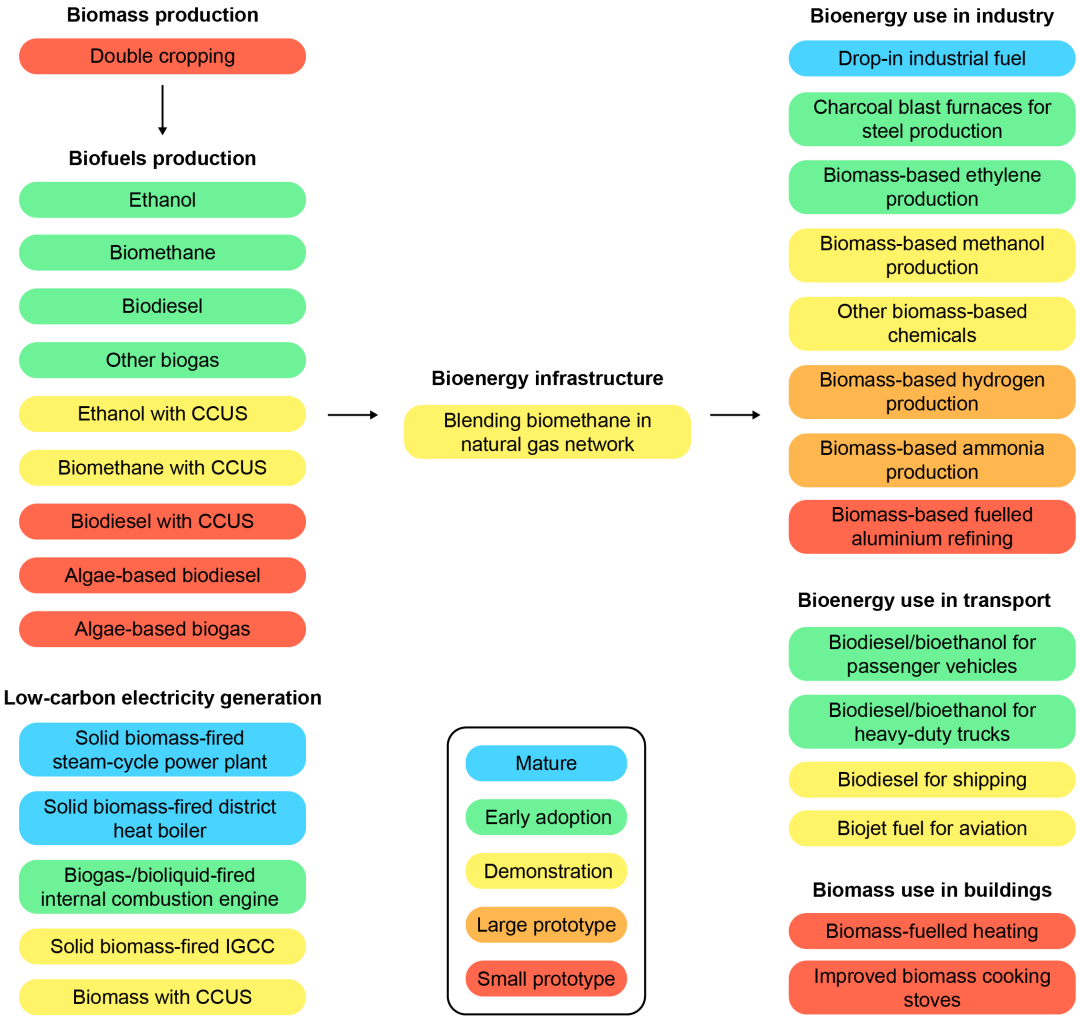
phase (Figure 2.22). Technologies related to road transport and to heating and cooking are similarly moving their way up the technology readiness ladder. Ethanol from corn and sugarcane is widely available in countries such as Brazil and the United States, and fatty acid methyl esters (FAME) biodiesel and hydrotreated vegetable oil (HVO) diesel are commercially available in a variety of countries, notably in Europe and parts of Southeast Asia. On the infrastructure side, biomethane blending is being implemented in Europe, particularly in Germany, with the help of policy measures. The state of technology development of many parts of the bioenergy value chain underscores the potential of bioenergy as a near-term decarbonisation opportunity, relative to other measures.

Figure 2.22 Technology readiness level of technologies along the bioenergy value chain



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Notes: CCUS = carbon capture, utilisation and storage. IGCC = integrated gasification combined cycle. Technologies included are at large prototype or at a more advanced stage. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, see: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all steps of the bioenergy value chain are operating at commercial scale today, with several biofuels production technologies and end-use applications still in the demonstration phase.

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However, there are critical links in the bioenergy value chain that remain in a demonstration or even prototype phase. These include advanced biodiesel and biojet fuel technologies, notably biomass-to-liquid (BTL). Advanced biodiesel plays an essential role in decarbonising long-distance transport, specifically heavy-duty trucks and shipping: heavy-duty trucking alone accounts for around half of advanced biodiesel demand from 2025 onwards, the vast majority supplied by BTL. Perhaps even more critical to achieving the Sustainable Development Scenario in the long run is the use of biojet fuel from BTL to decarbonise aviation. Biojet fuel alone accounts for over one-third of aviation fuel consumption by 2070 (fossil-fuel kerosene for 23% and synthetic hydrocarbons from CO_2 and hydrogen for more than 40%). The remaining fossil fuel usage is offset using negative emissions, a significant portion of which comes from BTL technology coupled with CCS. There are several commercial-scale BTL projects now in the pipeline, mostly in the United States, but also in Europe and Japan. The projects encompass a wide selection of BTL variations, from feedstock choices (forestry residues and municipal solid waste) to fuel output (advanced biodiesel and biojet fuel). One project will also include CCS to produce negative emissions. The success of these projects is vital to moving forward the development of advanced biodiesel and bringing the bioenergy value chain closer to maturity.

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References

Airbus (2016), Innovative 3D Printing Solutions Are "Taking Shape" Within Airbus, press release, Airbus, www.airbus.com/newsroom/news/en/2016/04/innovative-3d-printing-solutions-are-taking-shape-within-airbus.html (accessed 31 August 2020).

Air Products (2020), Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets, press release, Air Products, www.airproducts.com/Company/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market.aspx.

Beijing Municipality (2020), Beijing Municipality website, www.beijing.gov.cn/zhengce/zhengcefagui/202006/t20200610_1921162.html (accessed in June 2020).

Bioenergy Insights (2020), Chevron, Clean Energy Partner on "Adopt-a-port" Initiative, Bioenergy Insights, www.bioenergy-news.com/news/chevron-clean-energy-fuels-partner-on-adopt-a-port-initiative (accessed 31 July 2020).

Biofuels International (2020), Amazon Air Takes Off with Sustainable Aviation Fuel, Biofuels International, biofuels-news.com/news/amazon-air-takes-off-with-sustainable-aviation-fuel (accessed 1 August 2020).

Cotteller, M. and J. Joyce (2014), 3D opportunity: Additive manufacturing paths to performance, innovation, and growth, Deloitte Review, No. 14, dupress.deloitte.com/dup-us-en/deloitte-review/issue14/dr14-3d-opportunity.html.

Daikin (2020), Briefing to Analysts and Investors on FY 2019 Financial Results Ended March 31, 2020, Q&A Session, Daikin, www.daikin.com/investor/data/kessan/20200513/shitugioutou.pdf.

Daimler (2020), Volvo Group and Daimler Truck AG Are Planning to Form a Joint Venture, press release, Daimler, www.daimler.com/company/news/planning-joint-venture-volvo.html.

EC (European Commission) (2020), A Hydrogen Strategy for a Climate Neutral Europe, EC, Brussels, ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf.

ENplus (2020), The Impact of COVID-19 on ENplus Certified Companies, ENplus, Brussels, www.enplus-pellets.eu/en-in/component/attachments/attachments.html?task=download&id=524.

Financial Times (2020), Danish groups join forces to deliver green hydrogen project, Financial Times, www.ft.com/content/6d2c8d8a-a767-4e41-b0f9-3237dd711597.

Gazzetta Ufficiale (2020), Decree-Law 19 May 2020, No. 34, Gazzetta Ufficiale, Rome, www.gazzettaufficiale.it/eli/id/2020/05/19/20G00052/sg.

Huang, R. (2016), A Multi-Scale Life Cycle Framework for the Net Impact Assessment of Additive Manufacturing in the United States, Northwestern University.

IEA. All rights reserved.

Huang, R. et al. (2016), Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components, Journal of Cleaner Production, Vol. 135/1, pp. 1559-1570, doi.org/10.1016/j.jclepro.2015.04.109.

Hybrit (2020), Hybrit website, www.hybritdevelopment.com (accessed in June 2020).

Hydrogen Europe (2020), Post Covid-19 and the Hydrogen Sector: A Hydrogen Europe Analysis, Hydrogen Europe, Brussels, https://hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe%20Analysis_Post%20COVID-19%20and%20the%20Hydrogen%20Sector_final.pdf.

IEA (International Energy Agency) (2020a), Global EV Outlook 2020, IEA, Paris, www.iea.org/reports/global-ev-outlook-2020.

IEA (2020b), World Energy Outlook Special Report on Sustainable Recovery, IEA, Paris, www.iea.org/reports/sustainable-recovery.

IEA (2019a), World Energy Model: Scenario Analysis of Future Energy Trends, webpage, IEA, Paris, www.iea.org/reports/world-energy-model/sustainable-development-scenario.

IEA (2019b), World Energy Outlook 2019, IEA, Paris, www.iea.org/reports/world-energy-outlook-2019.

IEA (2019c), Material Efficiency in Clean Energy Transitions, IEA, Paris, www.iea.org/reports/material-efficiency-in-clean-energy-transitions.

IEA (2019d), Multiple Benefits of Energy Efficiency, IEA, Paris www.iea.org/reports/multiple-benefits-of-energy-efficiency.

IEA (2018a), Energy Service Companies (ESCOs): At the Heart of Innovative Financing Models for Efficiency, IEA, Paris, www.iea.org/reports/energy-service-companies-escos-2.

IEA (2018b). "The Future of Cooling: Opportunities for energy-efficient air conditioning", https://www.iea.org/reports/the-future-of-cooling.

IEA (2017), Technology Roadmap: Delivering Sustainable Bioenergy, IEA, Paris, webstore.iea.org/technology-roadmap-delivering-sustainable-bioenergy.

IEA (2016), World Energy Outlook Special Report on Energy and Air Pollution, IEA, Paris, www.iea.org/reports/energy-and-air-pollution.

IPCC (Intergovernmental Panel on Climate Change) (2019), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, IPCC, Geneva, www.ipcc.ch/srccl.

IPCC (2014), Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, www.ipcc.ch/report/ar5/syr.

Kahn, S. (2020), Against Coronavirus, for the Climate: With Responsibility and Technology "Invented for Life," Bosch is Tackling the Crisis, press release, Bosch, www.bosch-presse.de/pressportal/de/en/gegen-corona-fuer-das-klima-bosch-stellt-sich-verantwortlich-und-mit-technik-fuers-leben-der-krise-210880.html.

IEA. All rights reserved.

Mankins, J. (1995), "Technology readiness level: A white paper", NASA, Office of Space Access and Technology, www.researchgate.net/publication/247705707_Technology_Readiness_Level_-_A_White_Paper.

Material Economics (2018), The Circular Economy: A Powerful Force for Climate Mitigation, Material Economics, materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1.

Nature Energy (2020), Nature Energy Begins Biomethane Supply Deal with Shell Energy Europe, press release, Nature Energy, Odense SØ, natureenergy.dk/en/node/259 (accessed 31 July 2020).

Sherwood, S. et al. (2020), An assessment of Earth's climate sensitivity using multiple lines of evidence, Reviews of Geophysics, agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019RG000678 (accepted for publication).

UK BEIS (Department for Business, Energy & Industrial Strategy, United Kingdom) (2020), Notice on Changes to RHI Support and COVID-19 Response: Government Response, UK BEIS, London, assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/896387/Gov_Response_-_Notice_on_Changes_to_RHI_Support_and_Covid-19_Reponse_FINAL.pdf.

US DOE (Department of Energy, United States) (2020a), Department of Energy to Provide $22 Million For Research on Capturing Carbon Dioxide From Air, press release, US DOE, Washington, DC, www.energy.gov/articles/department-energy-provide-22-million-research-capturing-carbon-dioxide-air.

US DOE (2020b), Department of Energy announces $97 million for bioenergy research and development, press release, US DOE, Washington, DC, www.energy.gov/articles/department-energy-announces-97-million-bioenergy-research-and-development.

US DOE (2020c), Department of Energy to Provide $68 Million for Bioenergy Crop Research, press release, US DOE, Washington, DC, www.energy.gov/articles/department-energy-provide-68-million-bioenergy-crop-research.

Voegele, E. (2020), ENplus: Many European Pellet Producers Impacted by COVID-19, Biomass Magazine biomassmagazine.com/articles/17245/enplus-many-european-pellet-producers-impacted-by-covid-19 (accessed 31 July 2020).

Wohlers Associates (2017), Wohlers Report 2017 shows vibrant new business activity in 3D printing with softened growth worldwide, press release, Wohlers Associates, Fort Collins, CO, wohlersassociates.com/press72.html (accessed 24 July 2017).

World Bioenergy Association (2020), COVID19 and Bioenergy: Impacts and Future Outlooks, World Bioenergy Association, Stockholm, worldbioenergy.org/uploads/200612%20WBA%20COVID%20Survey%20Report%20Final.pdf.

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Chapter 3. Energy transformations for net-zero emissions

- No single fuel or technology can enable the entire energy sector to reach net-zero CO_2 emissions. Success depends upon a wide range of fuels and technologies, tailored to individual parts of the energy sector and to country-specific circumstances.
- Net-zero CO_2 emissions require a fundamental change in the way we produce and use energy, as demonstrated in the Sustainable Development Scenario. At net-zero emissions, low-carbon electricity, bioenergy, hydrogen and hydrogen-based fuels combined provide more than 70% of final energy needs, about the same share as currently provided by fossil fuels.
- The power sector is among the first to decarbonise, drawing on a wide range of available technologies including renewables, CCUS and nuclear. Global electricity generation nearly triples to 2070, equivalent to adding the People's Republic of China's ("China" hereafter) current power sector to the global system every eight years. About 70% of the growth is to satisfy rising electricity demand in end-use sectors, and 30% is to produce low-carbon fuels, in particular hydrogen.
- Around 300 Mt of hydrogen are produced from electrolysers in 2070 in the Sustainable Development Scenario. This requires 13 750 TWh of electricity, equivalent to half of global electricity generation today. Electrolyser capacity rises from 170 MW today to more than 3 000 GW by 2070. Hydrogen production with CCS also plays an important role in regions with low cost gas resources and available CO_2 storage.
- Industry, transport and buildings sector CO_2 emissions each drop by 90% or more by 2070. In the industry sector, electricity use doubles, but around three-quarters of cumulative emissions reduction to 2070 rely on pre-commercial technologies, including CCUS. Electrification also accounts for over 30% of cumulative emissions reduction in transport to 2070, followed by biofuels and hydrogen that play an increasing role to 2070 for long-distance transport. In buildings, electrification is the primary decarbonisation lever, alongside energy efficiency and renewables.
- The transition to net-zero CO_2 emissions requires significant investment in clean energy technologies. Overall investment needs through to 2070 are USD 31 trillion (or 10%) higher in the Sustainable Development Scenario than in the Stated Policies Scenario, and investment in new technologies becomes increasingly important over time. In the 2060s, almost half of total annual average investment is spent on technologies that are at the demonstration or prototype stage today.

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Introduction

No single technology can deliver the emission reductions required for reaching net-zero emissions. Decarbonising the entire energy sector means deploying a wide range of energy technologies, tailored to the needs of individual parts of the energy sector and to country-specific circumstances. The speed of progress towards net zero will differ between sectors and between regions. In the Sustainable Development Scenario, the global power sector is fully decarbonised in the 2050s and the global buildings stock and passenger car fleet reach zero carbon dioxide (CO_2) emission levels by 2070. However, some emissions remain in 2070 from long-distance transport modes (heavy freight, aviation, maritime shipping) and heavy industries (chemicals, iron and steel, cement), despite CO_2 reductions of up to 90% from today's levels in the case of heavy industries, and 55-85% in the case of long-distance transport modes (85% for heavy-duty trucks, 70% for shipping and 55% for aviation) (Figure 3.1).

There are a number of reasons for these decarbonisation trends across sectors. A key reason is that the availability of suitable technologies differs from sector to sector: in the power sector, for example, many clean energy technologies are commercially available today and are being deployed. In other sectors, fewer technology options exist and those that do are at an early development stage. For example, we do not yet have technologies to produce fossil-free iron and steel. In general we know the technologies that could contribute to achieving net-zero emissions, but they need further development. This underlines the critical importance of innovation. In the Sustainable Development Scenario, innovation and technological change are driven by necessity: they are simply needed to reach global net-zero goals. In the absence of relevant policies to support these technologies, such change is unlikely to be achievable (see Chapter 6).

Another key reason to explain varying decarbonising trends is the age structure of existing assets: expensive and long-lived assets are an impediment to progress in some sectors, and in particular in the near to medium term in industry, power and buildings stock, although technology options such as carbon capture, utilisation and storage (CCUS) retrofits in power and industry can help to reduce emissions of existing plants, if storage is available. Maritime ships and aircraft are also examples of expensive assets with long lifetimes.

The technology choices for decarbonising components of energy systems also vary between countries. Governments in countries may have different policy priorities reflecting local conditions and opportunities for specific low-carbon technologies. Countries with excellent renewable resources may focus on renewable technologies to cut emissions in the power sector, while regions with low cost fossil fuels and access to CO_2 storage may put more emphasis on CCUS as part of their strategy to

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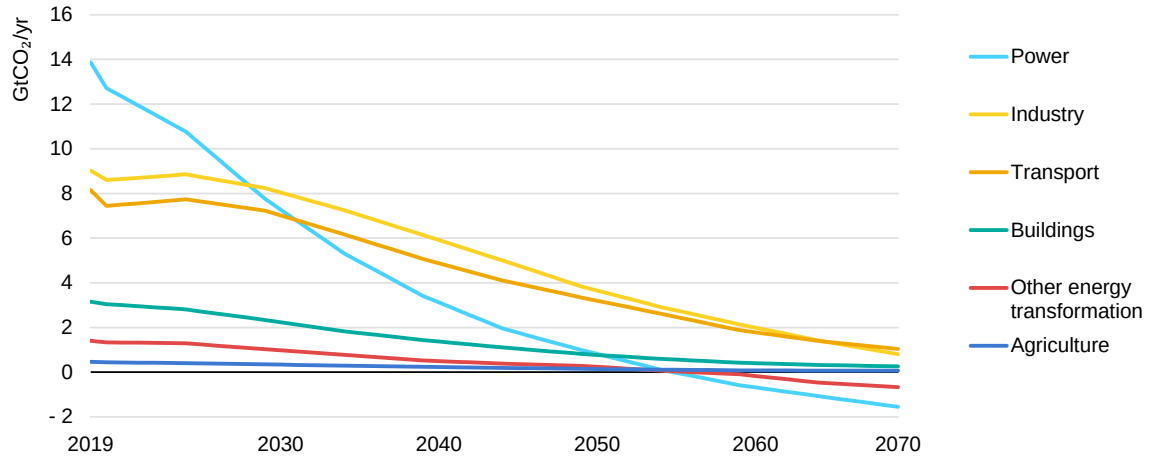
decarbonise power and industry. Choices about how to pursue decarbonisation in the buildings and transport sectors are influenced by considerations about where and how people live, with capital-intensive infrastructure technologies such as district heating or metro systems likely to be more attractive in areas with high population densities.

Against this background, this chapter explores the various technologies needed in key energy sectors in the Sustainable Development Scenario to reach overall net-zero CO_2 emissions. It starts with the power sector, the largest CO_2 emitter among all sectors today, and then moves on to the fuel transformation sector, before turning to the industry, transport and buildings sectors.

Figure 3.1 Global energy sector CO_2 emissions by sector in the Sustainable Development Scenario, 2019-70



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Notes: $GtCO_2$ = gigatonnes of carbon dioxide. Power includes heat generation. Other energy transformation includes coal mining, oil and gas extraction, oil refining, coal and gas transformation and liquefaction, production of hydrogen and hydrogen-based fuels, biofuels production with and without CCUS. Agriculture includes forestry and fishing.

The pace and degree of decarbonisation varies across sectors, with emissions from power generation and other transformation sectors turning negative in the 2050s in the Sustainable Development Scenario, while transport and industry continue emitting beyond 2070.

Power generation

The technological transformation of the power generation sector is a central element of the clean energy transition. Decarbonisation drives down the carbon intensity of electricity generation: it falls from 463 grammes of CO_2 per kilowatt-hour (gCO_2/kWh) in 2019 to below zero in net terms around 2055. Decarbonisation of the power generation fuel mix coupled with the rising share of electricity in final consumption makes a central contribution to achieving net-zero emissions in the Sustainable

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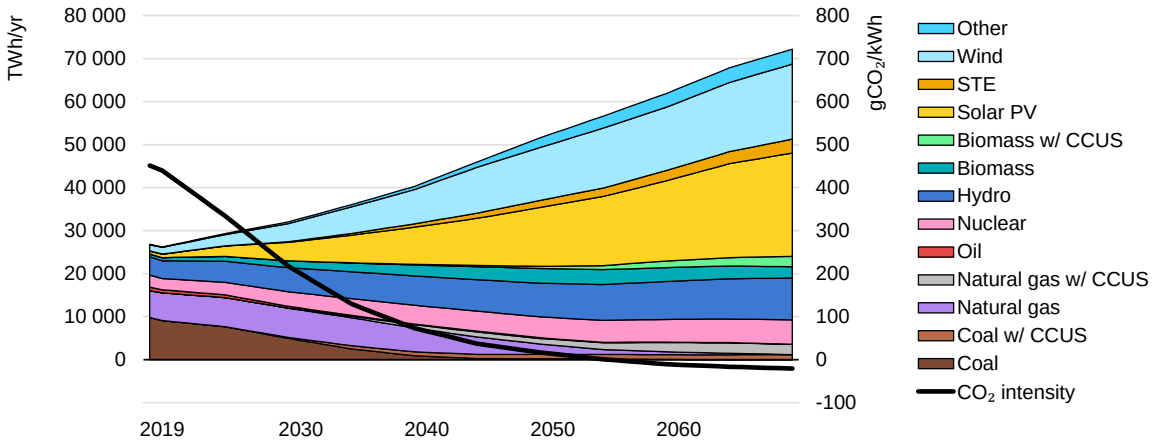
Development Scenario. Solar photovoltaics (PV), wind and other modern renewable energy technologies, together with nuclear power and fossil fuel power plants equipped with CCUS, convert energy into electricity without emitting significant amounts of CO_2,[1] while the rapid growth of electrification extends low-carbon power to more end uses. The share of renewables (including bioenergy with CCUS or bioenergy with carbon capture and storage [BECCS]) in the global power generation mix reaches 86% in 2070, with the remaining 14% of power from nuclear plants (8%), fossil fuel plants with CCUS (5%) and hydrogen (1%) (Figure 3.2). The share of primary energy that goes to power generation jumps from 38% today to over 60% in 2070.

Figure 3.2 Global power generation by fuel/technology in the Sustainable Development Scenario, 2019-70



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Notes: TWh = terawatt-hours; gCO_2/kWh = grammes of CO_2 per kilowatt-hour; STE = solar thermal electricity; PV = photovoltaic; CCUS = carbon capture, utilisation storage. Other includes geothermal power, ocean energy and hydrogen.

Global power generation sector achieves net-zero CO_2 emissions before 2060, largely from renewables which account for over 85% of the generation mix by 2070.

Total power generation expands almost three-times over the next 50 years in the Sustainable Development Scenario; this means that the equivalent of the People's Republic of China ("China" hereafter) current power generation is added to the world's electricity system every eight years. Increasing electrification of end-use sectors is responsible for 70% of the growth in electricity generation between 2019 and 2070 (see Chapter 2). Demand for electricity to be further transformed into other energy carriers or industrial feedstocks – heat, hydrogen, ammonia, methanol and hydrogen-based synthetic hydrocarbon fuels – is responsible for the other 30% (or 14 000 terawatt-hours [TWh], equivalent to about half of global electricity generation today). These fuels and feedstocks produced from low-carbon electricity are

[1] In the case of bioenergy, the CO_2 emitted in combustion is assumed to be entirely offset by the CO_2 absorbed by the biomass as it grows. For fossil fuel power plants with CO_2 capture, different designs with capture rates of 90% and 99% are assumed.

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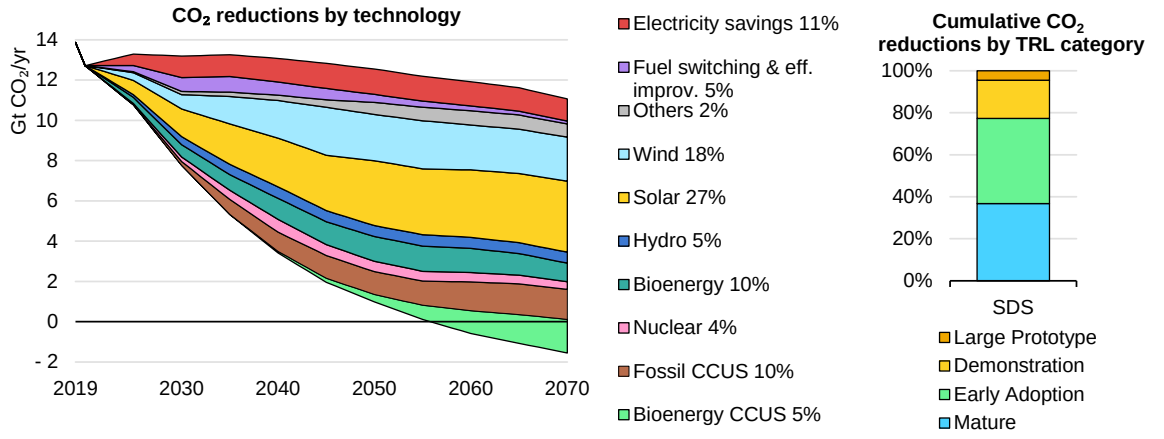
particularly important for the decarbonisation of those parts of the energy system where direct electrification is more difficult, such as long-distance road freight, maritime shipping and aviation. By 2070, around 19% of total electricity generation is used to produce hydrogen and hydrogen-based fuels, and feedstocks based on water electrolysis.

Figure 3.3 **Global CO_2 emissions in the power sector by scenario and decomposition of the difference by technology type**



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Notes: TRL = technology readiness level; eff. improv. = efficiency improvements; STE = solar thermal electricity. Others include geothermal and marine energy as well as hydrogen. Electricity savings refer to electricity demand reductions in end-use sectors through more efficient end uses of electricity, leading to emissions reduction in the power sector. The percentages in the labels indicate the contribution of each technology type to cumulative overall emissions savings by 2070. See Box 2.6 in Chapter 2 for the definition of the TRL categories *large prototype*, *demonstration*, *early adoption* and *mature*.

A broad portfolio of technologies decarbonises the power sector in the Sustainable Development Scenario: most are available today, though BECCS has not yet been demonstrated at commercial scale.

Overall, the power sector accounts globally for around 35% of the cumulative CO_2 reductions in the Sustainable Development Scenario compared with the Stated Policies Scenario. In the power sector, renewables provide about 62% of the cumulative reductions, followed by CCUS (including BECCS) with 15% and nuclear power with 4% (Figure 3.3).[2] Solar PV and wind combined account for more than 40% of the cumulative emission reductions: enabling technologies for the integration of variable renewables, such as demand response and energy storage, will be critical for realising these reductions. More efficient uses of electricity in buildings, transport and industry and material efficiency measures account for a further 15% of the cumulative CO_2 reductions in the power sector, while also reducing the need for

[2] One should keep in mind that the CO_2 reductions shown are relative to the Stated Policies Scenario, in which low-carbon technologies already are being deployed and providing CO_2 reductions over time. The share of low-carbon electricity generation increases in this scenario from 37% in 2019 to 67% in 2070, a major factor for the reduction of the average global CO_2 intensity from 463 gCO_2/kWh in 2019 to 190 gCO_2/kWh by 2070.

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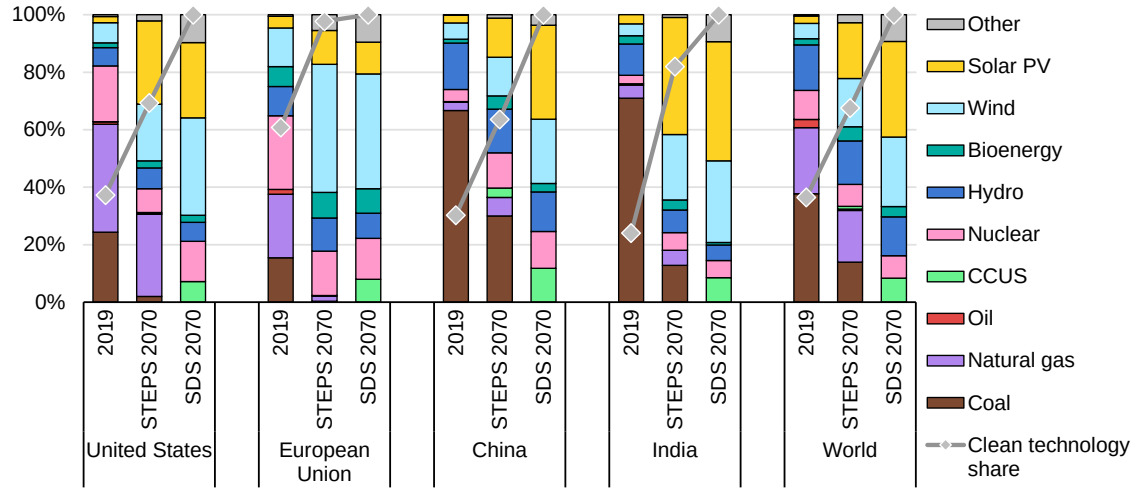
investment in generation and transmission assets. BECCS provides negative emissions of 1.7 $GtCO_2$ in 2070. These negative emissions offset remaining emissions in other parts of the energy system, notably in heavy industry and long-distance transport (see Chapters 4 and 5).

Decarbonisation pathways for the power sector differ across regions depending, among other things, on the availability of renewable energy resources and sites for CO_2 storage (Figure 3.4). In addition to solar PV, wind and nuclear power, CCUS applied to natural gas and bioenergy plants accounts for a share of 7% of the generation mix in 2070 in the United States, reflecting its vast CO_2 storage potential.[3] Wind power dominates in the European Union and accounts for around 40% of the generation fuel mix, reflecting its favourable conditions for wind. Solar PV accounts for 40% of the generation mix in India, where in combination with battery storage, it serves growing electricity demand driven by air conditioning demand. Solar PV plays an important role in China as well and together with wind provides more than half of total generation in 2070. Nuclear meets 13% of total generation in 2070 in China – more than three-times the current share – while power plants with CO_2 capture reach with 12% a similar share in 2070. Some countries reach net-zero emissions in the power sector by around 2050, notably in Europe.

Figure 3.4 Electricity generation mix by region, fuel/technology and scenario, 2019 and 2070



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; CCUS = carbon capture, utilisation and storage. Coal, oil, natural gas and bioenergy do not include CCUS. CCUS category includes coal, natural gas and bioenergy with CCUS. Other includes solar thermal, geothermal power, marine energy and hydrogen.

Electricity in all regions is almost completely decarbonised by 2070 in the Sustainable Development Scenario, with the technology mix reflecting local conditions and opportunities.

[3] More detail will be presented in a forthcoming *Energy Technology Perspectives* special report on CCUS.

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Reaching net-zero CO_2 emissions in the power sector requires rapid deployment of clean technologies. In the Sustainable Development Scenario, 475 gigawatts (GW) of solar PV is added each year on average over the period to 2070 (compared with 108 GW in 2019), together with 190 GW of wind (60 GW in 2019), 15 GW of nuclear power (5 GW in 2019), and 25 GW of fossil fuel plants equipped with CCUS and 7 GW of BECCS (none in 2019 with projected large-scale deployment after 2025). Nuclear power plays an important role in the transition to clean electricity in emerging economies in Asia, where electricity demand is growing strongly. That region accounts for more than 80% of the growth in global nuclear capacity, which climbs from 415 GW in 2019 to more than 780 GW by 2070. Most of the growth in nuclear capacity relies on existing nuclear reactor designs. Some advanced nuclear technologies, notably small modular reactors (SMRs), support the rising share of variable renewables. Today SMRs are at the prototype development stage: their potential for shorter lead times and lower investment requirements reduce investment risks compared with large-scale nuclear plants.

A major obstacle to the decarbonisation of the power sector is the relatively young age of many fossil fuel-fired power plants, in particular coal plants, notably in China. If all the existing coal-fired power plants and those under construction around the world today continued operating until the end of their technical lifetimes, they would emit around 4.5 $GtCO_2$ per year in the late 2050s. A mixture of measures is needed to unlock the CO_2 emissions from these plants and achieve net-zero power sector emissions in the 2050s in the Sustainable Development Scenario (Figure 3.5). Retrofitting with CCS helps to keep the youngest coal plants open where CO_2 storage is available, and around 190 GW of coal capacity is retrofitted with CCUS, mainly in China. Many existing coal plants change their role and are used mainly to provide reserve capacity to power systems, thus generating smaller amounts of electricity and CO_2 emissions. Co-firing with biomass in proportions up to 15-20%, which requires only minor technical modifications, also contributes to emissions savings in the near term. It is possible to co-fire ammonia in coal plants, as successfully demonstrated in Japan (Chugoku Electric Power Company, 2018). It is also possible to fully convert from coal-firing to biomass-firing – a more costly solution than co-firing - as successfully demonstrated by several recent projects. Early retirements of some existing coal-fired power plants, nevertheless, are an important measure in the Sustainable Development Scenario: 600 GW of the existing coal capacity of 2 100 GW are retired earlier than in the Stated Policies Scenario.

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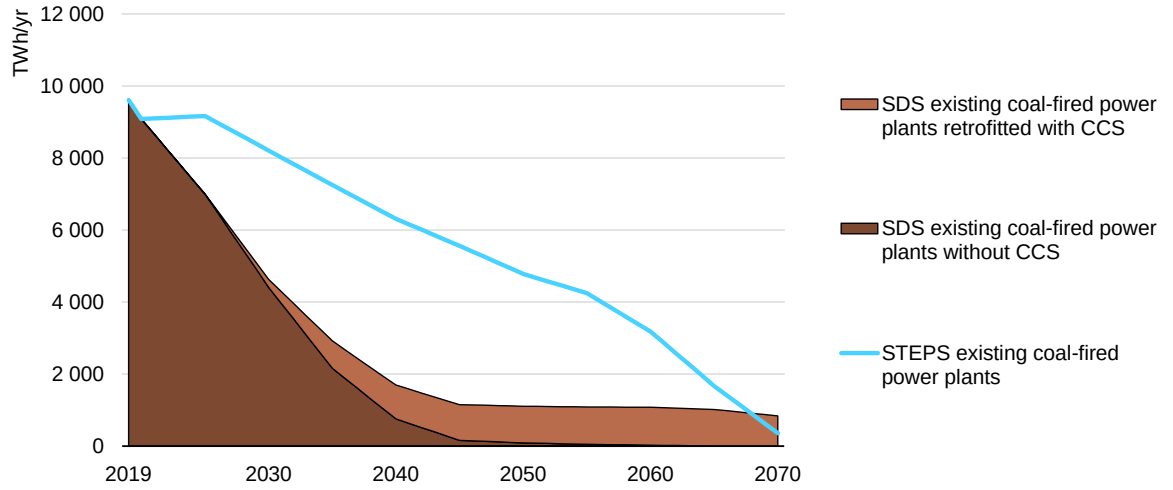
Figure 3.5 Coal-fired electricity generation from existing plants in the Stated Policies and Sustainable Development scenarios, 2019-70



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Notes: TWh = terawatt-hours; SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario; CCS = carbon capture and storage. Existing coal-fired power plants refers to plants in operation or under construction in 2019. Co-firing of biomass is applied to around 85% of the coal power plants retrofitted with CCUS.

Electricity generation from existing coal-fired power plants without CCS is almost completely phased out by 2045 in the Sustainable Development Scenario. Retrofitting with CO_2 capture allows coal generation of around 1 000 TWh to continue past this point.

Variable renewables – solar PV, onshore and offshore wind – dominate the generation mix in 2070 in the Sustainable Development Scenario, with a global average share of 57%. Integrating increasing amounts of variable renewables into power systems is a major task in the transition to clean electricity. As the share of variable renewables increases, electricity systems need increasing flexibility to ensure that they can supply sufficient power to meet demand when variable renewables generation (VRE) is low. Various ways of providing such flexibility include:

- **Flexible generating technologies,** which can be ramped up and down at short notice and adjust their output to that of VRE. Examples include gas turbines, steam turbines, combined-cycle power plants, gas engines, solar thermal plants that store energy, reservoir hydropower plants and nuclear power plants. In the Sustainable Development Scenario, around 4 000 GW of gas turbines and combined-cycle power plants without CCUS (12% of total installed capacity) that run with natural gas, biomethane or hydrogen as fuel for under 500 hours on average in 2070 are the main source of flexibility and reserve capacity on the generation side. Thermal generation and hydro plants also provide ancillary services, such as frequency support, voltage stability and inertia. New wind turbines designs and PV systems are potential sources of frequency support. Wind turbines can provide inertia support through very fast control of the blades (pitch control) or the ability to extract the kinetic energy from the rotor (Ramboll, 2019).

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- **Enhanced network interconnections,** which can contribute to flexibility by balancing the load across wider geographic areas and by pooling sources of flexibility from across those areas reducing the amount of ramping that needs to be provided by generating plant. Long-distance high-voltage direct current (HVDC) east-west transmission lines are particularly valuable for providing PV-generated power at early morning or late afternoon, while north-south transmission lines offer potential for seasonal balancing. Flexible high-voltage grid technologies, allowing better control of HVDC lines and the development of meshed HVDC grids, are currently at the demonstration stage, but will become important for long-distance transmission lines, while also enabling the integration of wind turbines in large offshore wind installations, where traditional alternate current lines are not economic or feasible.
- **Demand-side response,** which has a large part to play in meeting rising flexibility needs, in particular by shaving peak demand and redistributing electricity to time periods when the load is lower and electricity is cheaper. The growing use of electricity to power vehicles and heat pumps for water and space heating (in combination with thermal storage) will increase opportunities for shifting electricity demand over time periods, facilitated by increasing digitalisation (see Chapter 2, Box 2.7).
- **Energy storage technologies,** which can store electricity when VRE generates more power than the system needs and then discharge it when VRE generation is low. Pumped hydroelectric storage has been around for many decades, with global capacity of 158 GW in 2019. It remains an important option, in particular for storage of 10-15 hours, with global capacity of pumped storage almost doubling to 300 GW by 2070. With cost declines, stationary batteries are becoming more and more attractive as another storage option, whether in the form of behind-the-meter storage in combination with rooftop solar PV, utility-scale battery storage plants or grid storage to reduce bottlenecks. In the Sustainable Development Scenario, utility-scale storage capacity worldwide increases from 173 GW in 2019 to 2 100 GW in 2070, most of which is provided by batteries with an average discharge duration of five hours. Expansion of electric vehicles could also boost energy storage: the 2 billion electric light-duty passenger vehicles on the road in 2070 in the Sustainable Development Scenario potentially represent over 150 TWh volume of energy storage that could be used for grid support through vehicle-to-grid (V2G) inverters. In regions with good solar conditions for solar thermal electricity generation, plants with thermal storage can provide additional flexibility. Hydrogen and hydrogen-based fuels produced from electricity via electrolysis such as methane and ammonia provide better options than batteries for long-term and large-scale storage, although they

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are currently expensive compared to other seasonal balancing options, in particular flexible generation from gas turbines.

Most of the technologies needed to reach net-zero CO_2 emissions in the power sector are commercially available today. Overall, around 80% of the cumulative CO_2 reductions in the power sector in the Sustainable Development Scenario relative to the Stated Policies Scenario can be achieved with technologies that today are mature or at the stage of early adoption (Figure 3.3). Nuclear and hydropower are relatively mature technologies, though both raise environmental concerns. Nuclear also faces concerns about cost-competitiveness. New advanced reactor nuclear designs are under development. Thanks to drastic cost reductions in recent years, solar PV and onshore wind are cost competitive in many parts of the world today. Offshore wind (technology readiness level [TRL] 5-9, depending on the design) is expected to reach cost-competitiveness with fossil fuels in the next few years.[4] There is further potential to reduce costs and improve the performance of solar PV and wind through innovation, for example by using hybrid materials for wind turbines or smart inverters for rooftop PV systems in distribution grids to collectively manage ancillary services to electricity networks. The prospects for BECCS becoming cost competitive largely depend on carbon credits/penalties (TRL 7-8); a pilot plant has been in operation in the United Kingdom since 2019 and a 50 megawatt (MW) plant in Japan is expected to start operation in 2020; learning from these plants may help to drive down costs.

Alternative clean fuels

To reach net-zero emissions, low-carbon fuels in the form of electricity, bioenergy, hydrogen and hydrogen-based fuels (ammonia and synthetic fuels) provide around 70% of all final energy needs in 2070 in the Sustainable Development Scenario, similar to the share served today by fossil fuels. Clean liquid and gaseous fuels from non-fossil sources in particular will be needed in the decades ahead for those parts of the energy system where direct electrification is more difficult. In some cases, alternative fuels are compatible with the existing fossil fuel distribution infrastructure and end-use technologies, often referred to as “drop-in” fuels. In the Sustainable Development Scenario, alternative fuels in the form of liquid biofuels, biomethane, low-carbon hydrogen and other hydrogen-based fuels (ammonia and synthetic hydrocarbon fuels produced from hydrogen and CO_2) play an important role in decarbonising energy use in transport, buildings and industry.

[4] See Box 2.6 in Chapter 2 for more information on TRLs.

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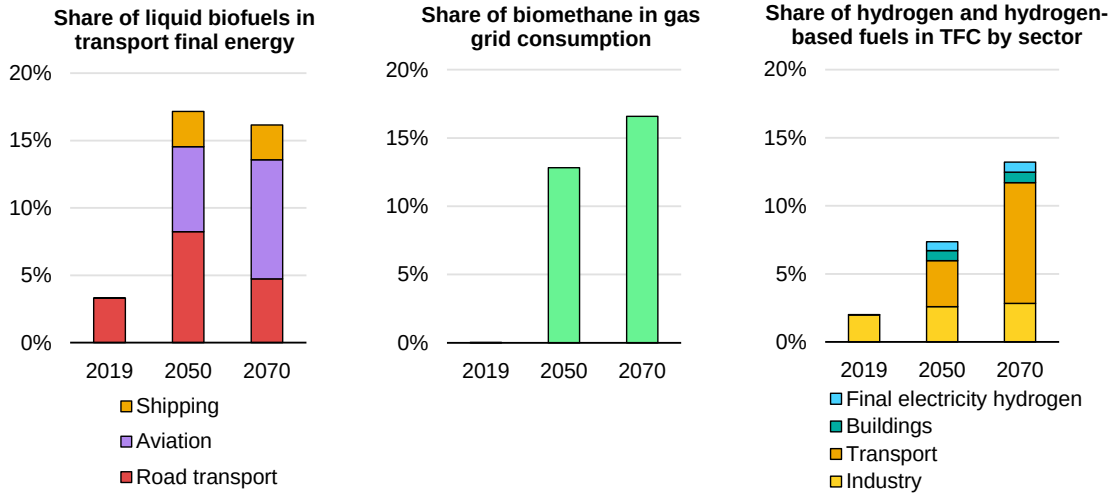
Figure 3.6 Role of hydrogen and liquid and gaseous biofuels in the Sustainable Development Scenario



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Notes: TFC = total final energy consumption. Hydrogen-based fuels refer to the fuel use of synthetic hydrocarbon fuels produced from hydrogen and CO_2, and ammonia. Final energy demand of hydrogen includes in addition to the final energy demand of hydrogen, ammonia and synthetic hydrocarbon fuels, the onsite hydrogen production in the industry sector and the final electricity produced from hydrogen.

Clean fuels in the form of hydrogen, hydrogen-based fuels and biofuels meet 20% of global final energy demand in 2070 in the Sustainable Development Scenario, in particular in areas where direct electrification is difficult.

Overall, alternative fuels meet 20% of global final energy demand in 2070, with hydrogen and hydrogen-based fuels alone meeting 13% of all final energy needs. Liquid biofuels use, though only representing 5% of total final energy demand, is critical for decarbonising the transport sector: they meet 16% of all transport energy demands and are used in particular for aviation, maritime shipping and heavy-duty trucking (Figure 3.6). Biomethane and biogas are responsible for just 2% of total final energy use, but biomethane accounts on average for over 15% of global grid gas consumption in 2070 as a result of being blended with natural gas in existing gas grids. Both biomethane and biogas are used for cooking in emerging economies as well as for power generation: overall biogas and biomethane consumption reaches around 390 million tonnes of oil equivalent (Mtoe) in 2070.

Biofuels

Liquid biofuels derived from sustainable biomass can provide a lower carbon alternative to conventional petroleum-based diesel and gasoline. Some liquid biofuels can be blended with conventional fuels, while drop-in biofuels can completely replace conventional fuels (or be blended to very high levels): no change is required in either case to existing fuel distribution or vehicle technology.

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Conventional biofuels consist of fatty acid methyl ester (FAME) biodiesel produced from oilseed crops (such as soybean oil and palm oil), and ethanol derived from sugar crops (such as sugarcane and sugar beets) or starchy crops (such as corn and wheat). These technologies are well-established and conventional biofuels are produced on a large scale – output totalled around 2 million barrels per day (mb/d) before the Covid-19 pandemic. With conventional biofuels, careful attention must be paid to sustainability concerns. These include competition for agricultural land with food crops and potential direct and indirect land-use change impacts, which can adversely affect biodiversity. Sustainability assessments should be carried out on a case-by-case basis.

Advanced biofuels can mitigate some sustainability considerations. Sustainable biofuels can be produced from residues and wastes from the agriculture, forestry and food industries, or from non-food crops grown on marginal land. Advanced biofuels require complex processing to turn biomass into usable biofuels. Advanced biofuel technologies include cellulosic ethanol, biomass-to-liquid (BTL) thermochemically produced fuels, hydrotreated vegetable oil (HVO) biodiesel from wastes and residues, and hydro processed esters and fatty acids (HEFA) biojet fuel from wastes and residues. BTL and HVO/HEFA are technically drop-in biofuels. Cellulosic ethanol and HVO/HEFA are commercially operating today, with HVO/HEFA facilities using both oilseed crop and waste and residue feedstocks (used cooking oil, animal fats). BTL is in the demonstration phase and requires further development to reach commercial application. However, it holds great promise as a means to tap into abundant municipal solid waste, forestry residue and agricultural residue resources. While HVO/HEFA are promising biofuels with potential to expand from current production levels, their potential growth is ultimately constrained by limited availability of low biogenic waste and residue resources and of sustainable oilseed crops. For these fuels to be genuinely carbon neutral, clean energy needs to be used during the entire feedstock supply and production processes, which is not necessarily the case today.

Globally, biofuels met 3.5% of all transport liquid fuel demand in 2019, totalling 95 Mtoe, the vast majority of it in the form of conventional biofuels. In the Sustainable Development Scenario, liquid biofuels expand rapidly, reaching around 390 Mtoe (around 8 mboe/d, about one-quarter of transport liquid fuel production) by 2040: this expansion is driven mainly by BTL technology, which is expected to begin large-scale commercial deployment by 2030 (Figure 3.7). Ethanol use in the chemical sub-sector also takes off, accounting for almost one-fifth of the 147 Mtoe of ethanol produced in 2040. Around the same time, CCUS begins to play a significant role in biofuels production, though deployment starts earlier, with one ethanol plant with CO_2 capture in operation today in the United States. CCUS facilities can be added at relatively low cost to biofuel production because ethanol fermentation, BTL syngas cleaning and biogas upgrading all produce a stream of very pure CO_2. The use of

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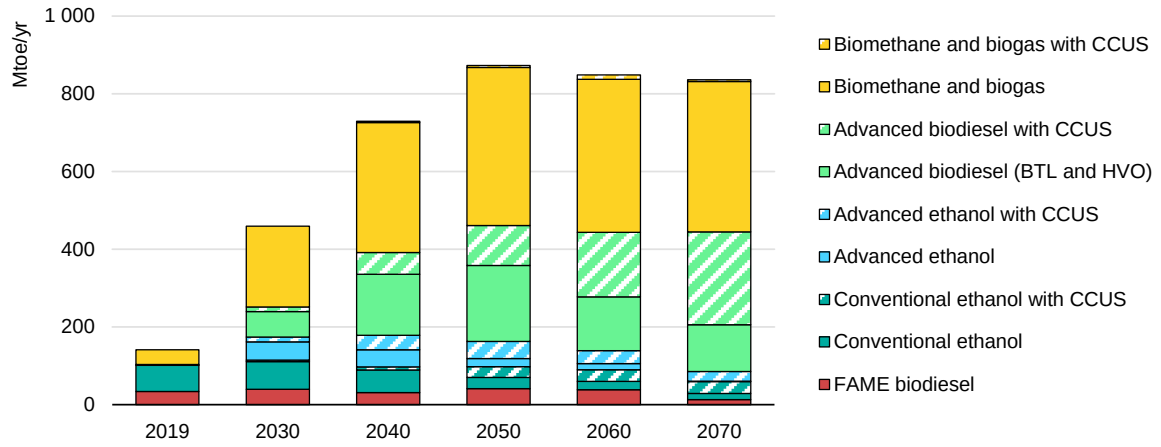
CCUS in conjunction with sustainable biomass (BECCS) generates negative CO_2 emissions that offset emissions elsewhere in the energy system. By 2070, CCUS is used in conjunction with over one-third of the almost 840 Mtoe of biofuel production, yielding 870 million tonnes (Mt) of negative emissions. CCUS raises the cost of biofuels production by 10-30% in 2070, but is economic in many parts of the world thanks to rising carbon penalties or equivalent policy measures such as clean fuel standards.

Figure 3.7 Global biofuels production by technology in the Sustainable Development Scenario, 2019-70



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Notes: Advanced biodiesel here includes biojet fuel production. Biomethane and biogas numbers shown here include power generation, gas grid injection and transport use. The vast majority of liquid biofuels are consumed in transport, while a small portion is consumed in industry.

Biomass-to-liquids – an emerging technology – drives rapid growth in biofuels supply in the Sustainable Development Scenario.

Biogas and biomethane also play an important role in the Sustainable Development Scenario. Biogas can be produced from organic waste feedstocks, such as crop residues, animal manure and organic municipal solid waste or wastewater sludge, by means of anaerobic digestion, which is a mature technology (IEA, 2020a). The resulting biogas, a mixture of methane, CO_2 and smaller quantities of other gases, is used today for power generation in internal combustion engines with an installed global capacity of around 8 GW, and for the production of electricity and heat in co-generation plants. Biogas can also be used as a clean cooking fuel to replace traditional biomass use in emerging economies. By removing the CO_2 and other contaminants, biogas in addition can be upgraded to biomethane, which can be blended into natural gas grids and used in existing end-use applications. Biomethane can also be produced via biomass gasification and methanation, but this production route plays only a minor role today due to its higher costs. In both production routes for biomethane, the CO_2 produced during the production process can be captured

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and stored, resulting in negative emissions. Alternatively, the CO_2 can be converted together with hydrogen to produce additional methane. Germany is home to the largest such plant, using hydrogen sourced from water electrolysis (Biocat, 2015).

In the Sustainable Development Scenario, total biogas and biomethane production worldwide grows from 30 Mtoe today to 335 Mtoe in 2040 and 390 Mtoe in 2070. Global average blending shares for biomethane into natural gas networks reach 8% in 2040 and 16% in 2070. Biogas-fired internal combustion engines, a modular technology with relatively high part-load efficiencies, are a flexible generation operation in the Sustainable Development Scenario, supporting the integration of variable renewables. Anaerobic digestion remains the dominate route for biomethane production in the Sustainable Development Scenario, as the lignocellulosic feedstocks needed for biomass gasification are used instead for liquid biofuel production.

The cost of producing both liquid and gaseous biofuels is strongly influenced by feedstock costs, which can account for as much as 80% of the levelised costs, particularly for conventional biofuels. Fossil fuel and carbon prices also influence the competitiveness of biofuels with both conventional and other alternative fuels. The growing role of CCUS in the Sustainable Development Scenario is driven mainly by much higher CO_2 prices than prevail today.

Hydrogen and hydrogen-based fuels

Hydrogen today is produced primarily by steam reforming of natural gas and is mainly used as a feedstock in the chemical and refining industries (IEA, 2019a). This changes in the Sustainable Development Scenario, which sees global hydrogen production growing rapidly to around 445 million tonnes of hydrogen (MtH_2) (1 280 Mtoe) for energy use and 75 MtH_2 (215 Mtoe) for process use in 2070, or about seven-times the current level of use of hydrogen as feedstock in industry and refining (Figure 3.8). Around 60% of the hydrogen used for energy purposes (260 MtH_2 or 750 Mtoe) is consumed in the transport, buildings and power sectors and refineries, while the rest is further converted into hydrogen-based fuels: ammonia for maritime shipping and synthetic kerosene for aviation. Of the hydrogen consumed directly in 2070, the transport sector accounts for over 60% (covering almost 20% of the sector's energy needs, mainly in road transport); the power sector for just under 30% (less than 3% of global electricity generation); and space and water heating in the buildings sector for 10% (2% of the sector's fuel mix). The hydrogen produced for process use in the Sustainable Development Scenario is used in chemical (60% of demand) and steel production (40%).

Figure 3.8 Global hydrogen production and demand in the Sustainable Development Scenario, 2070

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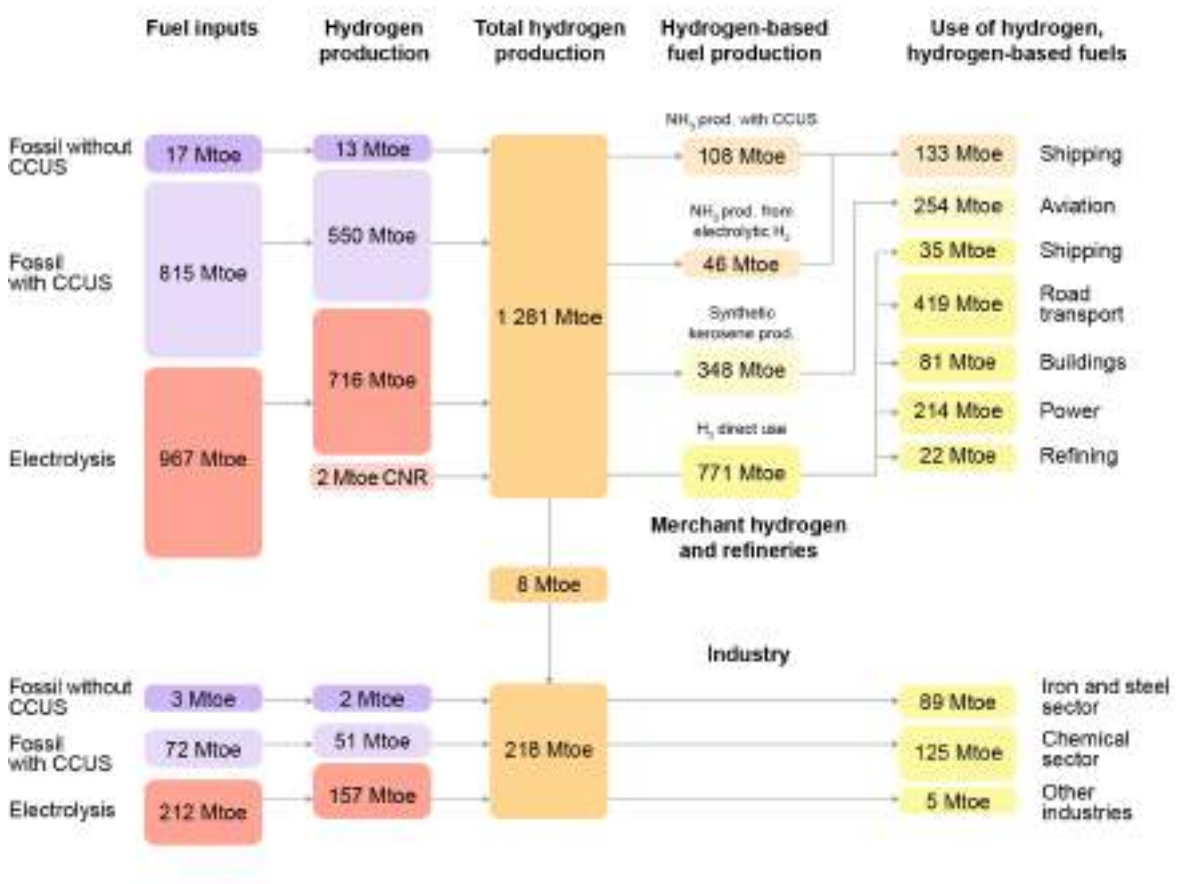

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Note: CNR = hydrogen as by-product from catalytic naphtha reforming in refineries; prod. = production; NH_3 = ammonia; H_2 = hydrogen.

Today hydrogen is produced largely from unabated fossil fuels and is used only in refining and chemical sub-sectors. In the Sustainable Development Scenario, low-carbon hydrogen production technologies dominate, and hydrogen has a wide range of uses across the energy system.

Hydrogen

Fossil fuels without CCUS initially continue as the main source of hydrogen production worldwide in the Sustainable Development Scenario. However, after 2030 almost all the growth in output comes from low-carbon hydrogen, increasingly using renewables-based electricity in regions with good solar and wind resources, or from fossil fuels in combination with CCUS, and in particular from natural gas (Figure 3.9). The split between water electrolysis and fossil fuels with CCUS is roughly equal, but moves slightly in favour of water electrolysis. In 2070, electrolytic hydrogen accounts for nearly 60% of global hydrogen production and fossil fuels

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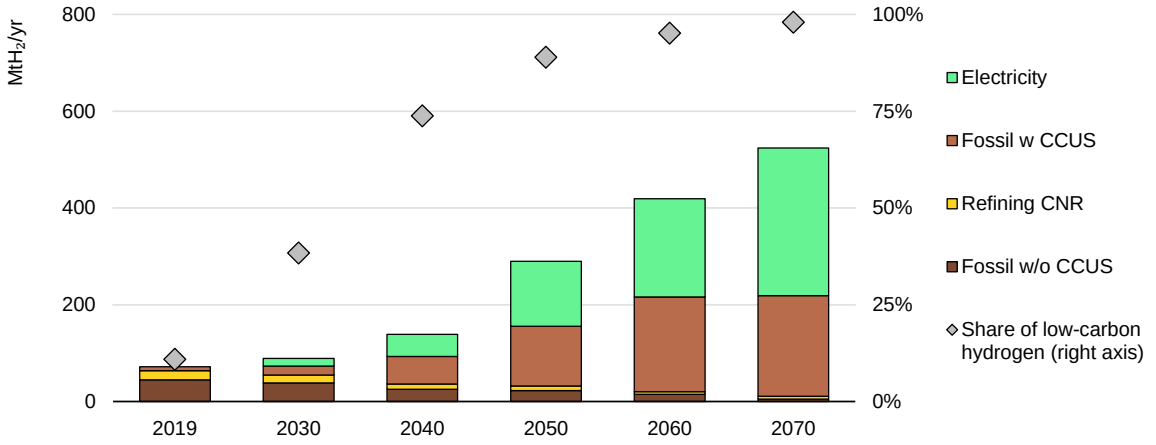
with CCUS for 40%, with the remainder coming mostly from unabated fossil fuels and from the creation of small amounts of hydrogen as a by-product of catalytic naphtha reforming in refineries.

Figure 3.9 Global hydrogen production by technology in the Sustainable Development Scenario, 2019-70



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Note: CNR = hydrogen as by-product from catalytic naphtha reforming in refineries.

Today, hydrogen is produced almost entirely from fossil fuels without CCUS. Low-carbon hydrogen production dominates in the Sustainable Development Scenario, with almost all hydrogen production either from low-carbon electricity or fossil fuels with CCUS.

Water electrolysis splits water in an electrochemical process into hydrogen and oxygen. Electrolysis is not a new technology: alkaline electrolysis was used from the 1920s to the 1960s to produce hydrogen for fertiliser production before being eclipsed by hydrogen produced from natural gas. Today, water electrolysis globally accounts for less than 0.1% of dedicated hydrogen production. With declining costs for renewable electricity, there is renewed interest in electrolytic hydrogen which has resulted in an increasing number of projects with significant electrolyser capacities being commissioned or announced. For example, a 10 MW electrolyser paired with 20 MW of solar PV started operation early in 2020 in Japan to provide hydrogen for stationary fuel cell systems and fuel cell vehicles (NEDO, 2020). H2V has announced the H2V59 project in France, which will produce 28 000 tonnes of hydrogen per year (around 100 MW electrolyser) for injection into the natural gas grid (H2V59, 2020).

In the Sustainable Development Scenario, global installed electrolyser capacity rapidly increases from around 170 MW in 2019 to more than 3 300 GW by 2070, running on average at around 4 000 full-load hours per year to ensure least-cost hydrogen production (IEA, 2019a) and being supported by a mixture of grid electricity and dedicated renewables-based electricity plants, depending on local conditions. Production is dominated by regions and countries with low cost

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renewable electricity, such as Chile, China, Europe, Africa and the Middle East (Figure 3.10). This rapid growth depends on the scaling up of manufacturing capacities and on its ability to bring down the costs of water electrolysers. While today global manufacturing capacity stands at around 1.5 GW/year, the average annual deployment rate to 2070 increases to 60 GW/year in the Sustainable Development Scenario. As a result, the average cost of electrolysers fall from USD 850-1 100 per kilowatt electric (kW_e) today to below USD 300/kW_e around 2050 in the Sustainable Development Scenario.

Besides the ramp-up of electrolyser capacity, clean electricity generation for electrolysis needs to be rapidly expanded. By 2070, around 13 750 TWh of electricity are used for hydrogen production in the Sustainable Development Scenario, corresponding to almost 20% of global electricity generation. This required increase in electricity generation to produce low-carbon hydrogen is major challenge when it comes to the roll-out of hydrogen, as it further adds to the significant infrastructure requirements that are associated with the more widespread production and use of low-carbon hydrogen. But it is also a major opportunity to tap into low-cost renewables generation: dedicated electricity generation from renewables can be an important option for hydrogen production. With declining costs for solar PV and wind generation, electrolysers built at locations with excellent renewable resource conditions can benefit from low electricity costs combined with relatively high full-load hours for the electrolyser, thus becoming a low cost option for hydrogen, even when taking into account the transport costs from those locations to the end users. In areas where both solar PV and onshore wind resources are favourable, combining both in a hybrid plant has the potential to further increase the full-load hours and to lower costs.[5]

Nuclear power can also be used for electrolytic hydrogen production. Projects at existing nuclear power plants have been announced in the United Kingdom and the United States (Lancaster Guardian, 2019; Power Magazine, 2019). The heat from a nuclear power plant could be used to provide electricity and steam for steam oxide electrolysis. Research is underway to develop materials for an electrolysis cell that are well suited to the temperature levels (around 300°C) of nuclear energy heat sources (US DOE, 2018).

Hydrogen production from natural gas with CCUS, which could include retrofitting some existing steam reformers with CO_2 capture equipment, is another option in regions with low cost natural gas and access to CO_2 storage such as the Middle East, North Africa, the Russian Federation ("Russia" hereafter) and the United States. Seven projects based on the production of hydrogen from natural gas with CCUS are in operation today with a combined annual production of 0.35 MtH_2. Several more have

[5] The analysis for some of the renewable electricity supply options for dedicated hydrogen production is based on geospatial analyses done for *The Future of Hydrogen* (IEA, 2019a).

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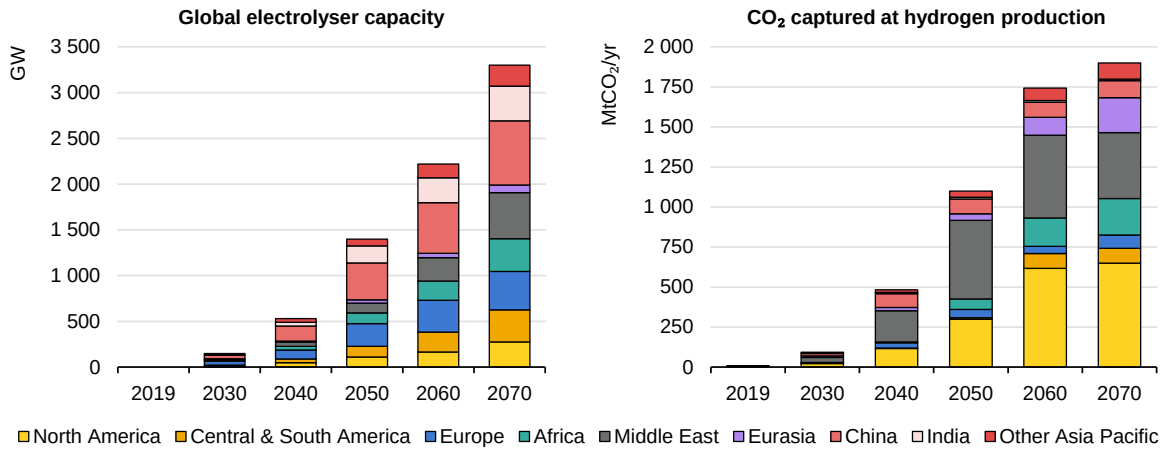
been announced, including the H21 project in Leeds in the United Kingdom, which aims to convert the city gas network to 100% hydrogen (H21, 2020). Existing coal-based hydrogen plants in China and elsewhere could similarly be equipped with CCS, if adequate storage is available. In the Sustainable Development Scenario, hydrogen production from fossil fuels with CO_2 capture reaches 210 MtH_2 in 2070, meets 40% of global demand and leads to the capture of 1.8 $GtCO_2$, representing one-quarter of total CO_2 being stored in the Sustainable Development Scenario.

Figure 3.10 Global development of electrolyser capacity and CO_2 capture from hydrogen by region in the Sustainable Development Scenario, 2019-70



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Production and technology choice profiles for low-carbon hydrogen differ across regions reflecting factors such as the availability of suitable renewable energy resources, CO_2 storage and access to low cost natural gas.

The cost-competitiveness of low-carbon hydrogen produced from natural gas with CCUS or from renewables-based electricity mainly depends on the costs of gas and low-carbon electricity. Today, the cost of hydrogen produced from natural gas varies between USD 0.7 and 1.6 kilogrammes of hydrogen (kgH_2), and adding CO_2 capture increases the costs to around USD 1.2-2.0/kgH_2, whereas producing hydrogen from renewables electricity generally costs around USD 3.2-7.7/kgH_2 (Figure 3.11). With cost reductions for renewable technologies as well as electrolysers in the Sustainable Development Scenario, the cost of producing hydrogen from renewables-based electricity becomes competitive with natural gas with CCUS in several parts of the world.

Other factors are also relevant to the choice between alternative low-carbon hydrogen production options. For hydrogen production from fossil fuels in combination with CCS, the geological availability and public acceptance of CO_2 storage are prerequisites. For water electrolysis, access to adequate supplies for seawater desalination represent only a small fraction of total hydrogen production costs (IEA, 2019a).

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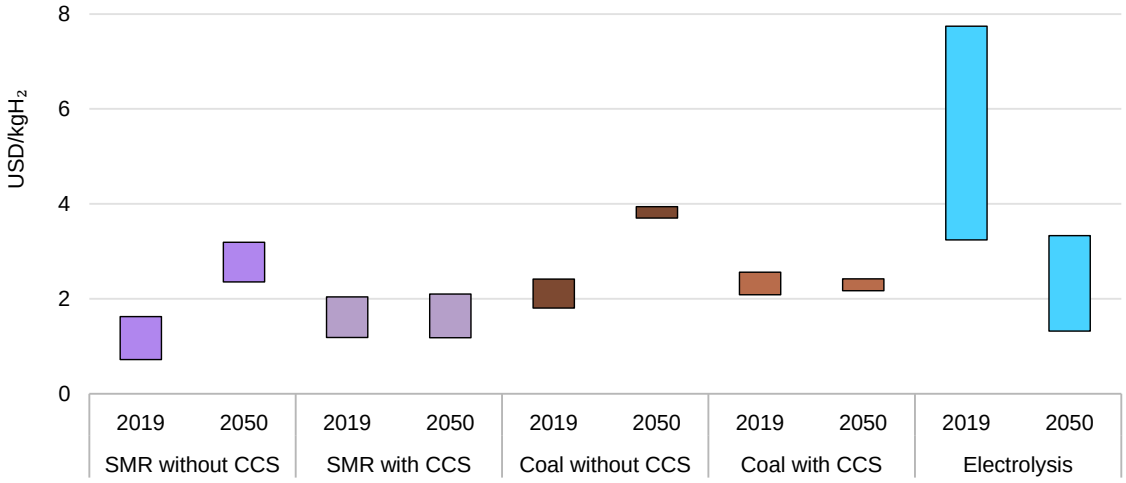
Figure 3.11 Hydrogen production costs by technology in the Sustainable Development Scenario, 2019 and 2050



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Notes: CCS = carbon capture and storage; SMR = steam methane reforming; coal = coal gasification. Electrolysis based on dedicated renewables-based generation.

Capital expenditure (CAPEX) assumptions: SMR without CCUS - USD 910/kWH_2 (2019 and 2050), SMR with CCS - USD 1 583/kWH_2 (2019) and 1 282/kWH_2 (2050); coal without CCUS - USD 2 672/kWH_2 (2019 and 2050); coal with CCS - USD 2 783/kWH_2 (2019 and 2050); electrolysis - USD 872/kW$_e$ (2019) and USD 269/kW$_e$ (2050).

Operating expenditure (OPEX) assumptions (as % of CAPEX): SMR without CCS - 4.7% (2019 and 2050), SMR with CCS - 3.0 % (2019 and 2050); coal with and without CCS - 5.0% (2019 and 2050); electrolysis - 2.2% (2019) and 1.5% (2050).

Efficiency assumptions (lower heating value): SMR without CCS - 76% (2019 and 2050), SMR with CCS - 69% (2019 and 2050): coal without CCS - 60% (2019 and 2050), coal with CCS - 58% (2019 and 2050); electrolysis - 64% (2019) and 74% (2050).

Full-load hour assumptions: SMR and coal gasification 8 322 hours (2019 and 2050); electrolysis 3 000-4 000 hours (2019) and 2 000-3 000 hours (2050). *Stack lifetime*: 100 000 hours.

System lifetime assumptions: 30 years.

Fuel price assumptions: natural gas - USD 1.4-6.3 per gigajoule (GJ) (2019) and USD 1.7-7.0/GJ (2050); coal - USD 1.6-3.8/GJ (2019) and USD 1.0-2.2/GJ (2050); electricity - USD 36-116 per megawatt-hour (MWh) (2019) and USD 20-60/MWh (2050).

CO_2 capture rate assumptions: SMR with CCS - 95%, coal with CCS - 90%.

CO_2 price assumptions: USD 0-15/tCO_2 (2019) and USD 180/tCO_2 (2050).

CO_2 transport and storage cost assumptions: USD 20/tCO_2. Representative *discount rate* for this analysis is 8%.

Low-carbon hydrogen production is not currently competitive with hydrogen from fossil fuels, but could become competitive in the long term if large-scale deployment brings down costs.

Hydrogen-based fuels: ammonia and synthetic fuels

The principal benefit of converting hydrogen into ammonia or synthetic hydrocarbon fuels is their higher volumetric energy density, which makes them easier to store and transport, and means that less fuel by volume is needed for vehicles, ships and aircraft. Such fuels also offer the benefit of broad compatibility with the existing fossil fuel-based infrastructure. The additional steps required to produce those means that

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energy losses can be significantly higher than for producing pure hydrogen, making them more expensive. In large part because there are no good alternatives for many elements of the aviation and shipping sectors, they play an increasingly important role in those sectors in the Sustainable Development Scenario, especially in the long term, supported by rising carbon prices and other policies.

- **Ammonia** is produced from low-carbon hydrogen and nitrogen using the well-established Haber-Bosch process. The hydrogen used in the process is derived from steam reforming of natural gas, but it can also be produced from electrolytic hydrogen. Some small-scale demonstration projects producing ammonia from electrolytic hydrogen have been in operation for several years. Air Products, ACWA Power and NEOM, a new city planned in Saudi Arabia, recently signed an agreement to invest USD 5 billion in a project for producing ammonia using electrolytic hydrogen in Saudi Arabia (Air Products, 2020). With current technologies, producing ammonia from electrolytic hydrogen requires in total 23 000 GWh of electricity per Mtoe of ammonia: around 90% of this is used to produce hydrogen, around 7% to produce nitrogen and the rest is used in the Haber-Bosch synthesis. The overall energy efficiency of ammonia production from electrolytic hydrogen is around 50% (lower heating value [LHV]). Unlike hydrogen-based synthetic hydrocarbon fuels, ammonia production does not require any carbon, but it does require nitrogen. The toxicity of ammonia means that its handling requires care and would probably be limited to professionally trained operators, which could restrict its potential.
- **Synthetic hydrocarbons** (methane, diesel, kerosene and methanol) are produced by converting hydrogen and a carbon source into long chain hydrocarbons, which are then upgraded to usable fuels. There are several technological routes that can be used to produce synthetic hydrocarbons, including the Fischer-Tropsch process, which uses carbon monoxide (CO) as the carbon source. To be carbon neutral, this CO has to be generated from biogenic CO_2 from a bioenergy source or alternatively from CO_2 captured from the atmosphere using direct air capture (DAC) technologies. The production of these fuels requires significant amounts of electricity. Overall, the production of 1 litre of synthetic kerosene from electrolytic hydrogen together with CO_2 captured through DAC requires around 25 kWh of energy. Over 80% of this is electricity used to produce hydrogen, around 15% is electric and thermal energy used for the capture of CO_2 through DAC, and the rest is used in the Fischer-Tropsch synthesis. With current technology performance, only around 40% of the energy input ends up in the final liquid product, although process optimisation could potentially increase the overall conversion efficiency beyond 45%. Some projects aiming to produce synthetic hydrocarbons have been announced recently. For example, the Norsk-e Fuel project is planning the first commercial plant in Europe using

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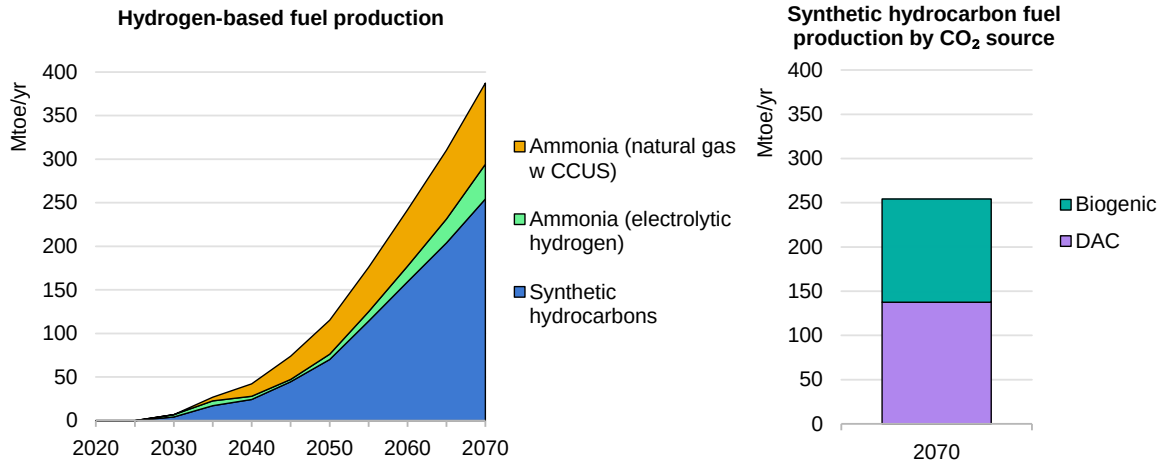
this technology, which is expected to become operational in 2023 with a production capacity of 10 million litres annually (Norsk-e Fuel, 2020).

In the Sustainable Development Scenario, 250 Mtoe of synthetic hydrocarbons are produced in 2070, mainly from electrolytic hydrogen, together with 130 Mtoe of ammonia, 70% of which is produced from natural gas with CCUS and the remainder from electrolytic hydrogen (Figure 3.12). Synthetic kerosene meets 40% of aviation energy demand in 2070, while ammonia meets over 50% of fuel demand for maritime shipping. Producing these fuels requires around 390 Mtoe of electrolytic hydrogen, or about 9% of total electricity generation in 2070, as well as 700 Mt of CO_2 as feedstock from biomass use or DAC. The electricity required in 2070 is roughly equivalent to the current annual electricity generation of the United States, Canada and Japan combined; the CO_2 feedstock required is roughly equivalent to the current annual CO_2 emissions of Germany.

Figure 3.12 Production of hydrogen-based fuels in the Sustainable Development Scenario, 2019-70



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Notes: Biogenic CO_2 refers to CO_2 captured at biomass conversion processes, such as biofuel production or biomass-fired power plants.

Synthetic kerosene for aviation dominates the production of hydrogen-based fuels, with the necessary CO_2 mostly being sourced via direct air capture.

Hydrogen-derived fuels could also play an important role in energy trade, allowing countries with significant renewable energy potential to export their solar or wind resources in the form of hydrogen-derived fuels to other countries that lack similar resources. This potential for trade is recognised in several national hydrogen strategies, with Germany and Japan recognising the case for hydrogen imports and Australia recognising the opportunity to provide them. In the Sustainable Development Scenario, around 60% of all ammonia being globally produced is

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internationally traded in 2070, while 50% of synthetic kerosene is traded, underlining the opportunities for trade in hydrogen and hydrogen-based fuels.[6]

The economics of producing clean ammonia and synthetic hydrocarbon fuels depend on various factors, in particular the cost of hydrogen. Production costs are influenced by the cost of fossil fuels in combination with CO_2 storage for the hydrogen production route using CCUS, and by the availability of low cost and low-carbon electricity for the electrolytic hydrogen route. The efficiency of the conversion process is currently around 40% for synthetic hydrocarbons and 50% for ammonia: improving these percentages, would help to reduce production costs. In the case of synthetic hydrocarbon fuels, the availability and cost of the CO_2 feedstock input is another factor affecting costs. CO_2 costs currently range from USD 30/tonne from ethanol plants to USD 135-340/tonne from DAC. However, whether a producer of CO_2 would be willing to sell it to a synthetic fuel manufacturer at close to the cost of capture would depend on the prevailing CO_2 emissions price or the level of any competing financial benefit for sending the CO_2 to long-term geological storage, if available. The competitiveness of hydrogen-based fuels will also depend on the adoption of policy measures either penalising the use of fossil fuels, such as CO_2 prices, or incentivising the use of clean fuels, such as clean fuel standards. If, for example, synthetic kerosene can be produced at a cost of USD 200/barrel, a CO_2 price of USD 375/tonne would be needed for synthetic kerosene to become competitive with fossil kerosene at an oil price of USD 50/barrel (Figure 3.13). The very high CO_2 prices (or equivalent policy measures) that would be needed for synthetic hydrocarbon fuels to compete with fossil fuels means that their use is limited to parts of the energy system where alternative low-carbon options are not viable, such as aviation (see Chapter 5).

[6] Ammonia production and trade here refers to its use as fuel in shipping and does not include ammonia production and use in the chemical sub-sector.

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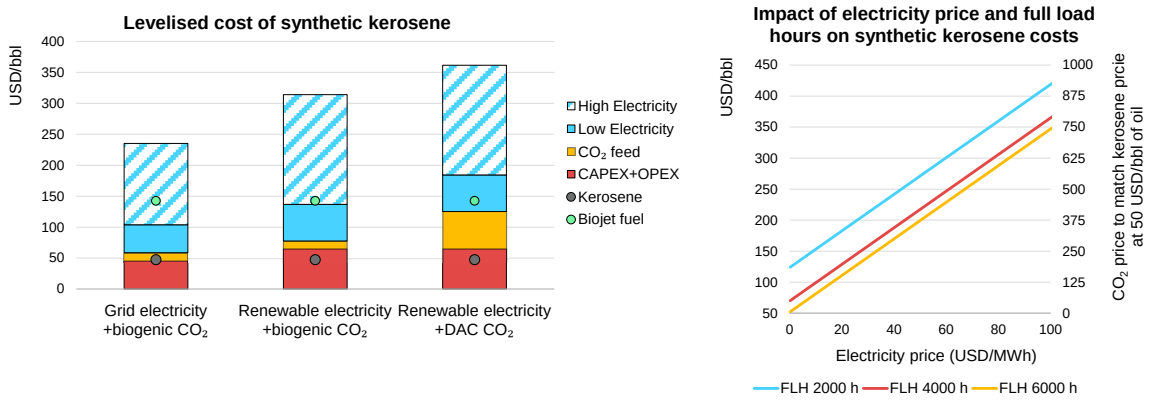
Figure 3.13 Projected synthetic kerosene production costs from different sources and impact of electricity costs and full-load hours, 2050



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Notes: bbl = barrel; FLH = full-load hours. Costs projected in 2050. Left graph is a sensitivity analysis considering the use of dedicated renewables-based electricity and CO_2 from DAC as the CO_2 feedstock.

Capital expenditure (CAPEX) assumptions: USD 355/kW_e with grid electricity, USD 269/kW_e for electricity from dedicated renewables-based plants and USD 564/kW of fuel for the synthesis stage.

Operating expenditure (OPEX) assumptions: 1.5% of CAPEX for electrolysis and 4% for the synthesis stage.

Efficiency assumptions (lower heating value): 74% for electrolysis and 73% for the synthesis stage.

Full-load hour assumptions: 5 000 hours for grid electricity and 3 000 hours for electricity from dedicated renewables generation.

Stack lifetime: 100 000 hours. System lifetime: 30 years.

Electricity price assumptions: USD 15-44/MWh for grid electricity and USD 20-60/MWh for electricity from dedicated renewables generation.

Kerosene and biojet fuel prices based on current prices.

CO_2 feedstock price assumptions: USD 30/tonne CO_2 for biogenic CO_2 from biofuel conversion plants and USD 142/tonne CO_2 from DAC. Representative *discount rate* for this analysis is 8%.

A combination of low electricity costs and high CO_2 prices is needed to make synthetic hydrocarbons competitive with conventional fossil fuels.

Industry

The high energy intensity of industrial processes, long lives of factories and machinery and a lack of currently viable low-carbon alternatives to conventional fossil fuels in some sub-sectors make deep CO_2 emissions reductions from industry particularly difficult.[7] This is reflected in the Sustainable Development Scenario projections: industry emerges as the second-largest CO_2 emitter in 2070 after transport, accounting for around 40% of residual emissions, even though emissions are 90% lower than in 2019 (Figure 3.14). About 70% of industrial CO_2 emissions today are generated when producing chemicals, steel and cement. This share increases to

[7] Technology needs and readiness for the chemical, steel and cement sub-sectors are discussed in detail in Chapter 4.

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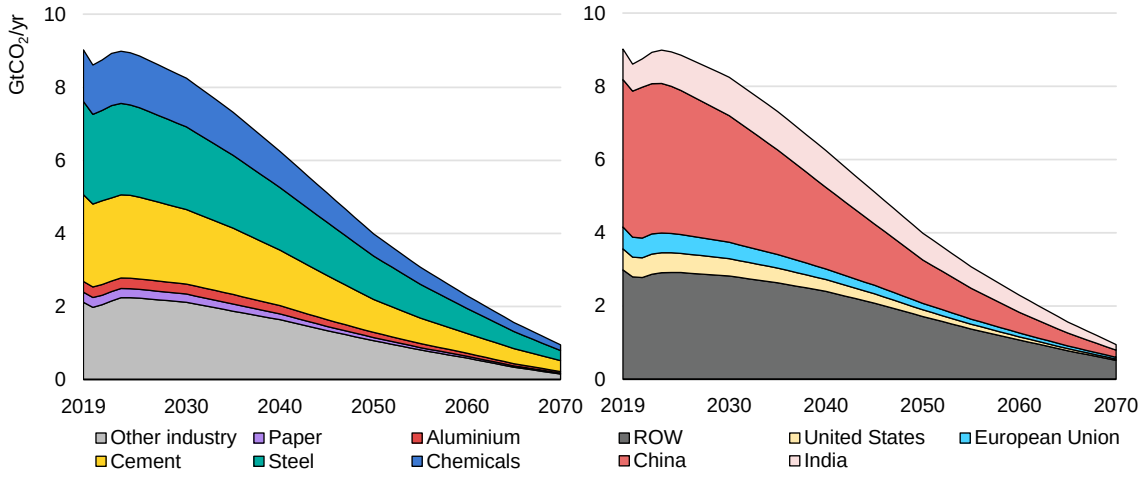
almost 80% by 2070, as other less energy-intensive parts of industry with commercially available and scalable low-carbon alternatives reach near-zero emissions by that year.

Figure 3.14 Global direct CO_2 emissions in industry by sub-sector and region in the Sustainable Development Scenario, 2019-70



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Notes: ROW = rest of world. Includes direct energy-related and process emissions. Other industry includes less energy-intensive industries such as food and beverage, mining and textiles.

Chemical, steel and cement production increase their share of total industrial emissions to almost 80% by 2070 in the Sustainable Development Scenario as less energy-intensive industries approach full decarbonisation.

In the Sustainable Development Scenario, all regions make major efforts to reduce CO_2 emissions drastically from their industrial portfolio. Asia remains the leading producer of bulk materials, though production gradually shifts from China to India as its economy further develops (see Chapter 4). China's share of global industrial emissions, currently at 45%, more than halves by 2070 in the Sustainable Development Scenario. There are two main reasons for this. First, there is a structural shift in China away from the production of bulk materials, especially cement, towards less energy-intensive manufacturing activities such as electronics, batteries and industrial equipment. This structural shift is already underway, and it is reflected in the Stated Policies Scenario. Second, there are significant efforts to reduce the direct CO_2 footprint of industrial activity, leading to a reduction of 85-90% in direct CO_2 emissions for heavy industry sectors by 2070. By contrast, India increases by 75% its share of global industrial emissions by 2070 as its production of bulk materials grows robustly to meet domestic demand, which partly offsets efforts to roll out low-carbon industrial technologies. By 2070, India accounts for 15% of global CO_2 emissions from industry. Emissions from the industrial sector in the European Union and the United

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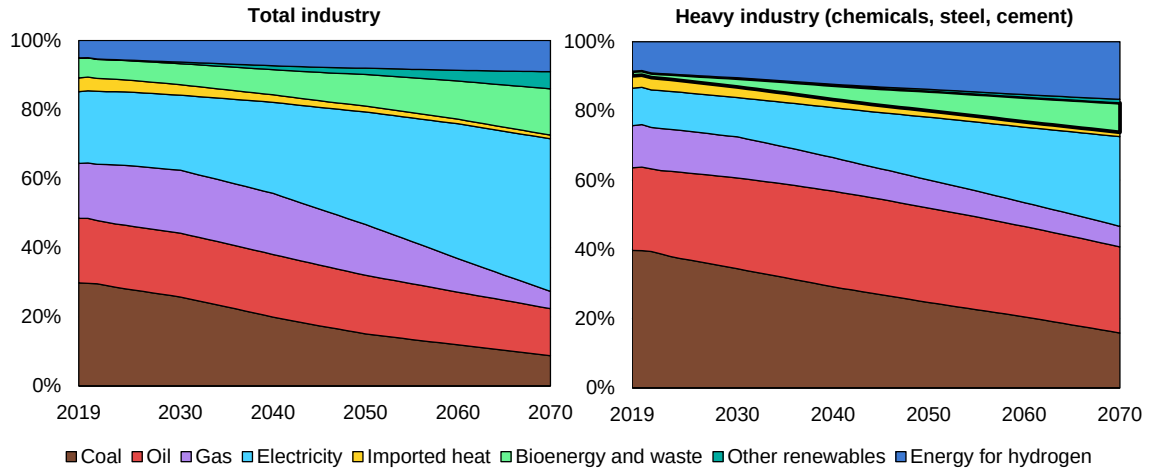
States are reduced by more than 90% in 2070 relative to current levels in the Sustainable Development Scenario, such that together they account for less than 10% of total emissions from industry.

Fossil fuels today account for around 70% of total final industrial energy demand. The production of chemicals, steel, and cement in turn accounts for about 60% of total industrial fossil fuel demand. Coal is the leading energy source used to produce these materials, accounting for roughly 50% of their total energy needs, although oil and gas are also heavily used as both feedstock and fuel in the chemical industry. By 2070, fossil fuel use in industry is reduced by over 60% in the Sustainable Development Scenario, and replaced primarily by electricity and bioenergy (Figure 3.15), while just over three-quarters of the remaining CO_2 emissions are captured and permanently stored.

Figure 3.15 Final energy demand by fuel shares for total industry and selected sub-sectors in the Sustainable Development Scenario, 2019-70



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Notes: Industry final energy demand refers to the IEA Energy Balance (IEA, 2020d) boundaries of total final consumption by industry, non-energy use for chemical feedstocks and energy consumed in the transformation sector by blast furnaces and coke ovens.

Fossil fuel use in industry is cut by over 60% in the Sustainable Development Scenario by 2070 and replaced primarily by electricity and bioenergy.

Electricity consumption in industry more than doubles by 2070 in the Sustainable Development Scenario. Electricity is used in the short-to-medium term directly for low and medium temperature heat and in secondary production routes for metals, using technologies that are commercially available or close to being so. Electricity is also used in the long term indirectly for electrolytic hydrogen production, for reduction purposes in steel production and as a feedstock for chemicals. Hydrogen in particular requires more electricity as the demand for hydrogen in industry increases by 80% (to around 360 Mtoe) by 2070, accounting for 9% of total industrial

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energy demand. Virtually all industrial hydrogen is produced from unabated fossil fuels today. In the Sustainable Development Scenario, 60% of the hydrogen consumed in 2070 is produced onsite via water electrolysis, with the majority of the rest being produced from fossil fuel plants equipped with CCUS. The bulk of the growth in renewables such as solar thermal and geothermal in the final industrial energy mix in the Sustainable Development Scenario is attributed to less energy-intensive industries, which have lower temperature heat requirements.

Technologies that enable the production of emissions-free bulk materials like chemicals, steel and cement are not yet available, but the industrial energy transition envisioned in the Sustainable Development Scenario hinges on their successful demonstration and widespread deployment. Around three-quarters of the cumulative direct industrial CO_2 emissions reductions by 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario come from the deployment of pre-commercial technologies or technology types for which some designs or components are not yet mature. Those technologies can be divided into two broad categories: those that use fossil fuels with CCUS, and those that replace fossil fuels with low- or zero-carbon fuels.

Overall, the use of CCUS is slightly more advanced than the use of low- or zero-carbon fuels. CCUS use takes advantage of mature technologies from other sectors (e.g. chemical absorption for the separation of gases, already applied commercially in power and fuel transformation) or applies similar fundamental principles that avoid the need to develop brand new processes based on new fuels. The separation of CO_2 is already an inherent part of commercial processes in the chemicals sub-sector, such as ammonia and methanol production, and capture and storage/utilisation projects for such emissions streams are in operation in the United States and China, with several other projects in the pipeline.

CO_2 emissions could be avoided through the use of decarbonised electricity to provide heat. While electric heating technologies are commercially available for low temperature and in some cases medium temperature heating, the application of electric technologies such as microwave, infrared and plasma arcs for high temperature heating is mostly at the prototype stage or below for large-scale applications (TRL ≤ 5). Induction and electric arc furnaces are exceptions, but both of these need a conductive material, and their main use is likely to be in specific applications within the metal producing industries such as electric furnaces for producing steel from scrap or sponge iron, and for aluminium smelting (Box 3.1). Electrification of the production of non-conductive materials that involve high temperature processes (e.g. cement, certain chemicals) is technically more complex, and this is reflected in lower technology readiness levels (see Chapter 4). Swedish cement producer, Cementa, and Vattenfall, a Swedish multinational power company, launched the CemZero project in June 2017 that aims to electrify cement kilns

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(Cementa, 2019), and a feasibility study has indicated that it is technically possible to electrify them using plasma technology; however, this technology would not eliminate process emissions. In 2019, BASF, Borealis, BP, LyondellBasell, SABIC and Total announced the creation of a consortium to jointly investigate how naphtha or gas steam crackers for the production of high-value chemicals could be operated using renewables-based electricity instead of fossil fuels (Borealis, 2019). VoltaChem is also working on the electric cracking option in the framework of the power-to-heat technologies (VoltaChem, 2020).

Box 3.1 Reducing process emissions and electricity needs in aluminium smelting

Major innovation efforts are underway to develop new anode designs in order to eliminate process CO_2 emissions associated with the degradation of the carbon anodes used in primary aluminium smelting. These process emissions currently account for about 40% of primary aluminium production direct emissions. In 2018, Alcoa and Rio Tinto announced the formation of a joint venture called Elysis to develop an inert anode (made from materials that do not degrade and thus do no produce process emissions), which is expected to be available for retrofitting existing smelters from 2024 (Elysis, 2018). RUSAL's Krasnoyarsk plant in Russia has already produced primary aluminium using inert anode technology at an industrial scale. Further technological improvements are expected to lower production costs, and mass scale production may start within three years.

Other R&D work is focused on reducing electricity consumption and thus indirect emissions from aluminium smelting. While conventional aluminium smelter cells have a single-pole arrangement, multipolar cells could be produced by using bipolar electrodes or having multiple anode-cathode pairs in the same cell. They have the potential to reduce energy consumption by 40%, due to lower operating temperatures and higher current densities (US DOE, 2007). However, multipolar cells require the demonstration of inert anodes, and the technology for this is still at an early stage. A prototype plant with a multipolar cell was developed by Alcoa in the 1970s, but it closed as a result of high costs and technical problems. More recent exploratory research and testing have been conducted in the United States by Northwest Aluminium and Argonne National Laboratory. Chloride electrolysis is another alternative aluminium smelting process originally developed in the 1960s. It offers potential to lower electricity needs by about 25% and enable easier carbon capture (Øye, 2018). Renewed R&D efforts would be required to bring this early stage technology to market.

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Aluminium smelters are large consumers of electricity. Improved load management will become more important as the share of variable renewable in the power generation mix rises, and options for integrating flexibility technologies and modifying operations are being demonstrated which would help with this. In May 2019, the aluminium company TRIMET began a successful first industrial-scale operation of its EnPot demand-response technology, consisting of 120 pots at its plant in Essen, Germany, following a smaller 12 pot trial that began five years earlier (Energia Potior, 2020). This "virtual battery" concept relies on installing adjustable heat exchangers that can maintain the energy balance in each electrolytic cell irrespective of shifting power inputs.

Technologies that use low-carbon hydrogen for primary steel and chemical production are more advanced than direct electrification technologies (see Chapte 4). Hydrogen-based direct iron reduction would open new low-carbon avenues for primary steel manufacturing, and a large prototype of this technology is currently being operated in Sweden. Various companies in the chemical industry are exploring means to produce low-carbon hydrogen using water electrolysis or CCUS.

Transport

Reducing CO_2 emissions in the transport sector over the next half-century will be a formidable task. It will require structural shifts in the modes used to move people and freight, a shift to low-carbon forms of energy and a stronger focus on using energy more efficiently. This calls for a broad mix of technologies, many of which are at the early stages of development and commercialisation. These include vehicle, powertrain and engine technologies, and the infrastructure needed to support alternative fuels, as well as digital technologies and software to enable service providers to harness the power of data (IEA, 2017a).

In the Sustainable Development Scenario, global direct CO_2 emissions from fossil fuel use in the transport sector fall by almost 90% from 8.1 Gt in 2019 to 1 Gt by 2070 (Figure 3.16). This primarily reflects a widespread shift to electric cars powered by decarbonised electricity. Almost all the residual emissions in 2070 are from road freight, maritime shipping and aviation, where switching to alternative zero-carbon fuels and technologies is particularly difficult. Their combined emissions fall by three-quarters over the projection period, but overall transport emissions in 2070 are still the highest of any sector (see Chapter 5).

Although transport demand growth in the Sustainable Development Scenario is less marked than in the Stated Policies Scenario, mobility per capita measured by passenger-kilometres travelled doubles between 2019 and 2070 on the back of rising

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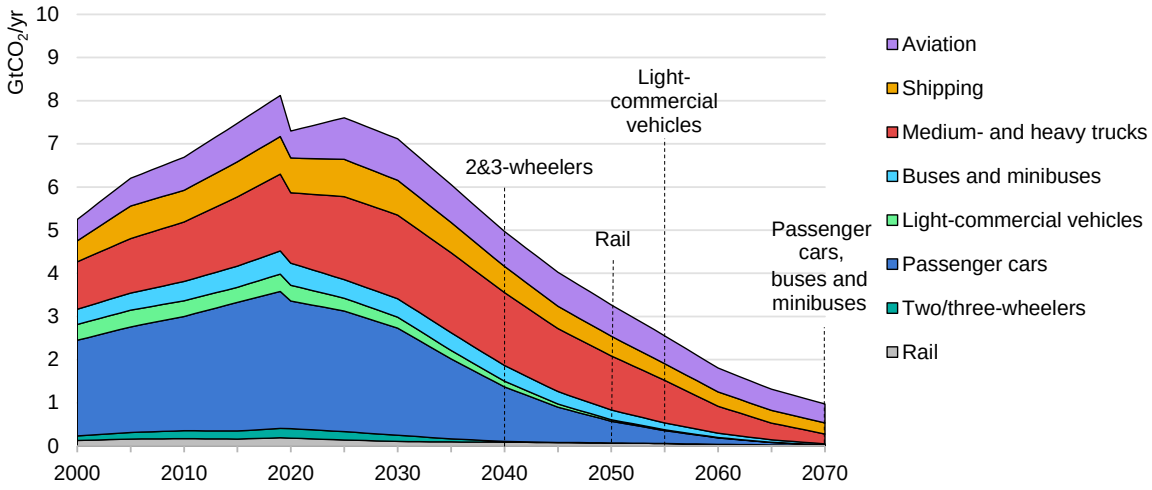
prosperity and population, and car ownership rises by 60%. Passenger and freight aviation numbers more than triple over the period. This is reflected in the demand for fuels. For example, biofuels production scales up from 2 mb/d in 2019 to 5 mb/d in the next decade in the Sustainable Development Scenario as it is used as an alternative to fossil fuels in road vehicles, and later as a zero emissions high energy density fuel for maritime shipping and aviation. By 2030, battery manufacturing capacity equivalent to the size of about 90 Tesla gigafactories (battery gigafactory capacity of 35 gigawatt-hours per year) is in place to support electric vehicles: by 2050, total battery manufacturing capacity is equivalent to 300 Tesla gigafactories. Meanwhile, supporting infrastructure for electric and fuel cell vehicles also scales up in the Sustainable Development Scenario, with nearly 19 million public chargers and nearly 13 000 hydrogen refuelling stations built by 2030. Further infrastructure deployment is needed in later years as heavy-duty trucking demands more fast chargers and larger hydrogen refuelling stations.

Figure 3.16 Global CO_2 emissions in transport by mode in the Sustainable Development Scenario, 2000-70



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Notes: Dotted lines indicate the year in which various transport modes have largely stopped consuming fossil fuels and hence no longer contribute to direct emissions of CO_2 from fossil fuel combustion. Residual emissions in transport are compensated by negative emissions technologies, such as BECCS and DAC, in the power and other energy transformation sectors.

Most modes of transport are decarbonised by 2070 in the Sustainable Development Scenario, but trucking, shipping and aviation continue to produce some emissions due to practical difficulties with their decarbonisation.

In the Sustainable Development Scenario, the pace at which direct emissions decline in different modes of transport is a function of several factors. These include asset operating lifetimes, scope for electrification or adoption of alternative low-carbon fuels, and the scope for providing passenger mobility and freight services in more sustainable ways.

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Two/three-wheelers, with lifetimes rarely more than a decade, reduce operational CO_2 emissions to near zero by 2040, with new sales of these vehicles having completely electrified in the 2030s. They also rapidly exploit the two to threefold improvement in fuel economy that comes from switching from an internal combustion engine (ICE) to an electric motor.

Rail is another mode where CO_2 emissions are cut rapidly, primarily by electrifying trains. New high-throughput conventional railway lines are almost entirely electrified from a very early date, and virtually all existing lines are electrified by the mid-2050s. A small stock of infrequently used and long-lived diesel locomotives remain in use beyond then, but their emissions are tiny relative to the rest of the transport sector, and options such as fuel cell or battery electric powertrains gradually become available even for these operations.[8]

Light-commercial vehicles switch rapidly in the short term to electricity and later to hydrogen-powered fuel cells when longer ranges or hours of operation are required. Large, well-coordinated fleets and logistics services, such as Amazon, DHL, FedEx and UPS switch first as they are in the best position to make use of data tracking, and to make upfront investments in efficient electric motors. Smaller and single-owner operations profit later from the growing range of available electric models, as well as from the roll out of charging stations for private cars and commercial fleets. For these reasons, light-commercial vehicles switch to electricity more quickly than privately owned cars, reaching net-zero emissions in the mid-2050s. Hydrogen fuel cell technologies gradually enter the light-commercial vehicle market in operations where costs and performance are competitive with electric vehicles, which mostly means in cases where taxis and fleet vehicles drive longer distances.

Passenger cars see the biggest fall in CO_2 emissions in absolute terms in the period to 2040 as electric vehicles make rapid headway. As the technologies enabling electric mobility scale-up and mature through the 2020s, powertrains that bridge the gap between conventional vehicles and electric ones play a significant transitional role. Hybrid electric car sales peak at around 15% of total car registrations in the early 2030s, and the market for plug-in hybrid vehicles peaks at a similar share later in the same decade. As the performance of batteries for electric mobility improves – notably as their energy density and durability increase and costs decline – these hybrid powertrains are gradually displaced by full battery electric vehicles in the years to 2050. China, the European Union, Japan and the United States lead the transition to zero-emission cars (including electric and fuel cell electric cars), with conventional car sales coming to an end in the 2040s.

[8] The contribution of railways to emissions is further diminished by the fact that it is the most energy-efficient motorised passenger transport mode, requiring 60-90% less energy on average per passenger-km than other modes (IEA, 2019b).

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However other countries continue to sell conventional cars through to 2060, and passenger cars as a whole approach zero emissions only in the final years leading up to 2070. By 2070, electric vehicles make up nearly 90% of the total passenger car fleet and fuel cell electric vehicles another 10%, and the remaining very small share of conventional cars still in the fleet is mostly over a decade old. The energy intensity of cars and other light-duty vehicles meanwhile declines through vehicle, powertrain and engine efficiency measures through to 2040, and then more rapidly in later years as more and more switch to electric powertrains, which are three-to-five times more efficient than ICE models.[9] Some electric vehicles (EVs), especially fleets that intensively operate their vehicles, also incorporate fuel cells as range extenders to store more energy on-board than batteries alone can.

Hydrogen fuel cell technologies gradually enter the light-duty vehicle market in operations where costs and performance are competitive with EVs, mostly in cases, such as taxis and fleets, where vehicles drive long distances. Several commercial car models using hydrogen fuel cells are already available from Hyundai, Toyota, Renault and Mercedes.

Electric buses and minibuses are increasingly being chosen by municipal fleet purchasers and operators on the strength of their air quality benefits and purchase subsidies and/or upfront financing. By 2070, about two-thirds of buses are battery electric and one-fourth are powered by hydrogen (hydrogen fuel cell electric buses are marketed today by Foshan, Geely, Van Hool and Toyota, among others). Long distances and intensive usage make battery electric buses less practical due to their low energy density and long recharging times, and these vehicles rely on diesel or biofuel alternatives for a longer period in the projections, but electrification using fuel cells, batteries and/or dynamic charging may become competitive in time, as with regional and long-haul trucking (see Chapter 5).

Heavy-duty trucks lag their light-duty cousins by more than a decade in their adoption of more efficient electric powertrains, slowing the pace of decarbonisation. The lack of availability of fast charging infrastructure along long-distance freight corridors is an obstacle for regional and long-haul trucking operations.

Shipping and **aviation** emissions also fall slowly relative to other transport modes, similarly reaching net-zero well beyond 2070 (see Chapter 5).

For the transport sector as a whole, energy efficiency improvements make the biggest contribution to cutting CO_2 emissions in the Sustainable Development Scenario relative to the Stated Policies Scenario, especially in the period to 2040.

[9] The Sustainable Development Scenario achieves the targets of the EV30@30, which aims for 30% of all road vehicles sold in 2030 to be electric. The target includes cars, LCVs, buses and trucks, and EVs include battery, plug-in, and fuel cell electric powertrains, but does not include two/three-wheelers.

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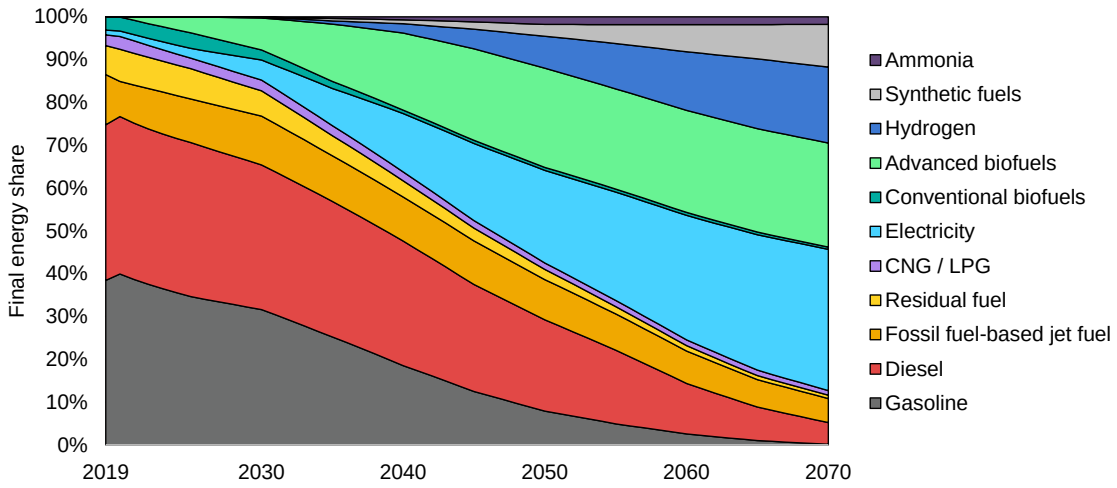
In road transport, fuel economy improvements in recent decades have been driven primarily by fuel economy/CO_2 standards, backed up by other market pull mechanisms such as "bonus-malus" type measures[10], as well as fuel taxes and city-level policies that provide alternatives to personal cars. Measures such as lightweighting, aerodynamics and the adoption of low rolling resistance tyres help achieve the target set by the Global Fuel Economy Initiative (GFEI) of 50% better fuel economy for newly registered passenger light-duty vehicles by 2030 relative to 2005 (GFEI, 2019). Strengthening of all these policies is instrumental in driving down the per-km CO_2 emissions of both light- and heavy-duty vehicles through the projection period in the Sustainable Development Scenario (IEA, 2017b). By contrast, to date efficiency regulations in maritime shipping and aviation have not required business to adopt efficiency technologies at rates that exceed what market signals already incentivise. In the Sustainable Development Scenario, the average energy intensity of passenger and freight transport falls by around 70% by 2070. Putting these hard to abate modes onto a trajectory in line with this will require measures to regulate or incentivise more rapid progress.

Figure 3.17 Global transport sector energy consumption by fuel in the Sustainable Development Scenario, 2019-70



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Notes: CNG = compressed natural gas; LPG = liquefied petroleum gas. Fossil fuel-based diesel takes longer to be replaced in the transport sector fuel mix than fossil fuel-based gasoline, as alternatives for diesel in heavy-duty trucking and intercity buses take longer to deploy.

Fossil fuels – today's dominant source of energy in transport– account for just 14% of final energy in 2070.

[10] France's bonus-malus programme was the first to implement "feebates": a tax at vehicle purchase or registration on cars with high fuel consumption from which the revenues are used to finance subsidies for the purchase of energy-efficient vehicles. Such schemes can be designed to be revenue neutral.

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A shift to electricity, biofuels and other low-carbon fuels (hydrogen and synthetic hydrocarbons) accounts for 70% of the decline in global CO_2 emissions from the transport sector to 2070 in the Sustainable Development Scenario. At first, biofuels play an important role, but they are eclipsed in the 2040s as electric powertrains, hydrogen and synthetic fuels become more available and competitive. The destination of the biofuels also changes: biodiesel is redirected towards shipping in the medium term, later complemented by biomass-to-liquid for jet fuel, while ethanol is used to produce biojet fuel for aviation. Modal shifts account for most of the rest of the CO_2 emissions reductions. By 2070, 30% of final energy needs in the transport sector are met by electricity (up from 1% in 2019), with biofuels providing 36% (up from 3% in 2019), and ammonia, hydrogen and synthetic fuels almost one-quarter of transport final energy demands (Figure 3.17).

Batteries are the core technology enabling the transport sector to decarbonise.[11] Lithium ion (Li-ion) batteries are projected to be widely used in light-duty EVs. Their costs are falling rapidly as they are deployed more widely, bringing learning benefits and economies of scale. Among alternative battery chemistries to Li-ion, solid state batteries with Li-metal anodes, which could achieve a density of 400-500 watt-hours per kilogramme (Wh/kg), are the most advanced. Prototypes have been tested and Toyota expects to demonstrate solid state batteries in a vehicle early in the 2020s, while a number of start-ups are focusing on the development of the technologies required to develop solid state electrolytes. This type of battery is expected to become commercially available between 2025 and 2035.[12] Successful demonstration and roll out of these alternative battery chemistries supports the nearly doubling in cell level energy density projected by 2070 in the Sustainable Development Scenario. This trend aligns with a continuation of recent rates of battery improvement and enables an expansion of the scope of batteries in transport, primarily in road and rail. Other alternative chemistries at lower readiness levels (early prototype or below and thus outside the scope of the Sustainable Development Scenario), including Li-sulphur, multivalent ions and Li-air would offer more potential for lowering costs, increasing energy density and improving recyclability. Such substantial increases in energy density, together with improvements on other performance metrics such as cost and durability, could make electrification viable for other transport modes and a more attractive commercial option for regional and long-haul trucking more quickly (see Chapter 6).

Battery technologies are already making progress in road transport, not just in cars and light-duty vehicles but also in trucks. Daimler, BYD and many other truck original

[11] The contribution of lithium-ion batteries to the Sustainable Development Scenario is predicated on decarbonising electricity generation and on ensuring that critical battery materials (such as cobalt and, later, lithium) are reused and recycled (See IEA, 2020c).

[12] For more details of recent and potential innovations in batteries for electromobility, see Chapter 4 of *Global EV Outlook 2020* (IEA, 2020c).

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equipment manufacturers already market medium-duty battery electric truck models, used mostly for urban deliveries or waste collection. Several other truck manufacturers have announced plans to sell at least one model of plug-in hybrid or battery electric truck, while Tesla and Freightliner have developed battery electric trucks with a range of 400-800 km that are being tested by corporate fleets.

Beyond road transport, battery electric ships are being demonstrated (TRL 8), though current battery energy densities limit their potential deployment to short routes.[13] In Norway, for example, 16 electric car ferries were in operation in 2019 and a further 37 are expected to enter operation by the end of 2020 (Nordic Energy Research, 2020). Yara, a global fertiliser company, in collaboration with Kongsberg, a maritime technology company, has developed an all-electric and autonomous container feeder ships. However, its demonstration, which was initially planned for early 2020, has been postponed in light of Covid-19 pandemic (Yara, 2020).

The use of batteries in aircraft is severely limited by current battery energy densities. Even if battery energy densities were to reach around 1 000 Wh/kg, electric aircraft flight would be limited to around 1 400 km, or a maximum of about 25-30% of current aviation fuel demand. Nonetheless, a number of aircraft manufacturers are planning to develop early prototypes of hybrid and full battery aircraft in the coming years. For instance, Airbus has set a target of developing an all-electric aircraft capable of seating 100 passengers by 2030.

Buildings

The buildings sector – including residences, offices, shops, hotels, schools and other public and commercial premises – today accounts directly and indirectly for 30% of the final energy consumed around the world, or around 3 100 Mtoe, including almost 55% of global electricity consumption.[14] When both the construction and use phases are taken into consideration, it contributes around 37% of today's global CO_2 emissions. Direct emissions from fossil fuel combustion in buildings for space conditioning and water heating as well as cooking and other service applications amounted to about 3 $GtCO_2$ worldwide in 2019 (Figure 3.18). Indirect emissions from the consumption of electricity and heat by the huge array of electrical and electronic devices used in buildings (e.g. air conditioners, heat pumps, household appliances and lighting) increase that figure to 9.8 $GtCO_2$. Producing the materials and

[13] Besides purely battery electric ships, also ships with conventional engines can plug in at port to power their auxiliary and hoteling loads, a practice known as 'cold-ironing'. Mandates are making equipping both ships and ports with the necessary infrastructure to cold iron are becoming more and more common, and the local air pollution and climate benefits are compelling. For more details on this practice, see *Global EV Outlook 2020* (IEA, 2020c).

[14] The residential sector is by far the largest component in the buildings sector in terms of floor area (80%), final energy use (70%) and CO_2 emissions (60%).

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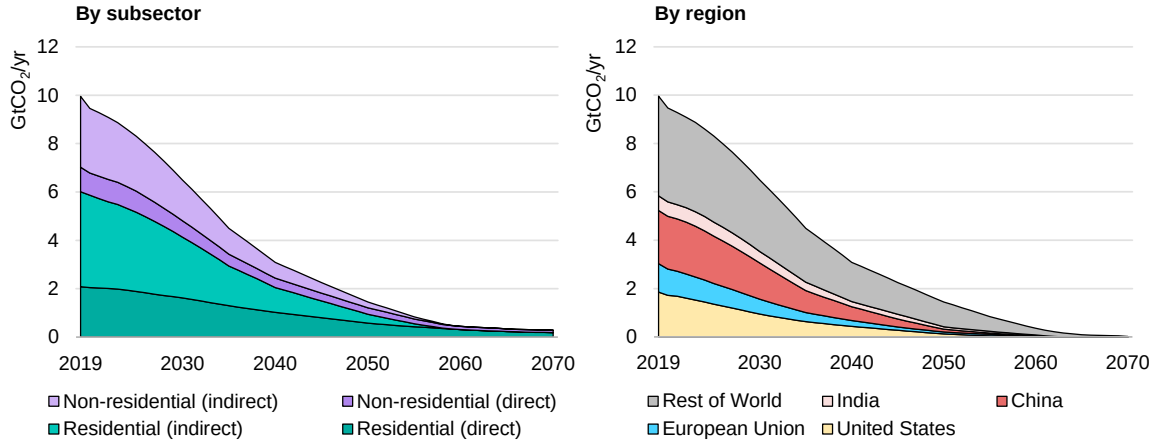
constructing buildings involves an additional 3.5 $GtCO_2$ of energy- and process-related CO_2 emissions in the industry sector, mostly from cement and steel manufacturing.

Figure 3.18 CO_2 emissions from the use phase of buildings by sub-sector and region in the Sustainable Development Scenario, 2019-70



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Note: Indirect emissions include the emissions associated with the generation of electricity and heat consumed in buildings.

CO_2 emissions in the buildings sector fall to net-zero by 2070 through measures such as high efficiency electric equipment, phasing out fossil fuel use and decarbonisation of heat and power supply.

Floor area – a key element of energy demand and related CO_2 emissions in the buildings sector – is projected to expand robustly in the period to 2070 as the world's population and GDP rise. In the Sustainable Development Scenario, floor area increases more than twofold in the period to 2070, which is equivalent to adding a city the size of Paris to the world every week. Half of the floor area additions will be in sub-Saharan Africa and India. Direct and indirect emissions from the buildings sector nevertheless are all but eliminated soon after 2060 thanks to the energy savings associated with more efficient and affordable building envelopes and equipment, further electrification of end uses and switching to clean fuels in buildings themselves and in the power sector.

Improvements to the building stock, achieved through new high performance construction and deep energy renovation of building envelopes, contribute around a third of the almost 30% reduction in the final energy use in buildings in the period to 2070 relative to the Stated Policies Scenario. Over a third of total global floor area is at the near-zero energy level by 2040. A number of regions, including China, European Union and North America, already have substantial experience of using building energy codes. However, only a few, including France, have made near-zero energy buildings the norm for new construction. In the Sustainable Development

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Scenario, the buildings sector in the European Union is one of the first to hit net-zero emissions, driven by its stated ambition of stepping up renovation efforts so that all buildings are near-zero energy by 2050.

In 2019, the 3 $GtCO_2$ of direct emissions from the buildings sector mostly derive from the combustion of fossil fuels for space and water heating (80%) and cooking (16%). Over the course of the projection period in the Sustainable Development Scenario, fossil fuel-based technologies for space and water heating are largely replaced by low-carbon electric heat pumps and heat exchangers connected to renewable energy sources, or to clean district heating systems (which mostly operate with large-scale heat pump technologies such as power-to-heat). Heat pumps and district energy systems account for almost half of global heating equipment sales in 2070 (Figure 3.19). Electrification and commercial heat are the largest contributors to the decarbonisation of heat, and they reduce CO_2 emissions related to heat demand by an average of 0.6 Gt annually, equivalent to all CO_2 emissions in Canada in 2019.

The proportion of heating equipment sales accounted for by heat pumps nearly triples by 2030 and continues to grow thereafter: heat pumps become the leading heating and cooling technology in buildings worldwide by 2040. For comparison, this means that the number of heat pumps sold in the residential sector over the next 20 years is roughly equivalent to the number of natural gas boilers sold in the same sector over the last 20 years. This sharp increase is driven by sales in high performing buildings, where heat pumps meet increasing space cooling and heating demand in many regions including China, North America and Europe Union. Heat pumps are primarily deployed in suburban and rural areas due to space and building constraints, although compact and/or retrofit solutions are emerging rapidly and being deployed on a larger scale, especially in Europe. While high efficiency heat pumps are scaling up in most regions, technology designs are geographic specific related to existing building stock and climatic characteristics and are able to provide high efficiency air-to-air heat pumps for near-zero energy buildings, ground-source heat pumps for very cold climates and compact systems including a heat battery for older renovated buildings. Nevertheless, there remains scope for some of these technologies to increase their efficiency and range of use through further innovation (IEA, 2020b).

District energy is best suited to densely populated areas that can exploit waste heat and provide flexibility to the electricity grid through thermal inertia. Heating and cooling networks expand in particular in densely populated European cities and, to a lesser extent, in the United States. The use of district energy does not lessen the need to decarbonise the existing heat supply, notably in Russia and China which together account for 65% of current total district heat supply.

Energy use in the buildings sector makes use of renewables through solar thermal heating, low-emission biomass boilers and geothermal energy with ground-source heat pumps. Solar thermal technologies supply around a third of water heating demand in 2040. This increases to around half in 2070 when solar thermal units are deployed particularly in emerging economies such as India and ASEAN (Association of Southeast Asian Nations) where the bulk of heat demand is related to sanitary hot

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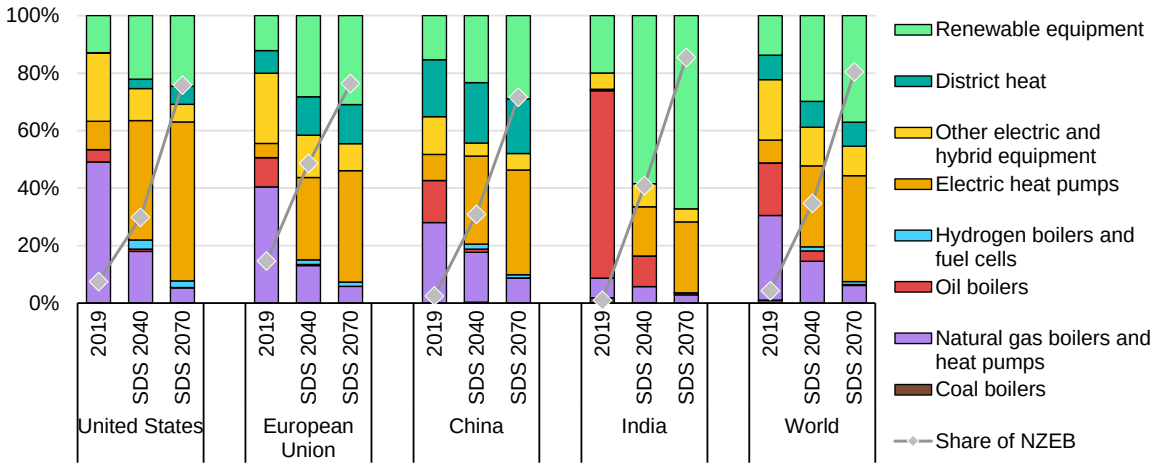
water, which solar thermal can provide with no or little operational expenditure. Where they can be installed, geothermal ground-source heat pumps offer efficient and reliable solutions for the whole year, since underground temperatures are relatively stable, enabling seasonal storage and offering high performance during cold spells (as a heat provider) or heat waves (as a cooling provider). Overall, more than 25% of final energy use in the buildings sector is met through direct use of renewables in buildings in 2070 in the Sustainable Development Scenario.[15]

Figure 3.19 Heating equipment sales share and share of near-zero energy buildings by region in the Sustainable Development Scenario



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Notes: SDS = Sustainable Development Scenario; NZEB = near-zero energy buildings.

Decarbonising heat in buildings requires increased co-ordination of measures to improve the building envelope and to adopt clean and efficient heating technologies.

Hydrogen blended into natural gas networks or supplied to buildings through dedicated networks accounts for only about 1.5% of the total reduction in cumulative emissions related to heat in buildings in the period to 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario. This small contribution is explained by a phase-out of natural gas boilers as blending rates do not exceed 6-7% in energy content (and 20% in volume), and that supply limitations of biomethane make it challenging to decarbonise the remaining emissions from heat in buildings. Since the direct use of hydrogen in fuel cells or hydrogen boilers is typically much more energy intensive than low-carbon heating alternatives, their use is limited to regions with existing gas infrastructure and/or in very cold climates (e.g. Russia, Canada) and poorly insulated buildings in the case of hydrogen boilers.

[15] Excluding own consumption of renewable electricity produced in the buildings, e.g. through solar rooftop PV as well as the renewable share in purchased electricity.

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Energy efficient buildings designs, electrification and increased renewables integration reduce residual direct emissions in the buildings sector to less than 300 Mt in 2070. Overall fossil fuel use in buildings is nearly phased out by 2070, though this masks specific technology trends at end-use application and regional levels.

- Coal and oil use for space and water heating drops dramatically in developed countries, falling to about 15% of today's level as early as 2040.
- The use of liquefied petroleum gas (LPG) and piped natural gas as improved cooking fuels in emerging economies rises sharply to 2030 as universal energy access is achieved. After 2030, growth in cooking services is met almost entirely by clean energy sources, including efficient solid biomass used in stoves adapted to local conditions, ethanol, biogas and electricity, and a small contribution from natural gas.
- Natural gas use in conventional and condensing gas boilers declines steadily. This drives their emissions down by 60% in the years to 2040, and nearly 95% by 2070. The slower pace of natural gas phase out compared with coal and oil is due to the presence of existing gas distribution networks in major heat markets, and the time necessary for their decommissioning or conversion. Switching to gas-fired heat pumps and hybrid heat pumps in the medium term contributes to provide space heating more efficiently as they are more efficient than condensing gas boilers.[16] Gas heat pumps are currently available for application in commercial and multi-family buildings, while hybrid heat pumps (combined with a condensing gas boiler) mostly are deployed in regions with extremely cold climates.
- Decarbonisation of power and heat generation causes indirect emissions from the electricity used by household applications and from district heat to fall even faster than direct CO_2 emissions. Efficiency gains also help to reduce demand. For example, the efficiency of LEDs increases from 90-110 lumens per Watt to 150-170 lumens per Watt, while inefficient electric technologies, such as, incandescent, halogen and fluorescent lightbulbs, electric resistance heaters and non-induction plates for cooking are phased out completely by 2070. Despite a growing demand for cooling services and electrical appliances, efficiency gains combined with power generation decarbonisation lead to savings of nearly 40 $GtCO_2$ by 2070 relative to the Stated Policies Scenario. For comparison, total energy-related CO_2 emissions worldwide in 2019 were about 33 Gt.

[16] The coefficient of performance of gas heat pumps is the ratio between the heat output relative to gas input. It typically ranges from 130% to 200% depending on climate, operations and equipment size; a significant improvement compared to gas boiler efficiencies (95-98%) for condensing gas boilers.

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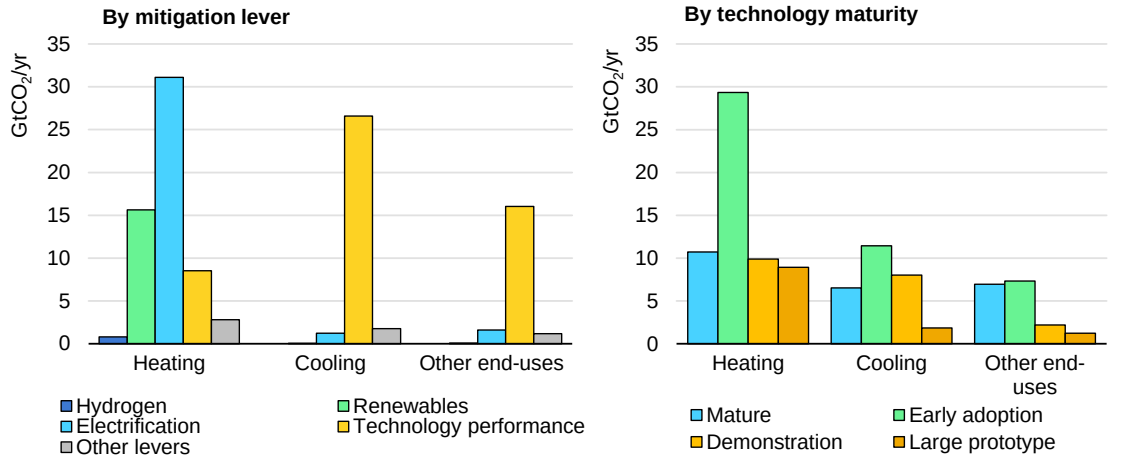
Around 70% of cumulative CO_2 emissions reductions to 2070 from the buildings sector in the Sustainable Development Scenario results from the deployment of solutions that are available on the market today, although most still require innovation to fully integrate across the diversity of climates and building types. Another 30% are currently at the demonstration or prototype phase (Figure 3.20).

Figure 3.20 Global cumulative CO_2 emissions reductions in the buildings sector by mitigation lever and technology readiness level in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2020-70



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Notes: Other levers include fuel shifts other than electrification, hydrogen and renewables (e.g. coal to natural gas heat pumps) and other factors impacting service demand. Other end uses include lighting, appliances, cooking and other services. See Box 2.6 in Chapter 2 for the definition of the TRL categories *large prototype*, *demonstration*, *early adoption* and *mature*.

Three-quarters of what is needed to decarbonise the buildings sector could be achieved through the use of mature and early adoption technologies: further innovation would bring additional gains.

The accelerated deployment of clean energy and envelope technologies that are already available is the main driver of global CO_2 emissions reductions in buildings in the Sustainable Development Scenario. This acceleration depends on further innovation and the achievement of economies of scale. For instance, high efficiency heat pumps are mass produced today, mostly for use in new construction: economies of scale would broaden their market potential. Broad application of early adoption technologies can benefit technologies in the innovation pipeline by cutting cost of common components and boosting learning-by-doing. For example, while the heat pump market today is dominated by vapour compression technologies (TRL 10), there is room for innovation when it comes to systems efficiency, cold-

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climate condition operations, use of cold and heat sinks, self-consumption (in combination with flexible electricity tariffs) and grid balancing using algorithms and other digital tools.

For the technology potential in the buildings sector in the Sustainable Development Scenario to be realised, innovation is needed in the following areas:

- Deploy packaged multi-service clean energy solutions that deliver cost reductions and performance improvements by exploiting the synergies that a variety of technologies can provide. For example, the scaling up and upgrading of serial renovation models brings economies of scale for building renovations through standardisation (e.g. prefabrication) and digitalisation (e.g. optimisation using 3D scanners), and also brings down the cost of heating and cooling equipment through reduced component sizing and reduced labour costs, as proposed by *Energiesprong* (Energiesprong, 2020). In the Sustainable Development Scenario, around 4 billion square metres of floor space is renovated to near-zero energy level each year to 2070, the equivalent of the current floor area surface of France.
- Exploit synergies across various end uses to improve the efficiency and quality of the service provided to consumers. For instance, recovering waste heat from the compressors of reversible heat pumps operating in cooling mode for hot water production could boost energy efficiency by 40-60% (TRL 8-9). There is also potential for commercial projects that combine district heating and cooling systems in an integrated district energy network to raise efficiency by 30-50%, making it more economical to exploit geothermal and waste heat sources.
- Deploy high performance technologies tailored for local conditions. For example, cold-climate heat pumps (TRL 7-9) for very cold climates, and reversible heat pumps for heating, hot water, cooling (TRL 9) and evaporative cooling (standalone for hot and dry climates or coupled with a membrane or a desiccant for humidity control in hot and humid climates).
- Implement material efficiency measures to help support the decarbonisation of the steel and cement industries, where emissions abatement is particularly difficult and costly.

Further innovation could be supported by advanced planning tools, such as integrated building simulation and optimisation tools (TRL 6-7) that can improve the design of complex and integrated solutions for new and renovated buildings.

It is difficult to know exactly where further innovation might lead, but promising areas include:

- **Electrification** has much to offer, including through the deployment of active components into the structure of buildings. For instance, electrochromic

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windows (TRL 8) change their properties as an electric current passes through them to adjust heat gain depending on the needs of the building, while photovoltaic (PV) windows (TRL 8) enable the use of some glass surfaces to act as effective PV panels, thus breaking the maximum limit for decentralised PV generation determined by roof surface area.

- **Flexibility measures** can reduce the need for grid and networks investment in upgrades: examples include demand-side response measures, pre-heating, pre-cooling, energy storage, and power-to-heat and vehicle-to-home measures. In the Sustainable Development Scenario, the combination of heat pumps and building-based PV can boost onsite energy supply and progress towards 100% renewable heating and cooling.
- **Combined technologies** are likely to be important. For example the climate and comfort box (TRL 4) developed under Mission Innovation Challenge 7[17] on affordable heating and cooling aims to exploit synergies between a heat pump and a battery to enhance onsite (e.g. rooftop PV systems, solar thermal) or grid-scale renewable electricity consumption and reduce power demand when the grid is congested. More generally, the automated control of individual or aggregated loads in response to price signals is being demonstrated in i.e. the United States, European Union and China (TRL 7). The development of district heating and cooling micro-grids would also allow higher system efficiency, peak load management and renewable energy integration. Combined systems that include distributed electricity generation (e.g. solar PV) and battery storage are in the early stages of market adoption in many markets.

Box 3.2 Technologies to reduce electricity and refrigerant needs for cooling in the buildings sector

Given the projected surge in cooling demand, making this service more efficient and climate-friendly is essential to limit its impact on the energy system and the environment. Integrating advanced components such as reflective roofs and dynamic components into the fabric of buildings along with passive measures, integrated storage and renewables has the potential to reduce space cooling needs. Ranging from small individual air conditioning units to large central facilities, the majority of space cooling systems are based on vapour compression refrigeration cycles. Wider deployment of more efficient vapour compression technologies offers important

[17] Mission Innovation is a global initiative of 24 countries and the European Commission working to reinvigorate and accelerate global clean energy innovation with the objective to make clean energy widely affordable. Mission Innovation Challenge 7 aims to make low-carbon heating and cooling affordable for everyone.

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energy saving gains. These gains can be boosted through improved controls and by exploiting surplus renewable energy, for example with ice storage heat pump system. Other technologies for cooling are being researched and demonstrated.

Membrane heat pumps are a pre-commercial alternative to conventional electric air conditioners. The technology couples a membrane vacuum dehumidification system with a membrane-based indirect evaporative cooler and operates using a vacuum pump (Bukshaisha and Fronk, 2019). The coefficient of performance of membrane heat pumps could be up to twice as high as for conventional vapour compression systems during extremely hot days, as they are much less sensitive to external temperature. Membrane heat pumps have been successfully demonstrated in expected operating conditions (TRL 7).

Considerable R&D is being carried out to identify refrigerants that minimise or eliminate greenhouse gas emissions (e.g. R-32, R290, R744, HFO 1234ze), associated with the operation of space cooling technologies. Solid state cooling has emerged as a promising alternative to technologies using refrigerants. Solid state cooling technology exploits caloric effects – the reversible thermal response of a given material to the adiabatic variation of the intensity of an applied field – in selected materials (magneto-, electro-, elasto- and baro-caloric). The technology can operate in reverse mode and several prototypes are being tested in laboratories. In hot and humid climates, the combination of evaporative cooling or a desiccant with a membrane system that is able independently to cool and dehumidify air could dramatically change the basic principles of conventional air conditioners. Several experiments are underway aimed at improving evaporative cooler and desiccant performance, and they include experiments to test solutions that were finalists in the Global Cooling Prize (Global Cooling Prize, n.d.). These concepts, which promise to eliminate the need for refrigerants and make thermal control systems more energy efficient than vapour compression cycle technologies, are at the validation level or early prototype level (TRL 3-4).

Investment implications

The clean energy transition envisioned in the Sustainable Development Scenario requires around 10% more global energy-related investment in the supply side than does the Stated Policies Scenario. Cumulative capital expenditure in the energy sector (including end uses) totals around USD 31 trillion (or almost USD 610 billion per year on average) more than in the Stated Policies Scenario over the period 2019-70 (Figure 3.21). The increased use of electricity and low-carbon technologies for power generation are the largest contributors to this higher investment need,

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increasing investment needs in the power sector by around USD 39 trillion to 2070 (or almost USD 760 billion per year). At around USD 24 trillion, the lion's share of this cumulative additional investment is for renewable energy source (USD 475 billion additional per year on average), followed by additional investment in the upgrade and extension of electric grids (around USD 10 trillion), CCUS with coal, gas and bioenergy (USD 3.6 trillion), and electricity storage (USD 3.2 trillion). It is accompanied by additional cumulative investment of about USD 19 trillion to 2070 (around USD 370 billion per year) to make energy use in industry, transport and buildings more efficient and to facilitate the use of low-carbon fuels such as electricity and low-carbon hydrogen. The resulting increase in investment in power supply and end-use sectors in the Sustainable Development Scenario is partly offset by lower investment needs in fossil fuel extraction and fuel transformation. Investments in fossil fuel supply are on aggregate USD 30 trillion (USD 595 billion per year) lower than in the Stated Policies Scenario due to lower demand. On the other hand, additional investment of USD 2.5 trillion through to 2070 (USD 48 billion per year) is needed for hydrogen and hydrogen-based fuels, as well as almost USD 915 billion for biofuels production.

On the demand side, additional investment in the Sustainable Development Scenario in more efficient and low-carbon technologies increases rapidly to around USD 550 billion per year by 2050, after which it goes into decline. In the buildings sector, significant investment is required over the next couple of decades to improve insulation. This investment extends the lifetime of the buildings stock relative to the Stated Policies Scenario and thereby reduces investment needs in buildings in the long-run, which in turn reduces overall demand for cement. In the transport sector, policies to reduce travel (e.g. through more teleworking) and increase the use of public transport reduce the need to invest in road vehicles in the long-run, leading to lower expenditure by individual consumers. Similarly, lower projected growth in air travel demand in the Sustainable Development Scenario compared to the Stated Policies Scenario offsets larger investments in energy efficiency measures in aircraft. In contrast, maritime shipping requires about USD 6 trillion of additional investment through to 2070 to meet the costs of a shift to low-carbon fuels such as ammonia and hydrogen, together with energy efficiency measures. Additional investment in transport infrastructure of about USD 21 trillion is needed across the board through to 2070, in particular for railways.

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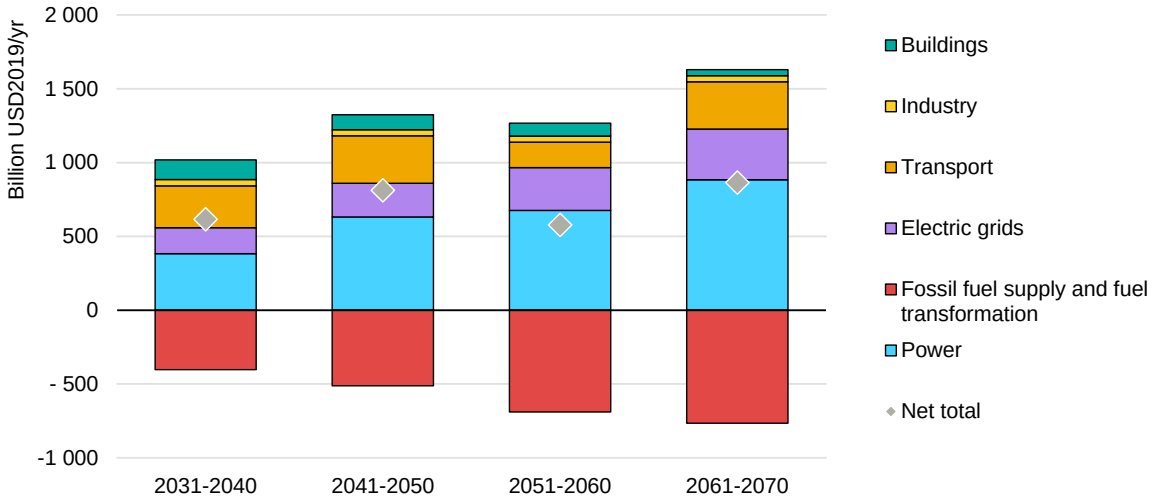
Figure 3.21 Change in average annual energy-related investment by sector and decade in the Sustainable Development Scenario relative to the Stated Policies Scenario



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Notes: Building sector investment includes only energy efficiency measures. Transport sector investment includes for vehicles the costs for the powertrain, but not the rest of the vehicles, also referred to as gliders (see ETP Model documentation for more information on investment accounting boundaries).

Achieving net-zero emissions in the Sustainable Development Scenario requires an additional annual average investment of USD 610 billion through to 2070, which is around 10% more than in the Stated Policies Scenario.

Reaching net-zero emissions by around 2070 in the Sustainable Development Scenario requires the development and large-scale deployment of technologies that are not commercially available today, particularly in heavy industry and long-distance transport. Technologies that are mature today or are at an early stage of adoption account for nearly 90% of overall investment during the 2030s in the Sustainable Development Scenario (Figure 3.22). While investment in such technologies continues to be needed, investment in new technologies becomes increasingly important over time. In the 2060s, nearly USD 4 trillion/year – almost half of total annual average investments – is spent on technologies that are at demonstration or prototype stage today. This is around 60% more than in the Stated Policies Scenario. The increase in average annual investments associated with heavy industries and long-distance transport is particularly large. The need for innovation in existing technologies and for the rapid development and deployment of new technologies underlines the importance of increased investment in R&D (see Chapter 6).

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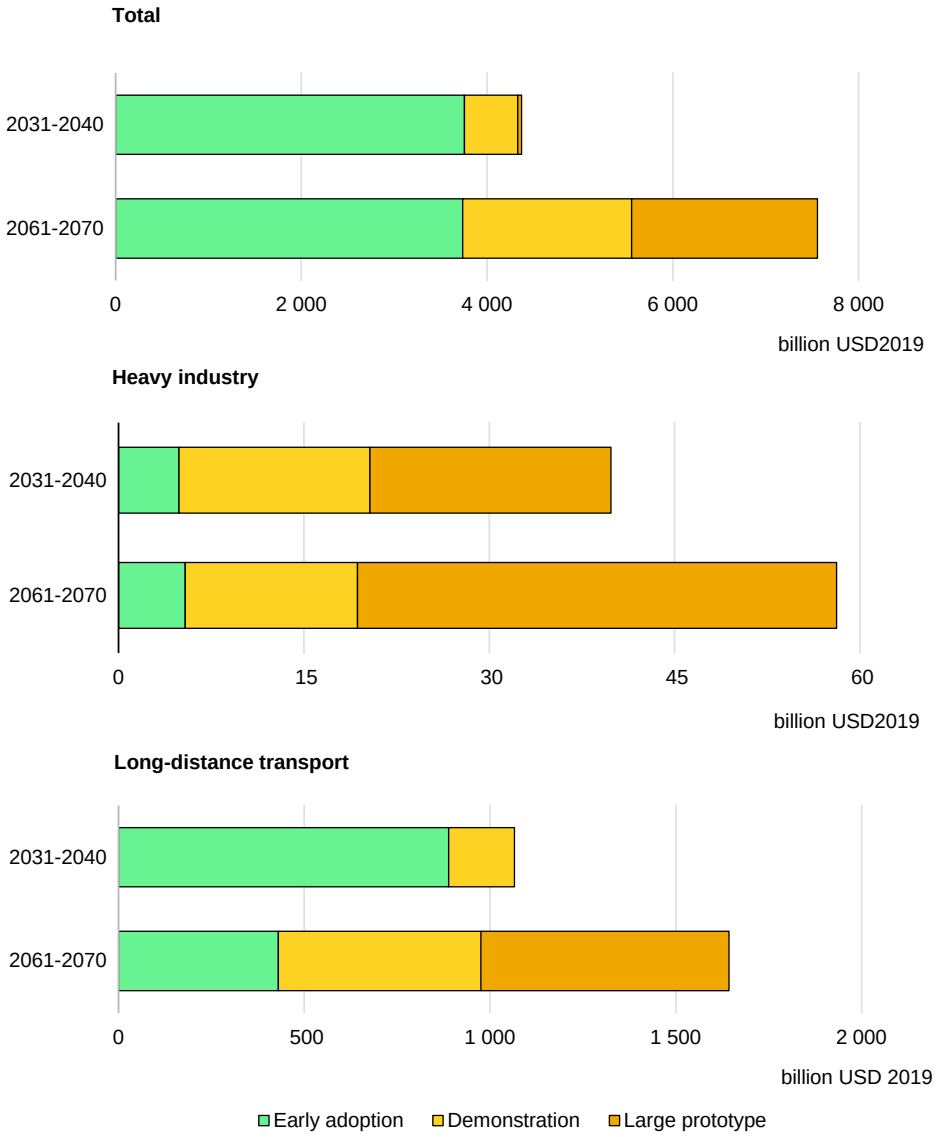
Figure 3.22 Average annual investment in technologies by technology readiness level in the Sustainable Development Scenario



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Notes: Annual investments displayed here exclude those related to mature technologies. The three broad technology readiness level categories refer to the status of technology types today.

Investment in technologies that are today at demonstration or prototype stage becomes increasingly important in the Sustainable Development Scenario, especially in areas where emissions are hard to abate.

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References

Air Products (2020), Air products, ACWA Power and NEOM sign agreement for $5 billion production facility in NEOM powered by renewable energy for production and export of green hydrogen to global markets (press release), 7 July 2020, www.airproducts.com/Company/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market.aspx.

Biocat (2015), BIOCAT Project visits Audi e-gas plant in Werlte (press release), 23 February 2015, biocat-project.com/news/biocat-project-visits-audi-e-gas-plant-in-werlte/.

Borealis (2019), Petrochemical companies form Cracker of the Future Consortium and sign R&D agreement (press release), 26 August 2019, www.borealisgroup.com/news/petrochemical-giants-form-consortium-cracker-of-the-future-and-sign-agreement.

Bukshaisha, A. and B. Fronk (2019), Simulation of membrane heat pump system performance for space cooling, International Journal of Refrigeration Vol. 99, March 2019, pp.371-381, doi.org/10.1016/j.ijrefrig.2018.12.010.

Cementa (2019), Cementa and Vattenfall take the next step towards a climate neutral cement (press release), 30 January 2019, www.cementa.se/sites/default/files/assets/document/d3/3a/20190130-cementa_and_vattenfall_take_the_next_step_towards_a_climate_neutral_cement.pdf.

Chugoku Electric Power Company (2018), Test Results of the ammonia mixed combustion at Mizushima power station unit No.2 and related patent application (presentation), 2018 AICHe Annual Meeting, 31 October 2018, nh3fuelassociation.org/wp-content/uploads/2018/12/1530-Chugoku-Electric-Power-Co.pdf.

Elysis (2018), Rio Tinto and Alcoa announce world's first carbon-free aluminium smelting process (press release), 10 May 2018, www.elysis.com/en/rio-tinto-and-alcoa-announce-worlds-first-carbon-free-aluminium-smelting-process.

Energia Potior (2020), EnPot-TRIMET Essen 120 cell installation (web page), www.energiapotior.com/trial-results.

Energiesprong (2020), Energiesprong, energiesprong.org/, (accessed August 2020).

GFEI (Global Fuel Economy Initiative) 2019, "Prospects for fuel efficiency, electrification and fleet decarbonisation" (working paper 20), www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf.

Global Cooling Prize (n.d.), Cooling for all, without warming the planet (website), globalcoolingprize.org/, (accessed August 2020).

H21 (2020), H21 Pioneering a UK hydrogen network... (web page), www.h21.green/.

H2V59 (2020), H2V59 tout savoir sur le projet (H2V59 all about the project) (web page), h2v59-concertation.net/.

IEA (International Energy Agency) (2020a), Outlook for biogas and biomethane: Prospects for organic growth, IEA, Paris, www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth.

IEA (2020b), Clean Energy Innovation, IEA, Paris, www.iea.org/reports/clean-energy-innovation.

IEA (2020c), Global EV Outlook 2020, IEA, Paris, www.iea.org/reports/global-ev-outlook-2020.

IEA. All rights reserved.

IEA (2020d), World Energy Balances (2020 edition), www.iea.org/data-and-statistics/.

IEA (2019a), The Future of Hydrogen, IEA, Paris, www.iea.org/reports/the-future-of-hydrogen.

IEA (2019b), The Future of Rail, IEA, Paris, www.iea.org/reports/the-future-of-rail.

IEA (2017a), Digitalization and Energy, IEA, Paris, www.iea.org/reports/digitalisation-and-energy.

IEA (2017b), The Future of Trucks, IEA, Paris, www.iea.org/reports/the-future-of-trucks.

Lancaster Guardian (2019), Hydrogen gas energy plant plan revealed for Heysham Power Stations (press release), 29 August 2019, www.lancasterguardian.co.uk/news/politics/hydrogen-gas-energy-plant-plan-revealed-heysham-power-stations-657231.

NEDO (New Energy and Industrial Technology Development Organization) (2020), The world's largest-class hydrogen production, Fukushima Hydrogen Energy Research Field (FH2R) now is completed at Namie town in Fukushima (press release), 7 March 2020, www.nedo.go.jp/english/news/AA5en_100422.html.

Nordic Energy Research (2020), Tracking Nordic Clean Energy Progress, www.nordicenergy.org/wp-content/uploads/2020/04/Tracking-Nordic-Clean-Energy-Progress-2020.pdf.

Norsk-e Fuel (2020), Norsk-e Fuel (webpage), https://www.norsk-e-fuel.com/en/, (accessed 30 July 2020).

Øye, B. (2019), Could the chloride process replace the Hall-Héroult process in aluminium production?, blog.sintef.com/sintefenergy/energy-efficiency/could-the-chloride-process-replace-the-hall-heroult-process-in-aluminium-production.

Power Magazine (2019), Exelon Is exploring nuclear power plant hydrogen production (press release), hwww.powermag.com/exelon-is-exploring-nuclear-power-plant-hydrogen-production/, (accessed 29 August 2019).

Ramboll (2019), Ancillary services from new technologies: Technical potentials and market integration, energinet.dk/-/media/229625DCEA984813BF322090E7926844.pdf.

US-DOE (US Department of Energy) (2018), "Energy Department announces up to $3.5m for nuclear-compatible hydrogen production", www.energy.gov/eere/articles/energy-department-announces-35m-nuclear-compatible-hydrogen-production#:~:text=Today%2C%20the%20Energy%20Department%20(DOE,compatible%20with%20nuclear%20energy%20sources.

US DOE (2007), US energy requirements for aluminium production, www1.eere.energy.gov/manufacturing/resources/aluminum/pdfs/al_theoretical.pdf.

VoltaChem (2020), Electric cracking (web page), www.voltachem.com/projects/electric-cracking.

Yara (2020), Yara Birkeland Project Paused Due to COVID-19, www.marinelink.com/news/yara-birkeland-project-paused-due-covid-478386

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Chapter 4. Technology needs for heavy industries

- The materials produced by industry play a critical role in our daily lives. They include steel for vehicles, petrochemicals for gloves and masks used in hospitals, cement for buildings we live and work in, among many other uses.
- Three heavy industries – chemicals, steel and cement – account for over half of industrial energy use and around 70% of direct CO_2 emissions from industry. In the Sustainable Development Scenario, heavy industry emissions fall 90% by 2070, with the remaining 600 $MtCO_2$ offset by carbon removal technologies.
- Various factors make it difficult to reach zero emissions in heavy industries. Today, most technologies that drastically reduce emissions are at an early stage of development. This includes technologies for providing large amounts of high-temperature heat, which in many cases cannot be provided by electricity using commercial technologies, and for reducing process emissions from chemical reactions inherent to current industrial feedstocks.
- Industry also requires expensive and long-lived equipment – blast furnaces and cement kilns typically operate for around 40 years – and this slows deployment of low-emission technologies. Moreover, many industrial materials are highly price-sensitive due to being traded in highly competitive global markets.
- Technology performance improvements and material efficiency together contribute the most to emissions reductions in heavy industry in the near term. Adopting the best available technologies yields gains in technology performance, while improving manufacturing yields, light-weighting and other material efficiency measures reduce growth in demand for materials.
- The buildings construction sector, which accounts for around 50% of demand for cement and 30% for steel, plays a key role in reduced material demand through buildings lifetime extensions and new building designs.
- In the long term, low-CO_2 processes that are not commercially available today account for around two-thirds of the total output of the three heavy industry sectors in the Sustainable Development Scenario. Carbon capture utilisation and storage (CCUS) and electrolytic hydrogen play leading roles, with an average of about 75 plants incorporating CCUS and 20 plants incorporating low-carbon hydrogen being added each year from 2030.
- Despite these extensive changes, the impact on end-use consumers is expected to be small – the cost increase for steel would raise the price of a car by only about 0.2% and that for cement would raise the price of a house by only about 0.6%.

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Introduction

Reducing CO_2 emissions from heavy industries – in particular the chemicals, steel and cement sectors – is far from straightforward, with many of the technologies that we are likely to rely upon for decoupling emissions from bulk material production in the future still at early phases of development. Exploiting these technology opportunities, in conjunction with demand-side mitigation strategies, will be crucial to meeting sustainability goals. This chapter explores these challenges and the opportunities available for achieving deep emissions reductions in heavy industry, with a focus on chemical, steel and cement production.

The outlook for heavy industry in the wake of Covid-19

Our daily lives would be unimaginable without the materials and goods produced in the industry sector. We need them for the buildings we live and work in, the vehicles and transportation infrastructure that keep us mobile, and much more besides. Economic and population growth are key drivers of demand for materials and manufactured goods, the production of which is, in turn, a key driver of industrial energy consumption and emissions.

The industry sector consumed around 3 900 million tonnes of oil equivalent (Mtoe) of energy in 2019, accounting for just over one-quarter of total primary energy demand.[1] Industry is currently highly reliant on fossil fuels, which account for nearly 70% of the energy supplied to the sector. Of this fossil fuel consumption, coal accounts for a little over 40% and oil and natural gas each account for a little under 30%. Electricity accounts for much of the remainder, with small amounts of bioenergy also being used in specific sectors.

Direct industrial emissions amounted to about 9 gigatonnes of carbon dioxide ($GtCO_2$) in 2019, or just over a quarter of the total attributable to the energy system, and slightly more than the direct emissions of the entire transport sector (about 8 $GtCO_2$).[2] About a quarter of industry sector emissions are process emissions that result from chemical reactions inherent to industrial production processes for certain materials, among which the biggest contributor is clinker production for cement. Indirect emissions resulting from power and heat generation for use in the industrial sector account for a further 7 $GtCO_2$.

[1] Throughout, industrial energy consumption includes the IEA Energy Balance boundaries of total final consumption by industry, non-energy use for chemical feedstock, and energy used in blast furnaces and coke ovens.

[2] Direct industrial emissions includes CO_2 emissions from fossil fuel combustion corresponding to the energy use boundary described above, along with CO_2 emissions from industrial processes within these sub-sectors. CO_2 emissions from non-renewable waste, indirect emissions from electricity generation and process emissions from fuel transformation are not included within this definition, nor are non-CO_2 greenhouse gases.

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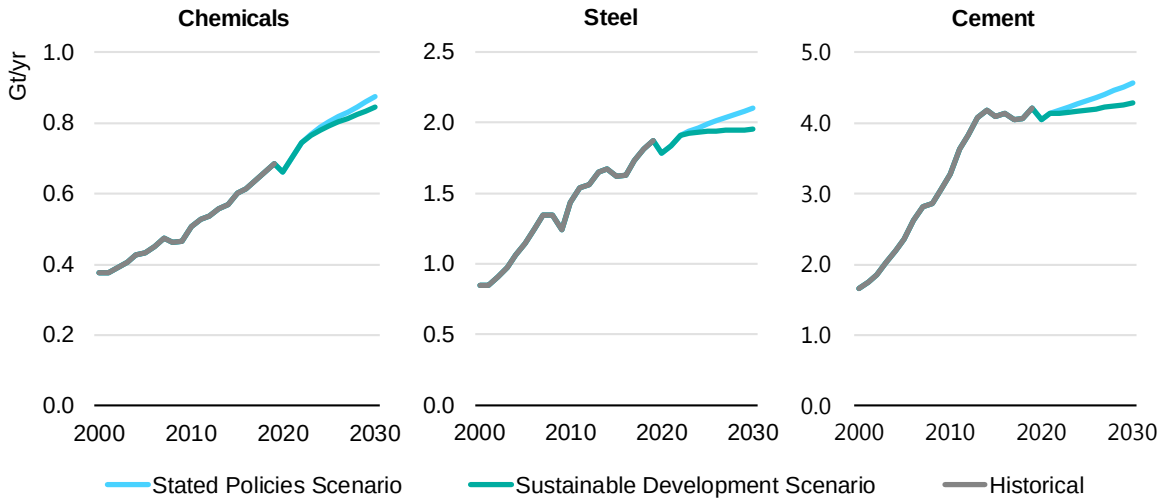
Figure 4.1 Production growth in key heavy industries, 2000-30



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Note: Chemicals includes the primary chemicals ethylene, propylene, and benzene, toluene, mixed xylenes, ammonia and methanol as an aggregate proxy for sector activity growth.

The Covid-19 pandemic is projected to interrupt production in heavy industries temporarily before growth resumes. Material efficiency is the key to permanently bending the curve.

Over the past two decades, as the global population has grown by 25% and global GDP has doubled, demand for key bulk materials like chemicals, steel and cement has grown by 80% to 150% (depending on the material [Figure 4.1]). During this period, some progress has been made in lowering the energy and emissions intensities of production, driven mainly by the commercial incentive to reduce costly energy inputs in what are highly competitive industries, and by government policies promoting energy efficiency. Nonetheless, this progress has been outweighed by increases in material demand, with the result that industrial energy use and CO_2 emissions have risen by 60% and 70% respectively since 2000.[3] While the industry sector is enormously complex, three energy-intensive "heavy" industries – chemicals, steel and cement[4] – deserve particular scrutiny, as they account for around 60% of the sector's energy use and 70% of its emissions.

[3] Demand growth over the period has been higher in a number of heavy industries relative to the less energy-intensive industry sub-sectors. This structural change explains why emissions have grown at a somewhat higher rate than energy consumption, and also is a major contributor to total industry emissions and energy consumption growth (60-70%) being less than demand growth for key bulk materials (80-150%); improvements in energy and emissions intensities are a smaller contributor to the difference.

[4] These sector names are used for brevity. They correspond to the IEA Energy Balance sectoral boundaries as follows: "chemicals" refers to the chemical and petrochemical sector, including non-energy use for chemical feedstock; "steel" refers to the iron and steel sector, including energy use in blast furnaces and coke ovens; "cement" refers to a portion of the non-metallic minerals sector. Throughout, "heavy industry" and "heavy industries" refer to these three sectors.

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The Covid-19 crisis led to a temporary decline in industrial energy consumption and emissions of around 5%, mainly due to reduced demand for key bulk materials. In the first half of 2020, demand was lower compared to the first half of the previous year by about 6% for cement, 5% for steel and 2% for chemicals.[5] Recovery is already clearly underway in the People's Republic of China ("China" hereafter), the world's largest industrial producer of many materials. As one of the first countries to implement and then subsequently lift lockdowns, industrial activity in China was hardest hit in February, and by April-May had already recovered to levels of activity higher than the same months the previous year (Bloomberg, 2020). This recovery was largely driven by government-funded infrastructure projects, such as railways, and by re-emerging demand for manufactured products like cars and electronics that had been suppressed during lockdowns (Qiu and Woo, 2020). In many other key economies, industrial production continued to decline in the second-quarter.

While material production has resumed in China, the country may struggle to maintain the rise in industrial output if domestic demand and demand for exports from other countries do not also return to growth. In the first four months of 2020, most countries experienced a 10-20% slowdown in construction activity (Eurostat, 2020; NBS, 2020b; United States Census Bureau, 2020). Trends from May to July 2020, however, seem to highlight a rebound in construction activity. As a result, global demand for bulk materials in 2020 is likely to be 3-5% lower than in 2019.

The pace at which the construction industry will recover will depend on a number of factors, including what policies are in place. Infrastructure and real estate measures feature in many stimulus packages because they are labour-intensive and can yield long-term economic value. This offers an opportunity to boost material efficiency and sustainability in construction. The circular economy is a major pillar of the European Union's recovery strategy in particular, encompassing construction waste management, the promotion of bio-based products, lifetime extension through enhanced product durability, as well as a doubling of renovation rates (EC, 2020). In the Sustainable Development Scenario, material efficiency contributes around a third of the cumulative reduction in global emissions related to cement and steel use in buildings construction compared with the Stated Policies Scenario. Policies and recovery packages that incentivise action in this area can contribute to progress towards long-term decarbonisation pledges.

The immediate future for the industry sector is highly uncertain, as it is for the energy system as a whole. The speed of industrial recovery depends on a number of factors, including whether additional lockdowns are required. Our projections are based on the assumption that industrial production resumes its global growth trajectory in

[5] The value for cement is an estimate based on various sources for national production including National Bureau of Statistics of China (2020a), FXEmpire (2020), USGS (2020), TCMA (2020) and Global Cement (2020). The value for steel is from World Steel Association (2020). The value for chemicals uses ethylene as a proxy, based on Platts (2020).

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2021, recovering to pre-crisis growth rates shortly afterwards, as occurred following the 2008 financial crisis. Bending the demand curve in the medium to long term, without reducing the quantity and quality of material services provided by the industry sector, will require active efforts to improve the efficiency with which materials are used and products are manufactured. However, even with significant progress on material efficiency, vast quantities of materials will still be required to support growing populations and economic prosperity, especially in the developing world. This means that deep reductions in industrial CO_2 emissions will ultimately require the decoupling of emissions from material production output, and new technologies have an essential role to play in making this happen.

Why are emissions from heavy industry "hard to abate"?

The overarching reason for designating emissions from certain sectors as "hard to abate" is the lack of maturity of the technologies that are likely to be relied upon to mitigate their emissions. While solar PV and electric cars are in use today in many markets, the same cannot be said for many technologies that will be required to achieve deep reductions in emissions in heavy industry (see also Chapter 5 on long-distance transport). For the industry sector, the specific factors that make emissions hard to abate include:

- **High-temperature heat requirements:** Heavy industry requires high-temperature heat for many of its processes, which today is almost exclusively provided by burning fossil fuels. Generating high-temperature heat from electricity, especially on a large scale and for electrically non-conductive applications, is impractical and costly with today's commercial technologies, and constraints on the availability of sustainable biomass limit its use as a substitute. Carbon capture, utilisation and storage (CCUS) and hydrogen technologies offer means to provide high-temperature heat while eliminating most emissions, but industrial applications of these technologies are in most cases still at early stages of development.
- **Process emissions:** Several industrial processes result in emissions from chemical reactions that are inherent to today's production processes. A key example is the CO_2 that results from the calcination reaction that is necessary to produce clinker, the active ingredient in cement. Preventing these and several other sources of process emissions requires CCUS, or fundamental shifts away from conventional production processes to methods involving different raw materials.
- **Long-lived capital assets:** Industrial plants tend to have long lifetimes; typically 30-40 years for plants in heavy industries. Retiring them early to switch to alternative technologies would incur very large costs. As such, emissions from

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recently built plants can be considered "locked-in" unless options are available to retrofit or adapt them to reduce their emissions intensity.

- **Trade considerations:** Many industrial products are traded in highly competitive global markets (e.g. steel, aluminium). This makes it challenging for an individual producer or region to turn to more expensive production pathways in order to reduce emissions without being undercut on price. Thin profit margins also make it challenging to fund the large upfront investments that are likely to be required for near-zero emission technologies.

The Covid-19 crisis has the potential to exacerbate these challenges. Given the long lifetime of industrial assets, investment decisions today will determine emissions levels for decades to come. At a time when attention is focused on keeping companies financially buoyant, there is a risk that the urgent (short-term financial stability) could overshadow the important (developing and deploying near-zero emissions technologies).

Pilot and demonstration projects for the innovative technologies that are required for achieving deep emission reductions in industry – many of which involve CCUS and hydrogen – could be at risk. Long delays to even a small number of these projects, or their cancellation, could prevent the technologies from reaching commercialisation in the next 5-15 years, imperilling the industry sector's necessary contribution to reaching net-zero emissions at the broader energy system level. However, it does not have to be like this. The Covid-19 recovery packages being developed by governments across the world present an opportunity to chart a new path for the industry sector based on a strong and co-ordinated policy response that prioritises clean technologies (Box 4.1).

Box 4.1 Accelerating progress in the wake of the Covid-19 crisis: The role of governments in supporting the transition in heavy industry

It is hard to see how the challenge of achieving deep emissions reductions in industry can be overcome without a multi-faceted policy response and collaboration between multiple stakeholders. While many components of the policy response that is needed are the same as or similar to those required for other sectors (see Chapter 7), some are unique, reflecting the specific nature of the challenges faced by industry.

The current Covid-19 crisis should not be a reason to halt progress in reducing emissions in the short term, nor should it reduce momentum in achieving long-term goals. Recovery packages present an opportunity to hasten progress: direct support can help maintain or create jobs, while being made contingent upon reducing emissions from production processes. Key targets for stimulus include: incentives for

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energy efficiency; improving material recycling systems; and strengthening progress in developing and demonstrating innovative clean technologies (IEA, 2020).

A policy framework for achieving deep emissions reductions in industry

Component	Examples	Importance for industry
1. Long-term emissions reductions planning and policy	Roadmaps and plans, legislated carbon pricing and tradeable emissions standards	Provides confidence for low-emission investments and innovations, helps low-emission options compete in markets
2. Management of existing and near-term assets	Requirements for retrofit-ready facilities, sunset clauses	Reduces or avoids potential for long-term lock-in of emissions-intensive assets
3. Market creation for clean technologies	Contracts for difference, minimum content regulations, low interest loans	Helps low-emission options compete in globally competitive markets
4. Development of early-stage technologies	R&D and demonstration funding, public-private partnerships, innovation co-ordination	Brings forward options to provide low-emission high-temperature heat and address process emissions
5. Acceleration of material efficiency	Improved scrap collection and sorting networks, design regulations that optimise lifecycle emissions	Maximises secondary production potential, alleviates pressure on low emissions technology deployment
6. International co-operation and a level playing field	Sectoral agreements, carbon border adjustments, technology transfer	Helps alleviate competitiveness concerns in globally competitive markets
7. Infrastructure planning and development	Co-ordination and finance for CO_2 transport and storage, decarbonised electricity, low-carbon hydrogen	Facilitates options to provide high-temperature heat with low emissions and to address process emissions
8. Tracking progress and improved data	Increased data collection, sustainability labelling, sustainable investment classifications	Helps track progress, identify best practices, directs finance towards low-emission options

A longer-term policy framework for clean energy transitions for industry should include the eight key components set out in the table above. All of these are necessary, and each reinforces the others, but it is worth drawing particular attention to the importance of long-term, predictable and credible policies in the light of the long lifetimes of many industry assets. International co-operation, in light of the global and competitive marketplaces in which most industries operate, is also paramount.

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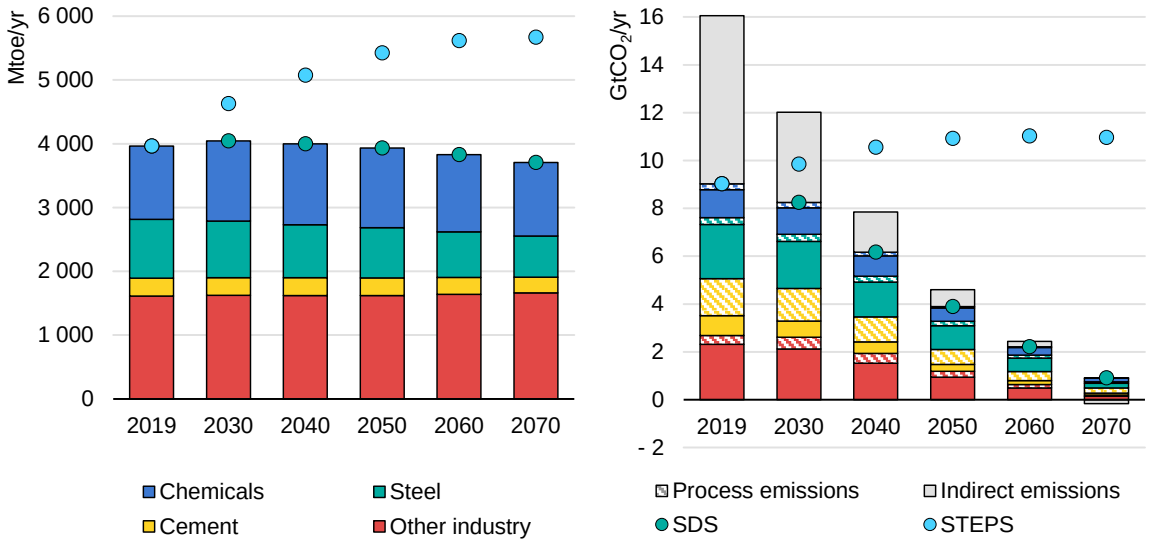
Industry in a net-zero emissions energy system

Due to the limited availability of commercial and scalable alternative production pathways, and the high costs and long lifetimes of existing facilities, reaching zero CO_2 emissions from heavy industry is expected to take somewhat longer than in other industries, and most other sectors. Nonetheless, industry makes strong progress in the Sustainable Development Scenario, with both the industry sector as a whole and heavy industry in particular reducing emissions by around 90% in 2070 compared to current levels (Figure 4.2).

Figure 4.2 Global industrial energy consumption and CO_2 emissions in the Sustainable Development Scenario, 2019-70



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. Industrial energy consumption includes total final consumption in industry, energy consumed by blast furnaces and coke ovens (iron and steel), and non-energy use (of which petrochemical feedstock is included within chemicals). Direct industrial emissions include energy-related emissions and industrial process emissions and those stemming from the transformation of fuels in coke ovens and blast furnaces. Indirect emissions are approximated based on the regional average grid intensity of imported electricity and heat, except for a portion of the electricity and heat consumed in the iron and steel sector, where the first choice of fuel for electricity is assumed to be coke oven gas and blast furnace gas. Markers on the right-hand graph correspond to the total direct CO_2 emissions from industry in each scenario.

While energy demand remains relatively flat in the Sustainable Development Scenario, steps taken to tackle CO_2 emissions result in a 90% reduction in direct emissions by 2070.

Despite increasing demand for industrial products, total energy demand in the Sustainable Development Scenario remains relatively flat in industry overall through to 2070, with a modest decline in heavy industry. The fuel mix, however, shifts considerably, with the share of fossil fuels in heavy industry declining from around 85% in 2019 to around 55% in 2070, and with commensurate increases in the share of electricity, including electricity for hydrogen production, and bioenergy. Fossil

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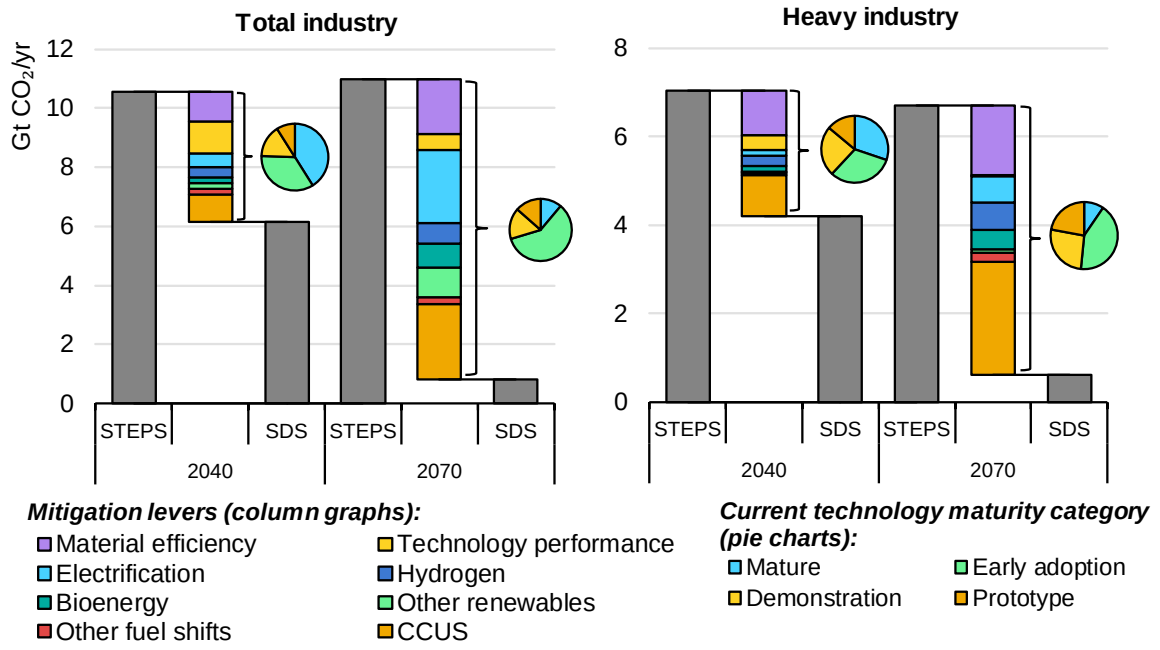
fuels continue to play an important role in 2070, but most of their use is coupled with CCUS. Of the residual heavy industry emissions in 2070, about 45% are process emissions, which come mostly from the cement sector, and 40% are emissions from coal, which come mostly from the steel sector. The residual emissions from these and other hard-to-abate sectors, in particular long-distance transport (see Chapter 5), are offset at the global level by carbon removal technologies in other sectors (primarily bioenergy with carbon capture and storage [BECCS] in power and heat generation), which are expected to prove cheaper than "last-mile" efforts to eradicate emissions entirely in the hard-to-abate sectors (see Chapter 2).

Figure 4.3 The technology portfolio for reducing direct industrial CO_2 emissions, 2040 and 2070



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

An array of strategies is required to reduce industrial CO_2 emissions, with innovative technologies like CCUS and hydrogen playing a large role, particularly in the longer term and in heavy industry.

A variety of measures are required to achieve deep emissions reductions in industry (Figure 4.3). Technologies that are already mature or in the early adoption phase play an important role. They deliver savings from technology performance improvements, material efficiency gains, switching to bioenergy, and the electrification of low- and medium-temperature heat. These savings are particularly important in the short term, but continue to play a role through to 2070. A particularly large contribution is made

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to the gains from material efficiency by the construction sector (including buildings and infrastructure), which currently accounts for about half of all demand for steel and all of the demand for cement. In the longer term, fundamental technology shifts are needed, and technologies currently at the demonstration and prototype stage play an integral role in these shifts. This is especially the case in heavy industry, where these technologies account for nearly half of the emissions reductions in 2070 relative to the Stated Policies Scenario. Innovative technologies incorporating CCUS and hydrogen – which are not yet commercially available – are key.

The remainder of this chapter provides a detailed assessment of the opportunities for emissions reductions in key heavy industry sectors – chemicals, steel and cement. It concludes with a discussion of opportunities to make more efficient use of these materials in the construction sector, which is one of the key end-use consuming sectors for heavy industry products.

Chemical production

Sector overview and demand outlook

The chemical sector, which directly contributes more than 1% of the world's GDP (Oxford Economics, 2019), is the largest industrial consumer of energy worldwide, accounting for 30% of total industrial energy use. Because around half of its energy inputs are used for feedstock (raw materials), which means that a large proportion of the carbon in the energy inputs ends up in the final product rather than being burned or otherwise emitted during the production process, the sector produces fewer CO_2 emissions than the steel and cement sectors do: it accounts for 16% of total direct industrial emissions.[6] Because oil and natural gas are the primary feedstocks for producing chemicals, with coal also being used to a lesser extent, the share of hydrocarbons in the overall sector's energy use is very high, at 85%. Chemical production accounts for around 14% of global oil demand (14 million barrels per day) and around 9% of global gas demand (315 billion cubic metres).

The chemical sector produces hundreds of thousands of different products, from plastics and fertilisers to pharmaceuticals and explosives. The energy intensity of production varies considerably from product to product. It is particularly energy-intensive to produce primary chemicals, which include ammonia, methanol, ethylene, propylene, benzene, toluene and mixed xylenes (the latter five are grouped

[6] Process emissions make up around 0.2 $GtCO_2$ of total chemical sector emissions of around 1.4 $GtCO_2$. These emissions occur when the amount of carbon present in the feedstock is higher than that required in the product. The most extreme example is ammonia, (which contains no carbon) produced using coal (which is 60-80% carbon by weight). This is widespread in China, as is coal-based methanol production, which contains a small share of carbon. Coal-based chemicals production is rare elsewhere.

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together as "high-value chemicals", while the latter three are known as BTX aromatics). Primary chemicals account for around two-thirds of the chemical sector's total energy consumption and the vast majority of its feedstock needs. In some cases, energy and feedstock account for as much as 90% of total primary chemical production costs, including capital expenditure.

Primary chemicals are subsequently transformed through various processes into final chemical products, including plastics, synthetic fibres, fertilisers, paints, additives and solvents. These processes tend to use comparatively less energy. The other main chemicals categories – speciality and fine chemicals, pharmaceuticals and consumer chemicals – generally require much less energy to produce, but rely for their starting materials on the production of energy-intensive upstream pre-cursors. Demand for some kinds of chemicals is growing relatively fast (3-4% per year for various plastics resins), whereas demand for others is growing more slowly (around 1% per year for ammonia).

Chemical production facilities are less geographically concentrated than those in the cement and steel sectors, with China accounting for around 20% of high-value chemical capacity, as opposed to around half of all capacity for cement and steel (see Chapter 1). In recent years, additions to primary chemical production capacity have been concentrated in the United States, the Middle East and China, and this is set to continue in the coming years. The shale revolution drove expansion of US production, which had previously been stagnating, and led to soaring output of ethane – a primary component of natural gas liquids and the second-most important feedstock for the chemicals industry globally after naphtha. Low feedstock costs have also underpinned expansions in the Middle East, notably in Iran and Saudi Arabia. However, the Covid-19 crisis, together with overcapacity in several regions, is likely slow expansions in the coming years.

CO_2 emissions are considered hard-to-abate in the chemical industry for three key reasons:

- **High temperature needs for non-conductive materials:** A steam cracker (a basic unit for producing ethylene, propylene and BTX aromatics, which are the building blocks of most chemicals) and other large units operate at temperatures close to 1 000°C. It is impractical and expensive to generate this amount of heat from electricity using current technologies, and research efforts aimed at lowering the costs of electrification are at a relatively early stage of development, while constraints on sustainable biomass availability limit its application in the sector. Other technologies like fossil fuels with CCUS and hydrogen-based production are still at pre-commercial stages.
- **Long-lived capital assets:** Upstream units such as steam crackers are very large, expensive to build and typically operated for around 30 years (some in Europe

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and the United States are much older). Retiring them early is possible, but would incur huge cost penalties, given the enormous investments required to construct them (a large cracker costs around USD 4 billion).

- **Trade considerations:** The markets for bulk chemicals and their derivatives, many of which can be transported economically over long distances, are international and highly competitive, which makes it difficult for producing countries to introduce any climate measure that raises costs without hurting its exports, unless all others agree to do the same. Measures such as carbon border adjustments could provide some protection, but would be politically challenging and controversial. Chemical supply chains are also highly complex and often span multiple countries, so measures in one jurisdiction could have a ripple effect across markets for feedstocks (inputs) and derivatives (outputs).
- **Fuels used as material inputs:** To eliminate emissions entirely from the chemical sector supply chain and its products, including during their use and disposal phases, all of the carbon and hydrogen required for feedstock would have to be sourced from a combination of CO_2 captured from the atmosphere and electrolytic hydrogen, recycled chemical products, and/or bioenergy. With current technologies and the limited projected availability of sustainable bioenergy, this constitutes an enormous long-term challenge.

The demand for chemicals is projected to grow in parallel with economic activity in the decades to come, as it has done historically, and this will require additional production capacity (Figure 4.4). To take just one example, the extensive use of fertilisers and agrochemicals to promote crop growth and provide protection against harmful organisms and pathogens is strongly linked to agricultural output, which will need to grow to meet the needs of a rising global population and increasing demand for food. This growth in total demand takes place even as measures are adopted to increase fertiliser application efficiency and reduce waste throughout the sustenance supply chain. In line with recent trends, and as with other industrial sectors, most of the growth in demand for these and other chemical products will come from emerging economies.

Despite the lull in demand brought about by the Covid-19 crisis, there are few signs yet of a sustained saturation in demand at the global level for plastics or other chemical products (e.g. rubber for tyres, polyester for clothing). Several chemical products, such as items of personal protective equipment, have actually seen a surge in demand during the crisis. The disposable mask market for example, is projected to grow from USD 800 million in 2019 to USD 166 billion in 2020 (The Economist, 2020). Nonetheless, there is growing interest in curbing the use of plastic for environmental reasons. Several countries have announced policies to phase out the unnecessary

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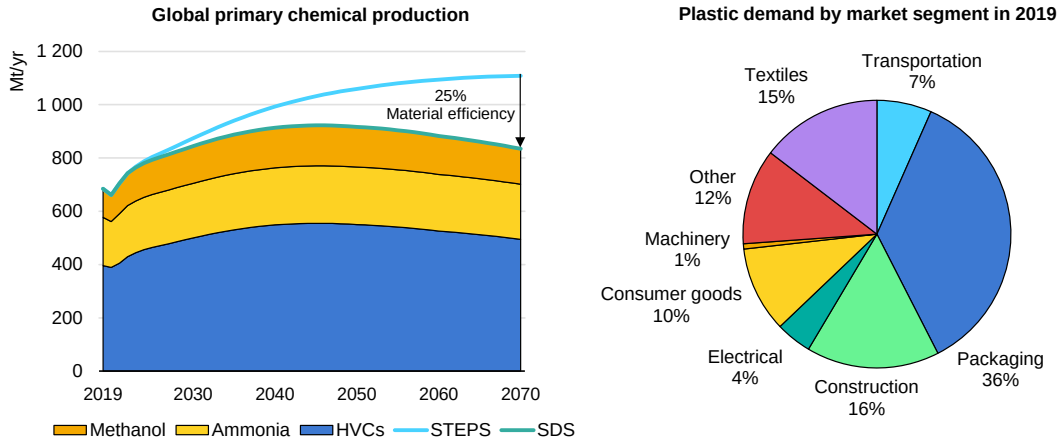
use of plastics, including single-use items like drinking straws and plastic bags, in response to their accumulation in the ocean and the grave consequences of this for human health and wildlife.

Whether and to what extent policies to phase out single-use plastics will have an impact on overall demand is uncertain, given the limited availability of affordable substitutes. Without effective and efficient packaging that today is often provided by plastics, waste in food and other supply chains would increase due to spoilage and damage to products during transit, thereby substituting one form of damage for another. Effective plastic waste management systems are needed, together with efforts to use plastics and other chemical-based materials more efficiently, and efforts to eliminate plastic from specific end uses. It is also important to keep in mind that packaging only makes up about one-third of demand for plastics, and that new uses of plastics, for example in textiles, are likely to continue contributing to increased demand.

Figure 4.4 Global primary chemical production by scenario and plastic demand by market segment, 2019-70



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Note: HVCs = high-value chemicals. STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario.
Source: Plastic demand by market segment based on Geyer, R., J.R. Jambeck and K.L. Law (2017).

Collection rates for key plastics more than triple in the Sustainable Development Scenario from today's levels. This and other material efficiency strategies reduce demand for primary chemicals by around 25% by 2070 relative to the Stated Policies Scenario.

Material efficiency can help to decouple virgin primary chemical production from GDP, and to limit growth in demand to some degree. An important aspect of material efficiency is the recycling and reuse of plastics. In the Sustainable Development Scenario, the rate of plastic waste collection more than triples by 2070, compared with today's levels, even as developing economies with low collection rates today dramatically increase their share of global plastic

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consumption. This increase is brought about by a strong policy push in the areas of sorting and collection at the local municipal level, and by incremental increases in the yield rates of commercial recycling processes.

Today, plastics are often "down-cycled", meaning that recycled plastic often cannot directly substitute for virgin plastic in several applications. In the Sustainable Development Scenario, there is a greater than twofold increase in the rate of secondary plastics providing direct substitutes for virgin resins by 2070, facilitated by enhanced collection and sorting practices, along with advances in plastic recycling technologies (such as chemical and feedstock recycling processes). The increase in collection rates and decrease in down-cycling rates results in around 180 Mt of primary chemical savings in 2070, relative to the Stated Policies Scenario. High-value chemicals account for over 90% of these savings, reflecting the fact that they play a bigger role in the supply chains of plastic materials than ammonia and methanol.

Demand for methanol (a chemical building block used mainly as an intermediate) peaks in the mid-2040s in the Sustainable Development Scenario, instead of growing continuously as it does in the Stated Policies Scenario. This divergence in trajectory arises partly because additional plastic recycling reduces the need for methanol production, but the main reason for this is the reduced use of liquid fuels in the transport sector in the Sustainable Development Scenario in modes where methanol and its derivatives are used as fuel additives. Fuel applications account for around one-third of the demand for methanol today, and are nearly phased out in the Sustainable Development Scenario (Levi and Cullen, 2018; Methanol Institute, 2019).

Because methanol contains carbon, and virtually all of it is derived from fossil fuel feedstock, it does not make sense on a life-cycle basis in the context of the Sustainable Development Scenario to displace gasoline or diesel in the transport sector with methanol derived from coal or gas. While methanol is produced on a large scale via electrolysis in the Sustainable Development Scenario, the limited availability of affordable biogenic or atmospheric CO_2 feedstock in the context of a decarbonising energy system raises the cost of methanol and makes it less attractive in substitutable applications. Another factor that plays a role in methanol demand peaking in the 2040s in the Sustainable Development Scenario is its declining share in the production of plastics via the methanol to olefins process which is deployed on a large scale today in China to open up the route to plastics produced from coal.

Ammonia production peaks in the late 2040s in the Sustainable Development Scenario, whereas it continues to grow slowly and steadily in the Stated Policies Scenario. As with methanol, plastic recycling plays a minor role in this peaking, but an increase in fertiliser application efficiency in the agriculture sector is the main

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driver. The combined impact of these strategies in the Sustainable Development Scenario is a reduction of around 17% in ammonia demand by 2070, relative to the Stated Policies Scenario. Sustainable farming practices, such as soil testing, precision application and enhanced monitoring, help to minimise the amount of synthetic fertiliser used per unit of food production in the Sustainable Development Scenario, while reductions in food waste (around one-third of food produced is wasted globally [FAO, 2011]) also help to reduce the quantities of fertiliser required to provide the same level of sustenance. Because of its zero-carbon and high hydrogen content, ammonia is increasingly used as an energy vector in the Sustainable Development Scenario: the ammonia used for this purpose is accounted for separately in the fuel transformation and transport sectors (see Chapters 3 and 5).

Another important point on the demand side for the chemical sector concerns urea. Urea is a carbon-containing fertiliser synthesised from ammonia and CO_2 (CO_2 is generally sourced from the concentrated emissions streams that arise in ammonia plants). Today more than half of the ammonia produced globally is converted to urea, with the remainder being used for a variety of nitrate-based fertilisers (containing no carbon atom) and various smaller volume industrial applications. When urea is applied to the soil in the agriculture sector, the CO_2 that was utilised to make it is released. In many cases, urea can be directly substituted by a nitrate-based fertiliser, although there are hurdles to overcome with respect to safety and security – ammonium nitrate is used to make explosives, and fertilisers that contain it are strictly controlled in several regions. In the Sustainable Development Scenario, urea demand increases initially, but then declines as nitrate-based fertilisers are used as substitutes where possible. By 2070, urea demand is around 40% of today's level, requiring around 135 Mt less CO_2 for feedstock than in the Stated Policies Scenario.

Technology pathways towards net-zero emissions

Because of the challenges involved in abating CO_2 emissions in the chemical sector described above, they are only eliminated worldwide after 2070 under the assumptions of the Sustainable Development Scenario, with residual emissions in 2070 being offset by negative emissions in the power and other energy transformation sectors. Total sector emissions nonetheless fall by about 90% from 1.4 $GtCO_2$ in 2019 to 0.2 $GtCO_2$ in 2070, with emissions intensity – the quantity of emissions incurred in producing 1 tonne (t) of output – also falling by 90% (Figure 4.5).

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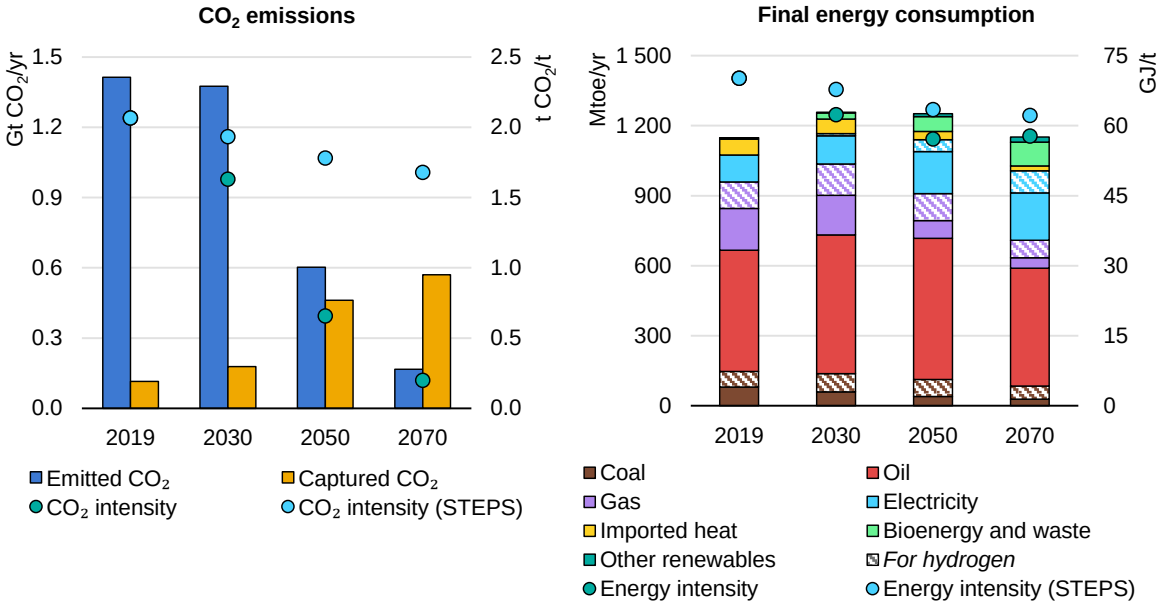
Figure 4.5 Global chemical sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70



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Notes: STEPS = Stated Policies Scenario. Captured CO_2 includes that which is captured then used as feedstock for urea production, as well as that which is captured and stored. Energy consumption includes that used as feedstock. Sectoral energy and CO_2 intensities are calculated based on total primary chemical production and total chemical sector energy consumption.

Emissions from the chemicals sector fall by around 90% between 2019 and 2070 in the Sustainable Development Scenario, thanks to material efficiency and technology performance improvements, increased use of bioenergy and electricity-derived hydrogen feedstock, and an extensive CCUS roll-out.

Most of the technologies needed to achieve deep reductions in the chemicals sector emissions – including CCUS and electrolytic hydrogen using variable renewables – are still at the pre-commercial or small-scale deployment stages of development for most types of chemicals production. It will probably take five to ten years for technological development, cost declines and supply chain scale-up to reach the point where they can start to be deployed on the very large scale required. Since it will take at least 25 years to replace all the chemical production capacity around the world, including that associated with plants that will be built in the coming years before alternative production pathways are available, CCUS – both for retrofits and new plants – is going to have a very important part to play.

In the short to medium term (2020-40), technology performance improvements and switching to alternative fuels provide a considerable portion of emissions savings in the Sustainable Development Scenario, accounting for around 30% and 40% respectively of reductions relative to the Stated Policies Scenario (Figure 4.6). Incremental gains in technology performance are obtained as the energy intensity of process units improves from current levels towards the best attainable levels. Further

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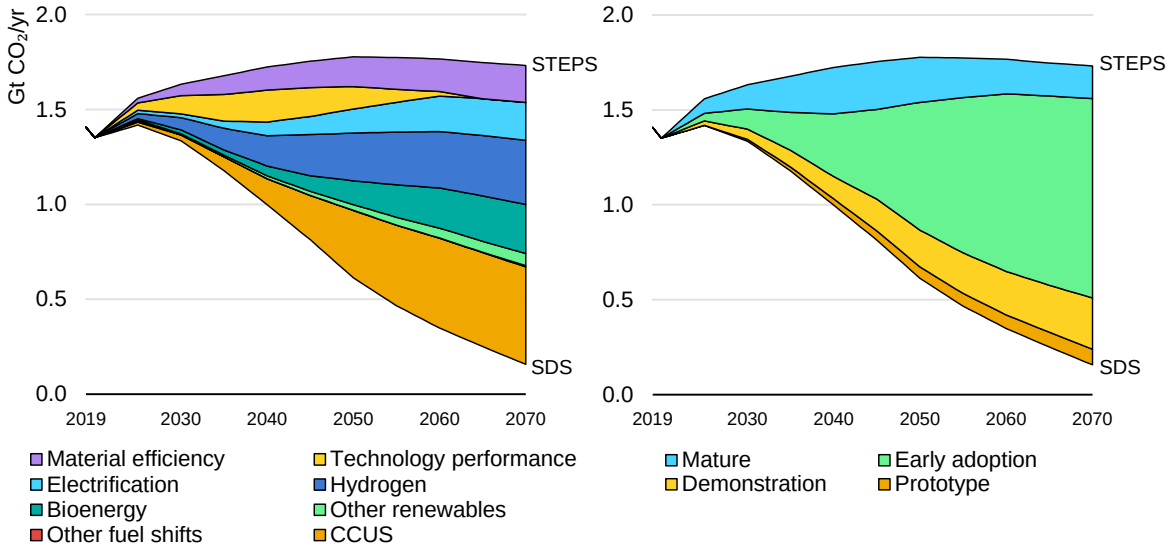
gains stem from higher levels of heat integration, updating ancillary equipment and utilities to the most efficient units available, smart process control and monitoring, and predictive maintenance, among other operational strategies.

Figure 4.6 Global CO_2 emissions reductions in the chemical sector by mitigation strategy and current technology maturity category, 2019-70



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. Electrification here includes only direct electrification, primarily via conventional technologies. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

CCUS and electrolytic hydrogen routes play the largest role in cumulative chemicals sector emissions reductions in the Sustainable Development Scenario. Electrification and the use of bioenergy for low- to medium-temperature process heat play an important role downstream.

A switch to alternative (less carbon-intensive) fuels and feedstocks and the adoption of more selective processes both also contribute to reducing the energy intensity of chemical production, reducing emissions directly (due to the lower carbon content of the feedstock) and indirectly (due to the reduction in energy required to process it). In addition, wider access to highly selective feedstocks enables producers to adapt production to the slate of products demanded. For example, 1 t of ethane can yield around 0.8 t of high-value chemicals (nearly all ethylene), whereas naphtha yields 0.6 t of a more balanced mix of ethylene, propylene and BTX aromatics, and catalytic cracking of naphtha is scaled up and adopted more widely in the Sustainable Development Scenario than in the Stated Policies Scenario (there is currently only one small plant operating in Korea). Ethanol dehydration to produce bioethylene is also a more selective process that helps to cut emissions. While bioenergy makes only a small contribution to emissions reductions in the first half of

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the projection period, by 2070 it accounts for around 10% of energy consumption in the chemical sector, five times its share in the Stated Policies Scenario.

Material efficiency gains that reduce virgin primary chemical production through the recycling and reuse of plastics also help to cut CO_2 emissions. These strategies account for almost 15% of cumulative emissions reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario.

In the longer term, the key technologies that bring further reductions in emissions are the electrolytic production of hydrogen for making ammonia and methanol, and the deployment of CCUS in conjunction with conventional process routes for all primary chemicals. The latter includes so-called "blue hydrogen" – hydrogen produced from fossil fuels in conjunction with CCUS.

By 2070, electricity makes up around a quarter of total chemical sector energy use in the Sustainable Development Scenario, compared with 10% in 2019. This electricity is used primarily for electrolysis in primary chemical production; it is also used to provide low/medium temperature process heat when primary chemicals are converted into intermediates and end-use chemical products. Electrolytic hydrogen production (see Chapter 2 and 3) in the chemical industry is not new: ammonia was produced via electrolysis (and other less efficient electrified methods) for decades during the mid-20th century, but those plants were generally powered by low-cost hydroelectric facilities with high capacity factors. Today there are no large-scale ammonia or methanol plants being fed by electrolytic hydrogen because electricity prices tend to be too high to make the technology competitive with natural gas. There are further challenges when it comes to utilising variable renewable electricity to produce chemicals and other industrial materials. Industrial process equipment tends to be limited in its ability to ramp up and down in response to variability in its energy inputs. Buffer storage can be used to overcome this challenge, but it adds significantly to the cost of production.

There is another technical constraint on the extent to which electrolytic hydrogen can be deployed in the short to medium term which relates to CO_2 requirements. The carbon in fossil fuels is currently the building block for most key chemical supply chains. While methanol requires carbon either in the form of CO_2 or CO, the ammonia supply chain specifically requires CO_2 for the production of urea. This CO_2 could be supplied from bioenergy or direct air capture, so that the process remains carbon-neutral when the CO_2 is later released downstream in other sectors (e.g. during fertiliser application or when plastic products reach the end of their lives). However, this would significantly increase the cost of producing these chemicals in a scenario in which limited biomass availability means that there are few point sources of biogenic CO_2, and in which direct air capture CO_2 supplied by low-emission sources remains costly. Despite these challenges, production of ammonia and methanol from

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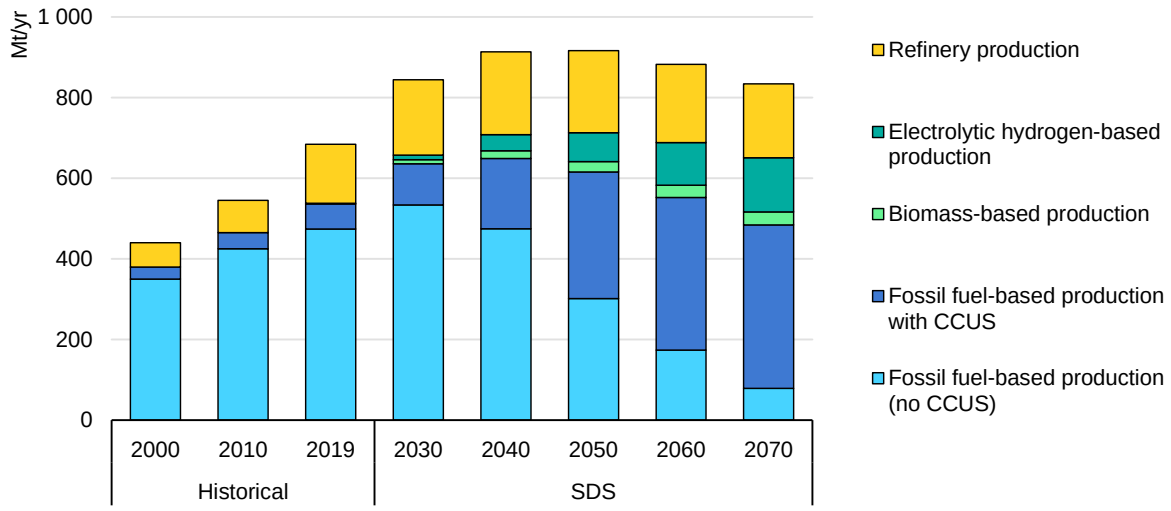
hydrogen increases considerably in the Sustainable Development scenario, with an average of eight plants being added per year from 2030 to 2070.

Figure 4.7 Global primary chemicals production routes by energy feedstock in the Sustainable Development Scenario, 2000-70



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Notes: SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. *Refinery production* refers to quantities of high-value chemicals sourced from refinery operations.

From just a small share of carbon capture and utilisation applied to ammonia for urea production today, CCUS-equipped routes expand rapidly, accounting for 50% of chemicals production by 2070, with hydrogen- and bioenergy-based routes accounting for a further 16% and 4% respectively.

The proportion of ammonia being converted to urea declines substantially in the Sustainable Development Scenario due to substitution by nitrate-based fertilisers, paving the way for greater use of electrolysis, which accounts for half of total ammonia production by 2070. Around one-third of methanol is currently used as fuel, either directly or through one of its downstream derivatives (e.g. methyl tert butyl ether), but this use is expected to diminish relative to other uses in which the carbon contained in the methanol becomes sequestered in a durable product. In methanol's case, however, the carbon is still required for synthesis, so the use of fossil fuel-based capacity equipped with CCUS is expected to remain the most competitive method of production through to 2070.

In the Sustainable Development Scenario, CCUS applied to fossil fuel-based chemical production increases to more than 400 Mt of chemicals production in 2070, by which time around 85% of all production on fossil fuels is equipped with CCUS (excluding refinery-sourced chemicals) (Figure 4.7). This roll-out is equivalent to 19 chemical plants with CCUS being added on average each year from 2030 to 2070 and results in 14 $GtCO_2$ captured cumulatively by 2070. The concentrated CO_2

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streams in ammonia plants – where they are not being used to synthesise urea – are already captured on a significant scale today, notably in Canada, China and the United States. These emissions streams are currently used in enhanced oil recovery applications, but permanent storage projects are in the planning phase (Table 4.1).

Several process routes for high-value chemical production are equipped with CCUS across all regions towards the end of the projection period in the Sustainable Development Scenario, mainly because a large amount of oil and natural gas is still used in high-value chemical production and there are few alternative ways of reducing emissions. The oil is mainly used for feedstock, but it leads to process emissions, and the natural gas is mainly used to provide heat in steam crackers, which leads to energy-related emissions: both types of emissions need to be captured. High-value chemicals can be produced via electrolytic methanol and the methanol-to-olefins/aromatics pathways, but the same constraint on the availability of biogenic or direct air capture CO_2 feedstock at a reasonable cost applies as it does for methanol generally, and that means it is cheaper to use conventional processes (e.g. steam cracking) equipped with CCUS. For ammonia and methanol, unabated coal-based production in China is substituted by a mixture of CCUS-equipped capacity (both retrofit and new-build) and electrolytic hydrogen-based production.

The application of CCUS and electrolytic hydrogen varies over time and by region, with the CO_2 requirements of each chemical's supply chain, rising electricity prices and the cost of electrolysers of adequate size being key hurdles for the electrolytic route in the medium term. CCUS provides a bridge to substantial shares of electrolytic hydrogen-based ammonia production in the long term for two main reasons. The first is that it has already been commercially applied in the chemical sector and thus can be used immediately to reduce emissions. The second is that it has potential for early large-scale application, whereas electrolytic capacity relies on widespread, large-scale integration of renewables into the electricity supply, or the development of large captive renewables projects with associated buffer storage requirements, both of which may take time to develop.

Were all of the fossil fuel-based ammonia and methanol production equipped with CCUS in 2070 to be substituted by electrolytic hydrogen, a further 1 250 terawatt hours (TWh) of electricity and 300 gigawatts (GW) of electrolyser capacity would be required, assuming a 50% average capacity factor. This is nearly 10% of the total electrolyser deployment in 2070 in the Sustainable Development Scenario. Electrolytic hydrogen plays a larger role over time in the chemical sector, particularly in regions where the uptake of CCUS is limited for geological or political reasons, and where there is long-term access to low-cost, large-scale, captive variable renewables, for example in China.

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Readiness and competitiveness of emerging technologies

The technologies that contribute to emissions reductions in the Sustainable Development Scenario are at varying stages of development (see Chapter 2 for a cross-sectoral discussion). In the chemical sector, CO_2 capture and technologies applied to conventional process routes are closest to widespread deployment, though further development efforts will be needed to improve their operational performance and lower their cost (Table 4.1). Maintaining momentum on pilot and demonstrations projects currently underway, and ensuring that the current Covid-19 crisis does not divert attention from this, will be crucial to achieving long-term emission reductions in the chemical sector.

Several methods of CO_2 capture have already been proven in the chemical sector. Commercial production processes for ammonia and methanol require CO_2 removal to obtain the correct chemical composition. The CO_2 that is captured must, however, be used or stored safely for the long term if emissions are to be reduced, and that is much less often the case today. It is common for CO_2 captured during the production of ammonia and methanol to be used to make urea or to boost methanol production from natural gas, but CO_2 storage is limited to a few current and proposed projects. Current CCS projects include two commercial ammonia plants in the United States which have been operational since 2003 and 2013 (each 0.7-0.8 $MtCO_2$/yr) and one methanol plant in China which has been operational since 2016 (0.1 $MtCO_2$/yr): all three projects store CO_2 via enhanced oil recovery. Several more ammonia and methanol plants with CCS are scheduled to come online in the next few years – one in Canada, two in the United States and one in China. CCUS requires further scaling up for high-value chemicals, having not yet been applied at the commercial scale (TRL 7). Two pilot plants have been built in China (50-100 $ktCO_2$/yr), and there are plans to scale-up towards three larger-scale plants (0.4-0.5 $MtCO_2$/yr).

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Table 4.1 Status of the main emerging technologies in the chemical sector

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Carbon capture, utilisation and storage			
Chemical absorption	11	Today (Very high)	**Ammonia:** Multiple commercial plants in operation capturing CO_2 for use (TRL 11 for CCU), e.g. Petronas Fertilizer plant in Malaysia since 1999 and Indian Farmers Fertilizer Co-op since 2006 (MHI, 2020). Koch's Enid Fertilizer plant (0.7 $MtCO_2$/yr) in operation since 2003 using CO_2 for EOR (TRL 9 for CCS) (MIT, 2016a).
	9	Today (Very high)	**Methanol:** Commercial coal-based plants use capture as part of the production process (TRL 11 for the capture technology). Projects subsequently using the CO_2 at a plant in Brazil operating since 1997 and one in Bahrain operating since 2007 (TRL 9 for CCU) ($ZeroCO_2$, 2016; GPIC, 2020). No projects currently storing the CO_2 (TRL 5 for CCS).
	7	2025 (Very high)	**High-value chemicals:** The Sinopec Zhongyuan Carbon Capture Utilization and Storage Pilot Project at a petrochemical plant in Henan, China has been capturing 0.12 $MtCO_2$/yr for EOR since 2015, with plans to expand to 0.5 $MtCO_2$/yr (Global CCS Institute, 2018a).
Physical absorption	9	Today (Very high)	**Ammonia:** Capture technology widely used commercially as part of the production process (TRL 10-11 for capture); Coffeyville Resources plant commissioned in 2013 at commercial scale (0.7-0.8 $MtCO_2$/yr) in the United States, with CO_2 used for EOR (TRL 9 for full CCS chain) (MIT, 2016b). Several further plants with CCS are scheduled to come online in the near term at the Nutrien Redwater plant in Canada, Wabash Valley Resources plant in the United States, and the Sinopec Qilu Petchem facility in China (OGCI, 2019; Enhance Energy Inc., Wolf Carbon Solutions and North West Redwater Partnership, 2019; Sharman, 2019).
	7	2023 (Very high)	**Methanol:** Lake Charles Methanol is developing an industrial scale plant in the United States, with CO_2 stored via EOR; construction aiming to start in 2020 (Lake Charles Methanol, 2020).
	7	2025 (Very high)	**High-value chemicals:** Yangchang Petroleum built a capture plant at the Yulin coal-to-chemical plant (50 kilotonnes [kt] CO_2/yr) and is currently building a large-scale unit (0.36 $MtCO_2$/yr) at a second plant in Jingbian; CO_2 is stored via use for EOR (Global CCS Institute, 2016).
Physical adsorption	8	Today (Very high)	**Methanol:** The Xinjiang Dunhua (0.1 $MtCO_2$/yr) plant in China was commissioned in 2016, with CO_2 stored via EOR (Asiachem, 2018).
Hydrogen			
Electrolytic hydrogen supplied by variable renewables	8	2025 (Very high)	**Ammonia:** Two medium-sized demonstration projects are planned in Australia with 60-160 MW electrolysers (Arena, 2019; Yara, 2020). Various other pilot projects are in development, along with longer-term plans for larger scale projects, in other countries including Chile, Germany, Morocco, the United Kingdom and the United States (IEA, 2019).
	7	2025 (High)	**Methanol:** Several pilot plants – George Olah pilot (4 kt/yr) in Iceland commissioned in 2011, with plans to scale up to small demonstration scale (CRI, 2020); Mitsui Chemicals (0.1 kt/yr) in Japan since 2009 (Green Car Congress, 2009); the Carbon2Chem project in Germany since 2018, using hydrogen from electrolyser and CO_2 from steel plant (Thyssenkrupp, 2020a). Two planned demonstration projects received funding from the German government in 2019 (BMWi, 2020).

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Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Direct electrification			
Methanol production from methane pyrolysis	6	2030 (Medium)	• This process to produce hydrogen and solid carbon by heating methane using electricity is being tested by BASF in a pilot plant in Germany, aiming for an industrial-scale plant by 2030 (BASF, 2019). While tests for methanol production are fairly small scale, testing of methane pyrolysis outside of the chemical sector for hydrogen production puts the technology at TRL 6.
Steam cracker electrification **(high-value chemicals)**	3	--- (Medium)	• Six petrochemical companies together launched the Cracker of the Future Consortium in 2019 to explore using renewable electricity to run naphtha or gas steam crackers; the first steps involve screening technical options (Borealis, 2019). • VoltaChem is also exploring options (VoltaChem, 2020).
Bioenergy			
Biomass gasification	5	--- (Low)	**Ammonia:** Techno-economic evaluation of producing ammonia via biomass gasification completed, but suggest it is not yet economically viable (Brown, 2017; Andersson and Lundgren, 2014). Higher TRLs for other applications (for example biomethane, ethanol and methanol production), but not yet applied to ammonia.
	8	Today (Low)	**Methanol:** A first commercial plant began in Canada in 2016, deriving methanol from waste (Enerkem, 2016). Production is also taking place at the BioMCN facility in the Netherlands (OCI, 2020). A pre-commercial biomethanol project is also being considered in Sweden (VärmlandsMetanol, 2017).
Ethanol dehydration for **ethylene**	5-9	Today (Medium)	• Several commercial plants using ethanol produced via fermentation are currently in operation in multiple countries, two of the largest being the Braskem plant (0.2 Mt/yr) in Brazil and the India Glycols plant (0.175 Mt/yr) in India (ETSAP and IRENA, 2013; Mohsenzadeh, Zamani and Taherzadeh, 2017). • The spread of TRL corresponds to the ethanol feedstock: 9 for fermentation routes (first generation) and 5 for lignocellulosic biomass gasification (second generation). Ethylene production process is technically similar, but has not yet been linked to lignocellulosic feedstocks, which are less advanced and costlier.
Lignin-based **BTX** production	6	2030 (Medium)	• Successful pilot-scale test of BioBTX technology in the Netherlands (BioBTX, 2020). • ALIGN project launched by eight partners from Belgium and Germany in 2018 to upscale three lignin extraction processes, including through the LignoValue pilot in Flanders (200 kg/day) (Biorizon, 2018; Vito, 2018).
Feedstock substitution			
BTX production from methanol	7	2030 (Low)	• Three pilot plants were commissioned in 2013 and several commercial-scale demonstration projects are under development, mainly in China (Nextant, 2015).
Naphtha catalytic cracking **(high-value chemicals)**	9	Today (Low)	• A first commercial plant (40 kt/yr) is in operation at the KBR plant in Korea (Arne, 2017).

Notes: TRL = technology readiness level. CCU = carbon capture and utilisation. CCS = carbon capture and storage. EOR = enhanced oil recovery. For CO_2 capture technologies, the specified TRL refers to the whole carbon capture and utilisation or carbon capture and storage value chain applied within the chemicals sector (whichever is at a higher TRL), rather than the TRL of the capture technology only.

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Electrolytic hydrogen has been used in the past for ammonia and methanol production, with the hydrogen supplied from hydropower, but most of these projects have been supplanted by natural gas. Development is currently underway to produce ammonia and methanol instead from hydrogen supplied by variable renewables, with commercial projects at substantial scale expected within a few years (currently at TRL 7-8). Two medium-sized demonstration projects are planned for ammonia from electrolytic hydrogen produced using variable renewables in Australia (60-160 MW), and there are other such projects as well in countries such as Chile, Germany, Morocco, the United Kingdom and the United States. Pilot projects for methanol have been operating in Iceland since 2011 (4 kt/yr), Japan since 2009 (0.1 kt/yr) and Germany since 2018, and larger projects are now planned for Iceland and Germany.

Several routes using bioenergy are also under development. Ethanol dehydration technology for producing ethylene is also well-advanced, with a number of small plants already operating in countries such as Brazil and India using fermentation processes (TRL 9). Ethylene has not yet been produced from ethanol derived from lignocellulosic biomass gasification: while the ethylene production process is similar, lignocellulosic ethanol is costlier to produce and the technology is less advanced. The gasification of biomass and waste is meanwhile being applied to methanol production in Canada and the Netherlands (TRL 8), and has been considered in techno-economic studies for ammonia production. The production of BTX (a sub-category of high-value chemicals) from lignin is also being piloted (TRL 6) in Belgium, Germany and the Netherlands. Despite these various innovation efforts, however, bioenergy is still expected to play a relatively minor role in chemical production in the Sustainable Development Scenario, given the limited availability of sustainable biomass and the competition for this biomass from other sectors.

Various other innovative processes are also being explored. Direct electrification of steam crackers for high-value chemicals production is in the early stages of development (TRL 3), with technology options being explored by several companies, but prototypes have yet to be developed. While its low TRL suggests it may have difficulty competing with more advanced options, it could play an important role if the technology develops rapidly. Methanol production through methane pyrolysis, whereby methane is heated using electricity to produce hydrogen gas and solid carbon, is also being piloted in Germany. Other innovative options like BTX production from methanol and naphtha catalytic cracking provide potential for some emissions reductions relative to conventional processes, but the reductions are not large enough for them to play a key role in the Sustainable Development Scenario.

Numerous initiatives are underway to develop new recycling techniques for plastics.[7] Many of today's plastic recycling techniques result in "down cycling", in which recycled plastics are used to produce a lower value material. New techniques could produce recycled plastics of comparable quality and functionality as their virgin counterparts. Several processes are in the demonstration and early adoption phases

[7] For further information on specific projects, see the IEA's *ETP Clean Energy Technology Guide* at: www.iea.org/articles/etp-clean-energy-technology-guide.

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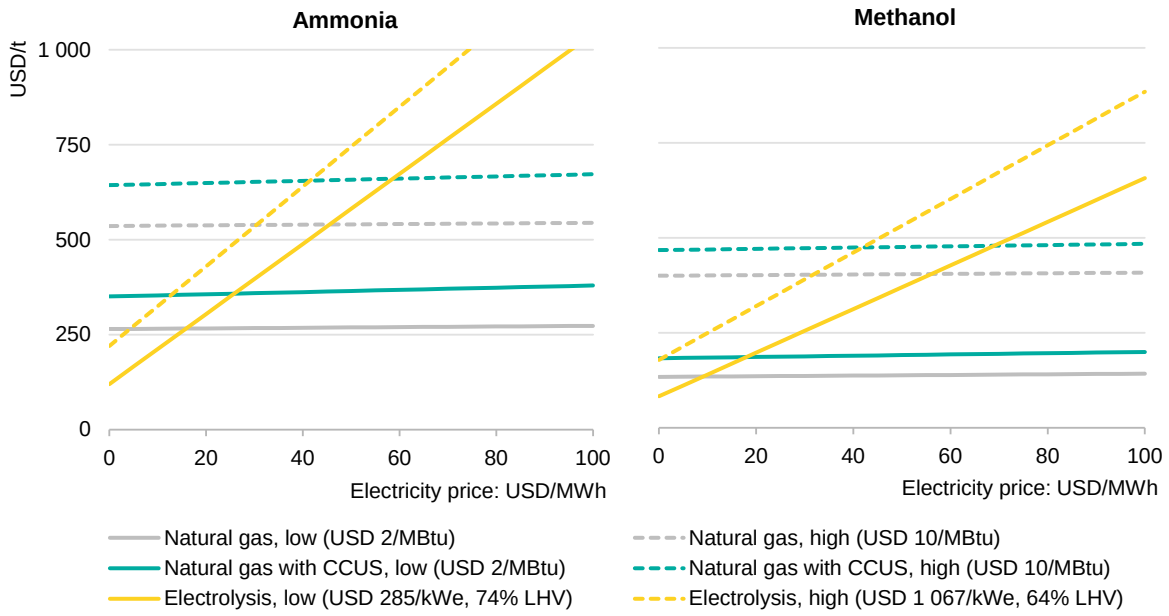
(TRL 7-9). Key processes under development can be categorised as follows: chemical depolymerisation, which uses chemicals to break down polymers into monomers; solvent dissolution, which uses solvents to purify and separate out a virgin-quality polymer; pyrolysis, which uses high temperatures to convert mixed plastic wastes into liquid hydrocarbons; and hydrothermal upgrading, which uses water under supercritical conditions to break down polymers. Once sufficiently developed, these processes will provide the opportunity to recycle a broader range of waste material and produce higher quality substitutes for virgin polymers.

The rate of long-term deployment of CCUS and electrolytic hydrogen technology in the Sustainable Development Scenario varies markedly across regions according to differences in natural gas prices, the availability of low-cost electricity, and the public acceptability and technical feasibility of CCUS. Once CO_2 feedstock sourcing is alleviated in the longer term (i.e. once atmospheric or biogenic CO_2 is available from various carbon removal and bioenergy transformation processes), the key determinant in the choice of technology for ammonia and methanol production in each region is the cost of natural gas relative to that of electricity.

Figure 4.8 Levelised cost of ammonia and methanol production under varying techno-economic assumptions



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Notes: CCUS = carbon capture, utilisation and storage. MBtu = million British thermal units. kWe = kilowatt electrical capacity. LHV = lower heating value. For the CCUS-equipped routes, both concentrated (process CO_2) and diluted (energy-related CO_2) streams are captured, with a 90% capture rate. CO_2 transport and storage costs of USD 20/tCO_2 captured are included, as are engineering, procurement and construction costs. An 8% discount rate, 25-year lifetime and 90% capacity factor are used for all equipment.

At electricity prices of USD 10-60/MWh for ammonia and USD 5-70/MWh for methanol, electrolytic hydrogen can compete with conventional production routes equipped with CCUS, with the specific break even costs depending on the price of natural gas.

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Installing facilities to capture CO_2 increases significantly the overall levelised cost of production – by around 20-40% in the case of near-100% capture of both concentrated and diluted streams of CO_2, based on today's costs. Nonetheless, in most regions, CCUS is still more cost-competitive than electrolytic hydrogen for producing ammonia and methanol in most instances. In regions with low natural gas costs (e.g. the Middle East), electricity costs below USD 20-25/MWh (megawatt-hours) would be required to make electrolytic hydrogen competitive with CCUS. For regions with higher natural gas prices, hydrogen can compete at somewhat higher electricity costs (below USD 60-70/MWh) (Figure 4.8).

In a context in which low-carbon electricity is in high demand across the energy system, such low prices for non-variable grid electricity may be difficult to achieve in most regions. Captive variable renewables (non-grid connected, sized and run for a particular application) could make the electrolytic route more competitive in a wider range of locations, if the cost of electricity generation regularly falls below USD 25/MWh. However, these conditions may only prevail in regions with abundant renewable resources, which may lie at some distance from centres of chemical production or demand, and in such a case, the cost of transporting the ammonia or methanol to those centres would need to be factored in. The variability of renewables also depresses the average capacity factor of the system, with the need for hydrogen buffer storage increasing the share of capital costs in the total levelised cost of production.

Steel production

Sector overview and demand outlook

Iron and steel production – a central pillar of the world economy – is a highly energy-intensive industrial sector. Worldwide, the sector accounted for 22% of industrial energy use and 8% of total final energy use in 2019. Energy typically makes up 10-25% of total production costs. Coal is currently the main source of that energy: it accounts for about 75% of the sector's energy use, with electricity and natural gas responsible for most of the rest in almost equal measure.

The CO_2 intensity of steel production is high, with each tonne of crude steel resulting in around 1.4 t of direct CO_2 emissions on average, or 2.0 t when including indirect emissions from imported electricity and heat generation.[8] Iron and steel production requires lime fluxes and graphite (graphite for anodes in electric furnaces), which

[8] Direct emissions include process emissions and energy-related emissions from fossil fuel combustion and transformation, including for the onsite provision of heat. Indirect emissions include both onsite electricity generation from off-gases and electricity/heat imports from the grid, with the latter calculated based on the average regional CO_2 emission intensity of power generation.

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together with ferroalloy production contribute 11% of the sector's emissions in the form of process emissions. Globally, the sector's direct CO_2 emissions amounted to 2.6 Gt in 2019, or 7% of total energy sector emissions and 28% of industrial emissions. When indirect emissions from electricity and heat generation are included (including from electricity and heat which is generated onsite from steel off-gases and that which is imported from the power and fuel transformation sector), total emissions amount to around 3.6 Gt.

The principal inputs to steelmaking today are iron ore, energy (mainly coal, natural gas and electricity), lime fluxes and steel scrap. Iron ore and scrap are used to provide the metallic charge, with scrap having a significantly higher metallic concentration (>95%) than iron ore (typically in the range of 50-70%). Metallic input of 1.05-1.2 t is required per tonne of steel. Energy inputs are used to provide heat to melt the metallic input, and in the case of iron ore, to chemically reduce it (remove oxygen) from its naturally occurring states found in the earth's crust.[9] "Primary" steel production refers to that which uses iron ore as its main source of metallic input, whereas "secondary" production is that based on scrap. However, in many instances, this distinction can become less clear-cut, as scrap is often used in primary production (typically up to 15-25%), and iron is commonly used in electric furnaces, which are the main units for secondary production. Consequently, when describing the situation in a given region or portfolio, it is instructive to quote the share of scrap in total metallic inputs alongside the shares of primary and secondary production.

Once scrap is collected and sorted, the secondary production route mainly requires electricity to melt the steel in an electric furnace, often along with a small amount of natural gas or coal to form a protective slag foam. Highly conductive graphite electrodes are also consumed during the process of heating the scrap metal to temperatures of up to 1 800°C. Electric arc furnaces are the most commonly used furnace for scrap-based production, but typically less energy-efficient induction furnaces are also used, particularly in China and India. Producing 1 t of steel via the scrap-based route requires around 2 GJ of final energy per tonne of crude steel.

The primary production pathway is more complex than the secondary route, comprising multiple different process arrangements. The most common primary production pathway is the blast furnace-basic oxygen furnace (BF-BOF) route, which accounts for around 70% of global steel production and around 90% of primary production. Coke and iron ore are both fed into the blast furnace from the top along; simultaneously, hot air and pulverised coal or natural gas (and in an experimental site in Germany also hydrogen) are injected through pipes in the side of the lower part of the furnace called *tuyeres*. This results in a counter-cyclical process of descending

[9] Key iron ore constituents include: magnetite, Fe_3O_4, 72.4% iron content; haematite, Fe_2O_3, 69.9% iron content; goethite, FeO(OH), 62.9% iron content; limonite, $FeO(OH)\cdot n(H_2O)$, 55% iron content; siderite, $FeCO_3$, 48.2% iron content.

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iron ore met by rising reducing gases. Lime fluxes and other additives are also used in the blast furnace in varying quantities to control the level of impurities and the temperature. The blast furnace produces molten iron ("hot metal") at temperatures up to 1 400-1 500°C. The hot metal is then fed to the BOF, often in conjunction with some scrap, where oxygen is injected to lower the carbon content from approximately 4-5% to the required level of carbon for the steel grade produced (typically around 0.25%).

Box 4.2 Iron and Steel Technology Roadmap

For more than a decade, the IEA's *Technology Roadmap* series has provided in-depth analyses of key technologies and sectors within the energy system. The publications have provided guidance to both the public and private sectors, with a focus on evidence-based recommendations about the priorities and steps needed to accelerate technology innovation and deployment, while placing an emphasis on broad stakeholder engagement. The Roadmap series already includes titles covering energy-intensive industrial sectors, including the cement and chemical industries, and steel is next.

The IEA's forthcoming *Iron and Steel Technology Roadmap* will explore the technologies and strategies necessary for the iron and steel sector to become more sustainable, providing an in-depth sectoral analysis that complements the material in this chapter. The *Energy Technology Perspectives 2020* analysis presented here will form the broader energy system context for the *Iron and Steel Technology Roadmap* publication. The Roadmap will look at both the challenges and the opportunities facing the sector and analyse the key technologies and processes that could bring about substantial CO_2 emissions reductions in the sector. It will also assess the sector's potential for resource efficiency, including increased reuse, recycling and demand reduction.

Realising a more sustainable trajectory for the sector will require co-ordinated efforts by all the main stakeholders, including steel producers, governments, financial partners and the research community, and the publication will contain an outline of priority actions, policies and milestones for these stakeholders to accelerate the sustainable transition of the iron and steel sector.

The other main method of primary steel production is the direct reduced iron-electric arc furnace (DRI-EAF) route. The principal differences between this route and the BF-BOF route are:

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- The type of iron ore that is typically used – high-quality DRI pellets in the first route, whereas BF-BOF has the flexibility to use iron ore with more impurities, and a combination of pellets, fines, sinter and lump ore.
- The state of the material when it is reduced – the iron ore is reduced in a solid state in the DRI furnace (as opposed to the liquid phase in the blast furnace), before being melted in the EAF, often in conjunction with some scrap.
- The main reduction agents – they are carbon and carbon monoxide in the BF-BOF route, while hydrogen and carbon monoxide play more balanced roles in the DRI-EAF pathway.
- The balance of energy inputs – DRI-EAF facilities today mainly use natural gas to generate the reducing syngas (carbon monoxide and hydrogen), but can also use coal, while BF-BOF producers mainly use coke and coal, with natural gas injection being less common.

The main BF-BOF and EAF (both DRI-EAF and scrap-based EAF) routes combined account for 98% of global steel production. Two other process units are also in use today, but see very limited penetration. Smelting reduction is an alternative class of processes for ironmaking that facilitates the use of iron ore fines directly (rather than agglomerated pellets and sinter) and avoids the use of a coke oven or coking coal. Several designs are currently commercially available or under development, but the process is yet to see widespread adoption within the industry. The open-hearth furnace is an outdated alternative to the BOF, and has largely been phased out given its inferior energy performance.

The iron and steel sector faces several hurdles in lowering its emissions over the coming decades:

- **A high share of coal in the sector's energy inputs:** Primary production relies heavily on coal (and in some cases natural gas) and coke made from metallurgical coal, the key role of which is to serve as a reducing agent in the production of molten iron while providing process heat. Although innovations are underway in hydrogen- and electricity-based production, and in production using biomass for a portion of fuel, switching away from fossil fuels entirely will be technically and economically challenging.
- **Long-lived capital assets:** The sector makes use of complex, capital-intensive process equipment with long economic lifetimes: a blast furnace is normally built to last at least 25 years, and many remain in operation for more than 40 years. Of the 2 300 Mt of annual steelmaking capacity today, 1 500 Mt is for steel production via the BF-BOF route. It is expected that more than 90% of the existing BF-BOF steelmaking capacity could be still operating in 2030 and around 35% in 2050. In certain instances, the existing stock could be retrofitted with carbon capture technology, and this could provide a more economical option than replacing it with a completely new processes, given that the basic surrounding infrastructure of the original plant could then be maintained. However, current

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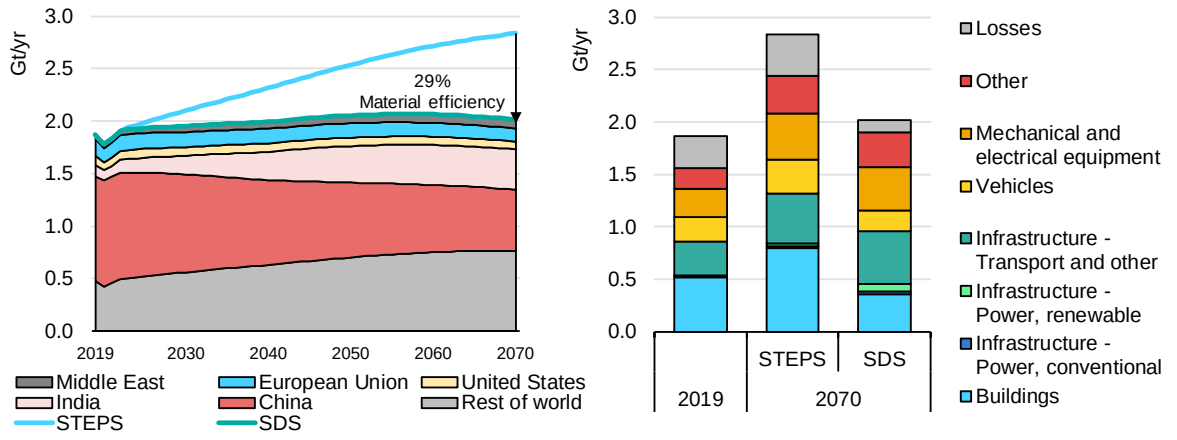
CCUS retrofitting is no more technologically mature for the bulk of existing capacity than some alternative production routes.

- **Trade considerations and low margins:** The international steel market is highly commoditised and competitive, making the economics of steel production very sensitive to local energy costs. For that reason, the industry has already invested heavily in lowering the energy intensity of steel production in recent decades, leaving relatively limited room for further energy intensity improvements within a given process route. Furthermore, competitive markets pose a challenge for adopting breakthrough technologies, since they are likely to significantly increase production costs and undermine competitiveness, especially for early adopters.

The use of steel is expected to increase in the coming decades, particularly for buildings and infrastructure. Many technologies that will be needed for a net-zero emissions energy system, including rail infrastructure, wind turbines, CCUS equipment and nuclear power plants, make use of large amounts of steel (Figure 4.9). In other words, steel needs energy and the energy system needs steel. In 2019, an average of around 240 kg of steel was produced for every person on the planet; in the Stated Policies Scenario, this figure rises to 260 kg by 2050, and to 270 kg by 2070.

Figure 4.9 Global steel production by region and end use, 2019-70



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. *Other* includes metal goods, domestic appliances and food packaging. Losses is equivalent to scrap generated in the semi-manufacturing and manufacturing stages.

The contraction of steel production in China is expected to be offset by rapid growth in India. In the Sustainable Development Scenario, material efficiency strategies help reduce global demand for steel by 29% by 2070.

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The Covid-19 pandemic has had a marked impact on steel production in 2020. We project that overall sectoral output will be down by around 5%, relative to 2019, although this estimate is highly sensitive to government policies on lockdowns in the remainder of 2020. This decline is broadly in line with the global trend for GDP, which is currently projected to fall 4.9% in 2020 (IMF, 2020). Not all regions see declining output. China, which accounts for just over half of global steel production, actually produced more steel during the first half of 2020 than it did during the corresponding period in 2019. While some of this material will have stocked up inventories, domestic demand has remained robust, and this accounts for around 90% of its production. In other countries, the outlook for the industry is more bearish, with output in the first half of 2020 in the United States and Europe down 18% and 17% respectively.

Material efficiency offers one way to reduce demand for steel – and therefore the need for energy to make it – while continuing to provide the same steel-based products and services that people demand. There remains considerable potential for reducing the need to produce new steel through light-weighting of products that are made of steel, reducing losses in the form of scrap in the production process, reusing steel components in products that reach the end of their life (such as steel beams in old buildings) and delaying the retirement of steel-based products and buildings (Allwood and Cullen, 2012). In the Sustainable Development Scenario, global steel demand grows only very gradually to 2060, after which it enters a gentle decline, and it is 29% lower in 2070 than in the Stated Policies Scenario, thanks to the adoption of a suite of material efficiency strategies. In both scenarios, the geographical distribution of steel production also changes. By 2070, China produces 30% of global steel production and India 20%, whereas today China accounts for more than half of global output, followed by the European Union with 9% and India with 6%.

Technology pathways towards net-zero emissions

In the Sustainable Development Scenario, the average direct emissions intensity of crude steel production declines to 10% of today's value, falling to 0.13 tCO_2/t by 2070, driven primarily by deployment of innovative technologies and increased secondary production (Figure 4.10). Since overall production levels are relatively similar in 2070 to the levels seen today in this scenario (they are kept from rising by the adoption of material efficiency strategies), this emission intensity reduction translates into a similar reduction in the total emissions of the sector, with emissions falling to around 0.3 $GtCO_2$ in 2070.

A variety of measures is required to make the Sustainable Development Scenario a reality (Figure 4.11). The most important measures in the short to medium term include technology performance, material efficiency and increases in the share of

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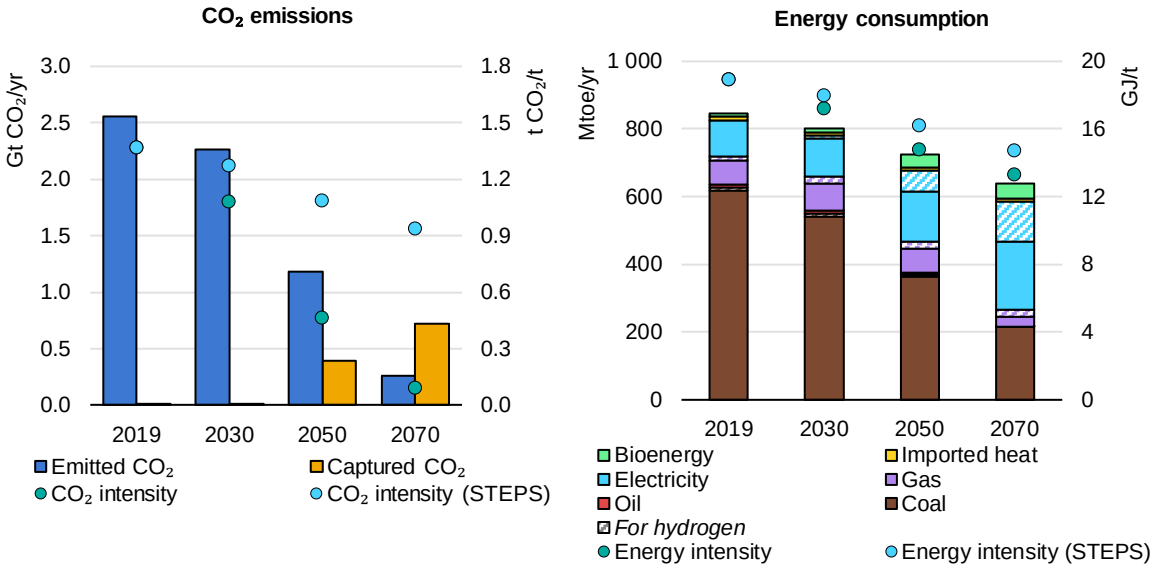
secondary production, with the latter two being inter-dependent and continuing to play a significant role throughout the projection period.

Figure 4.10 Global iron and steel sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70



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Note: STEPS = Stated Policies Scenario.

Iron and steel emissions fall by around 90% by 2070 in the Sustainable Development Scenario, thanks to widespread deployment of CCUS and hydrogen-based steelmaking.

Gains in technology performance lower the quantity of energy required for production in conventional process routes, though the contribution that this makes has an upper limit dictated by technical constraints. It may be possible to reduce the current average energy requirement to produce 1 t of crude steel via the BF-BOF route by around 20%, with the adoption of the best available technologies as well as operational improvements.[10] Specific measures include, for example, the application of coke dry quenching to coke ovens (which facilitates the recovery of latent heat and results in a higher quality coke, reducing the quantity required for blast furnaces) and top pressure recovery turbines (which facilitate the generation of electricity from blast furnace gas and consequently require less electricity from the grid). Most of this potential is exploited by around 2050 in the Sustainable Development Scenario, with technology performance improvements accounting for 19% of the annual emissions reductions in 2040 relative to the Stated Policies Scenario, but this technology

[10] In addition to the technologies used, energy intensity of steel production is also influenced by energy inputs, raw material inputs and operational conditions.

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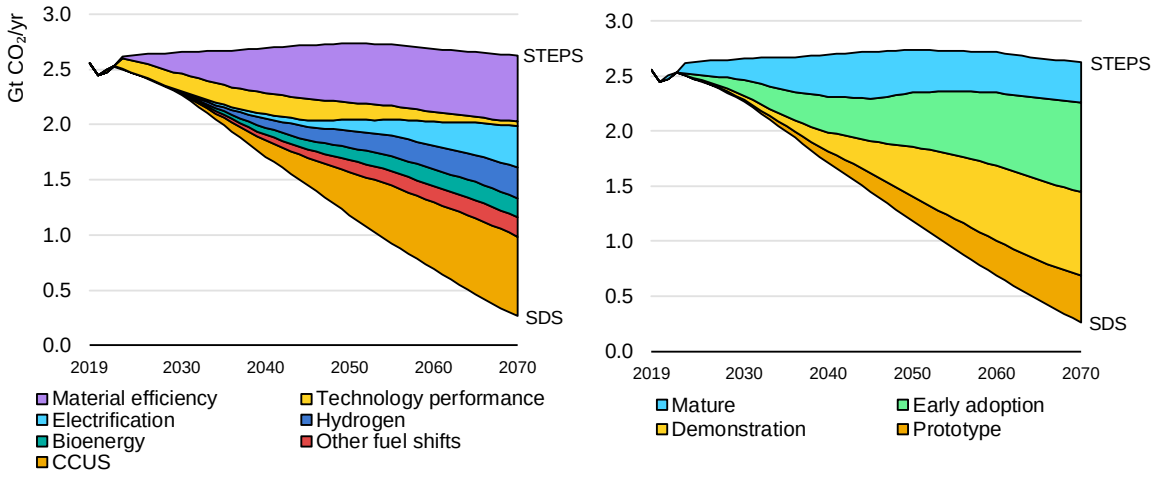
performance gap disappears by 2070 because optimal technology performance is also achieved in the Stated Policies Scenario by then.

Figure 4.11 Global CO_2 emissions reductions in the iron and steel sector by mitigation strategy and current technology maturity category, 2019-70



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. Electrification here includes only direct electrification, primarily via conventional technologies, including shifts towards secondary production and electrification of ancillary process equipment like pre-heaters and boilers. *Hydrogen* here refers specifically to electrolytic hydrogen, while so-called blue hydrogen (via natural gas-based direct reduced iron with CCUS) is included under CCUS. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

"Mature" and "early adoption" technologies are key to achieving early emissions reductions, while the long-term trajectory relies more heavily on "demonstration" and "prototype" technologies.

Material efficiency plays an important role by reducing the overall amount of steel that needs to be produced, accounting for a further 42% of the emissions reductions relative to the Stated Policies Scenario in 2040, and 25% in 2070. The lower share of emissions reductions attributable to material efficiency in 2070 is a result of other strategies such as innovative process routes playing a much larger role in the latter half of the scenario, even as savings from material efficiency also continue to grow. The key material efficiency strategies that are adopted in the buildings and construction sectors are explored in more detail in the final section of this chapter.

Increasing the share of scrap-based production is another important way of reducing the average emissions intensity of steel production. In the Stated Policies Scenario, an increase in scrap-based production relative to today is expected to occur: this reflects increasing scrap availability as steel-containing goods reach the end of their lives, and it results in scrap accounting for about half of total metallic inputs in 2070, compared with about one-third today (Figure 4.12). In the Sustainable Development Scenario, lower levels of steel production in the decades leading up to 2070 reduce

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scrap availability, but scrap-based inputs still reach half of metallic input in 2070 (lower total metallic input is needed in the Sustainable Development Scenario due to lower demand for steel). Targeted efforts help ensure that scrap availability is maximised: these include increases in scrap collection and improved sorting methods, particularly for reinforcing steel (rebar) and packaging, which currently have the lowest collection rates. The need for recycling measures is particularly important in emerging economies, where large amounts of steel-containing products will begin to reach the end of their lifetimes in the coming years. Also important is preventing copper contamination to ensure all grades (quality levels) can be produced from scrap. As copper is increasingly combined with steel in end-use applications in the Sustainable Development Scenario (e.g. motors in electric vehicles), the need for effective processes and methods to separate the two metals will become increasingly important, as will product design for recyclability.

Increases in scrap-based EAF production, as well as DRI-EAF, increase the share of electricity used in the Sustainable Development Scenario. Electrification of ancillary equipment and processes, such pre-heaters and boilers used for hot air provision and for rolling and casting, also contributes to direct electrification and thereby emissions reductions. Electrification contributes 9% of cumulative emission reductions, with shifts from coal to natural gas providing another 7%. Bioenergy plays a role too, with small amounts being blended into existing process units, and continued small-scale steel production in regions with access to low-cost sources of charcoal (e.g. Brazil) and other forms of biomass. The use of bioenergy contributes 7% of cumulative reductions.

In the longer term, the burden of emissions reductions shifts to the uptake of innovative processes for primary (ore-based) production, comprising technologies that are at earlier stages of their development. The four key technologies in this category are commercial natural gas-based DRI equipped with CCUS, in which hydrogen and carbon monoxide are the key reducing agents (gas-based DRI with CCUS); 100% electrolytic hydrogen-based direct reduction (100% H_2 DRI); oxygen-rich smelting reduction in conjunction with CCUS (innovative smelting reduction with CCUS); and conventional blast furnaces fitted with CCUS (innovative blast furnaces with CCUS).

By 2070, CCUS and electrolytic hydrogen together account for 43% of emissions reductions in the Sustainable Development Scenario, relative to the Stated Policies Scenario. As in the chemical sector, hydrogen generated using fossil fuels and equipped with CCUS (sometimes referred to as blue hydrogen) offers a relatively inexpensive way of reducing emissions from certain processes in the steel sector, especially for natural gas-based DRI-EAF production: a CCUS-equipped plant is already operating in employing this method of production in the United Arab Emirates.

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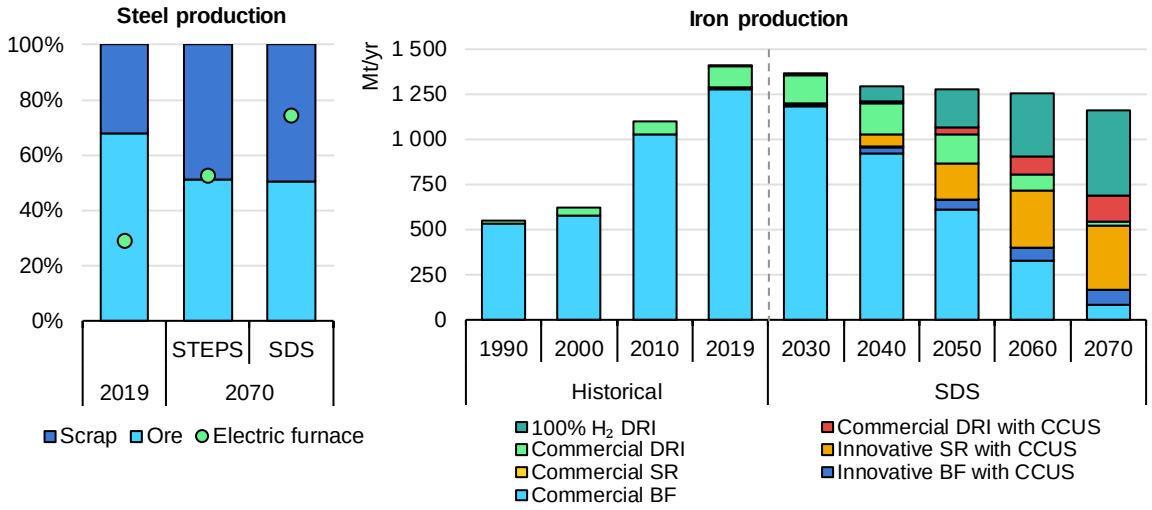
Figure 4.12 Global steel production by route and iron production by technology in the Sustainable Development Scenario, 1990-2070



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. DRI = direct reduced iron. SR = smelting reduction. BF = blast furnace. **Commercial BF** includes traditional coal, gas and charcoal-based blast furnaces, with and without top pressure recovery turbines, without CCUS. **Innovative BF with CCUS** includes blast furnaces with process gas hydrogen enrichment and CO_2 removal for use and storage (for example, as being developed by the COURSE50, IGAR and 3D projects), including CCUS retrofits to existing blast furnaces and those newly installed over the coming decade. **Commercial SR** refers to smelting reduction without CCUS (COREX and FINEX). **Innovative SR with CCUS** includes application of CCUS to existing smelting reduction concepts (for example COREX and FINEX) and novel smelting reduction concepts with CCUS (for example, as being developed by the HIsarna project). **Commercial DRI** includes gas and coal-based DRI without CCUS, including that which has a portion of blended electrolytic hydrogen. **Commercial DRI with CCUS** includes gas and coal-based DRI with CCUS. **100% H_2 DRI** comprises fully electrolytic hydrogen-based DRI (for example, as being developed by the HYBRIT project and ArcelorMittal in Hamburg). For further details on examples of projects developing these technologies, see Table 4.2.

While incremental gains in energy and material efficiency contribute the most to lowering iron and steel sector CO_2 emissions in the short to medium term, innovative technologies are the main drivers in the long term.

Electrolytic hydrogen plays a critical role in reducing emissions from primary steel production in the Sustainable Development Scenario in a variety of ways. It can be blended into existing process units, as is happening in initial pilot projects in Europe. Without any major changes to existing equipment, it can be used in the BF-BOF route as a substitute for up to 30% of the process energy requirements, which are currently met by coal; this type of arrangement is being explored in Germany. And it can be similarly used in the DRI-EAF route, where substitution of up to 30% of natural gas by electrolytic hydrogen can be achieved in existing furnaces. These blending efforts are perhaps best seen as a transition strategy to bridge the gap before deployment of the 100% H_2 DRI route, which starts to replace substantial amounts of existing capacity by the mid-2030s. Together these hydrogen-based technologies result in 30 Mt of hydrogen production via electrolysis by 2070 in the Sustainable Development Scenario. The H_2 DRI route alone accounts for 35% of primary steel

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production by 2070, requiring 12 new plants to be built on average each year from 2030 to 2070. The additional electricity demand to produce this hydrogen is 1 400 TWh – roughly equivalent to the total electricity demand of the whole iron and steel sector today – offsetting around 140 Mtoe of fossil fuels.

While electrolytic hydrogen-based routes seek to avoid CO_2 arising during production, the commercial DRI, innovative smelting reduction and innovative blast furnace routes – all equipped with CCUS – seek to manage the CO_2 that is generated by concentrating, capturing and storing it, or by using it for other products. These routes are deployed extensively in the Sustainable Development Scenario, which sees existing blast furnaces and DRI units retrofitted with CCUS, and CCUS incorporated into new-build facilities by initial design. Together they account for 55% of global primary steel production by 2070. Their roll-out is equivalent to 14 steel plants with CCUS being added each year from 2030 to 2070, amounting to over 15 $GtCO_2$ captured cumulatively by 2070. While there are no advanced blast furnace CCUS retrofit concepts ready for large-scale deployment very early in the projection period, their development is critical for the capture of emissions from both recently installed or refurbished equipment with good energy performance (e.g. in Europe and Japan) and those units that will be built in growth regions over the coming decade (e.g. in India). Most of the captured CO_2 in the period to 2040 is from existing plants, but by 2070 it stems primarily from newly built innovative plant designs.

Were CCUS deployment to be limited by some external factor – for instance a lack of public acceptance or sluggish technology and infrastructure development – the industry would likely need to rely more heavily on hydrogen-based production to maintain the same trajectory of emissions reductions. If all CCUS-equipped innovative smelting reduction and blast furnace installations in 2070 in the Sustainable Development Scenario were to be replaced by hydrogen-based production, the impacts on hydrogen and electricity generation infrastructure would be considerable. The additional demand for electrolytic hydrogen would require a further 250 GW of electrolyser capacity, and around 1 100 TWh of electricity, assuming a 50% average capacity factor for the electrolyser. This increase is equivalent to 30% of the total electricity demand of the iron and steel sector in 2070 in the Sustainable Development Scenario.

Energy use in the iron and steel sector varies among regions in the Sustainable Development Scenario, primarily reflecting differences in energy costs and the corresponding technologies that are deployed (see discussion and Figure 4.14 below). In the Middle East and the United States, the availability of cheap gas leads to widespread deployment of DRI with CCUS. In China, cheap coal favours innovative smelting reduction technologies in the medium term, while the H_2 DRI route plays an equally important role in the longer term and could potentially use low-cost dedicated renewables as the source of the electricity. In India, rapidly increasing

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demand for steel means that large amounts of new production capacity come online before innovative technologies are fully ready. These young plants are then retrofitted with CCUS in parallel with the roll-out of innovative smelting reduction, with H_2 DRI deployment following later. In European countries, where demand and local production are projected to remain flat or undergo a slight decline, emissions are reduced largely by increasing the share of secondary production and by a transition to hydrogen-based production in the longer term.

Readiness and competitiveness of emerging technologies

New technologies that have yet to be commercialised play an increasingly important role in the Sustainable Development Scenario, particularly in replacing existing production capacity over the second half of the projection period. A wide array of technologies is under development (Table 4.2), with the timing of their introduction and the rate at which they are deployed in the Sustainable Development Scenario varying according to their TRL, their economic competitiveness and supporting conditions. The acceleration of their commercialisation hinges on a substantial increase in RD&D efforts and supportive policy action (see Chapter 7), support that is critical now more than ever given the current challenges posed to the steel sector by the current Covid-19 crisis. It also hinges on the availability of the required inputs (renewable electricity and hydrogen) and infrastructure (CO_2 pipelines and storage facilities, grids, hydrogen networks).

Substantial innovation efforts are being directed towards lowering emissions from conventional blast furnace production. A number of projects at the pilot or large prototype stage (TRL 5) aim to deal with process gases by reforming gases into hydrogen for reuse in the blast furnace and CO_2 for later use or storage: they include the COURSE50 project in Japan and the IGAR, 3D, ROGESA and STEPWISE projects in Europe. If technologies that apply CCS to blast furnaces are successfully commercialised, they could enable retrofits and thus play an important role in addressing emissions from plants already built or to be built in the next decade. Some projects are specifically focused on converting steel off-gases to fuels or chemicals; their contribution to emissions savings is dependent on various factors, including what product they displace and what happens to the embodied CO_2 when the fuel is used or the product reaches end of life. While CCU could be useful for some applications and for helping develop capture technologies, in the longer term CCS will also be needed. Efforts are also underway to replace a portion of injected coal in blast furnaces with torrefied biomass (TRL 7) or hydrogen (TRL 6).

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Table 4.2 Status of main emerging technologies in the iron and steel sector

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Carbon capture, utilisation and storage			
Blast furnace: off-gas hydrogen enrichment and/or CO_2 removal for use or storage	5	2030 (Very high)	• Japan's COURSE 50 project has completed the first experimental testing phase; the second phase aims to reach full commercial scale by 2030; it can be deployed with CCUS (JISF, 2011). • Top gas recycling using vacuum pressure swing absorption proven in an experimental blast furnace under ULCOS (EC, 2014). Concepts being further developed at the ArcelorMittal site in Dunkirk, France. IGAR project testing reforming with plasma torches, with a lab-scale pilot successfully completed in 2017 and an industrial-scale demonstration likely to be completed by 2025-27. The "3D" project launched in mid-2019 by a consortium of 11 stakeholders will test amine-based carbon capture for blast furnace process gases, aiming for pilot scale (4 kt/yr CO_2) by 2021 and industrial scale (1 Mt/yr CO_2) by 2025. Final arrangement would feed plasma torches with recovered CO_2 from process gases. (ArcelorMittal, 2019a; 2019b; 2017). • The ROGESA pilot is testing H_2-rich coke oven gas in a blast furnace in Germany, with implementation in two blast furnaces expected as early as 2020 (Saarstahl, 2019). • The STEPWISE project is piloting a technology in Sweden to decarbonise blast furnace gas for use in power production (14 t/day CO_2 removal) (STEPWISE, 2020).
Blast furnace: Converting off-gases to fuels	8	Today (Medium)	• The first commercial plant began in 2018 in China by Lanza Tech, Shougang Group and TangMing; it produced 30 million litres of ethanol for sale in its first year of operation (Lanzatech, 2018; 2019). A second large-scale plant is under construction in Ghent, Belgium under the Steelanol/Carbalyst project by ArcelorMittal and Lanzatech, to be completed by early 2021 and with a capacity of 80 million litres of ethanol (ArcelorMittal, 2019a). • The FReSMe project, by a consortium of European partners, is piloting steel off-gas conversion to methanol (1 t/day); it builds on research from the STEPWISE project on CO_2 capture and the MefCO2 project on producing methanol from CO_2 (FReSMe, 2020; EC, 2019).
Blast furnace: Converting off-gases to chemicals	7	2025 (Medium)	• The Carbon2Chem pilot plant in Germany initiated by thyssenkrupp in 2018 has produced ammonia and methanol from steel off-gases; it is aiming for an industrial-scale plant by 2025 (thyssenkrupp, 2020a; 2020b). • Carbon4PUR, a project by a consortium of 11 partners across Europe, is piloting converting steel off-gases to polyurethane foams and coatings (20 t/yr) (Carbon4Pur, 2020).
DRI: Natural gas-based with CO_2 capture	9	Today (Very high)	• Operating plant since 2016 in Abu Dhabi with 0.8 Mt/yr of CO_2 capture capacity, with CO_2 used for enhanced oil recovery at nearby oilfield (ADNOC, 2017). • Two plants of Ternium in Mexico operating since 2008 capturing 5% of emissions (0.15-0.20 Mt/yr combined) for use in the beverage industry, with planning underway to upscale capture capacity (Ternium, 2018). • Commercial Finmet plant since 1998 at Orinoco Iron, Venezuela with amine-based CO_2 separation achieving close to 100% CO_2 concentrations as an integral part of the process, but captured CO_2 is not currently used or stored.*
Smelting reduction: with CCUS	7	2028 (Very high)	• Developed by the ULCOS consortium, the HIsarna pilot plant is currently operating at a Tata Steel plant in Ijmuiden, Netherlands (60 kt steel produced, CCS not yet implemented) (Tata Steel, 2017); a demonstration scale (0.5 Mt/yr) plant (TRL8) is expected in 2023-27 in India and an industrial scale (1.5 Mt/yr) plant with CCS (TRL 9) is targeted in the Netherlands in 2027-33. • Initial testing of amine-based CO_2 scrubbing in FINEX plant (Primetals, 2020).

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Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Hydrogen			
Blast furnace: Electrolytic H_2 blending	7	2025 (Medium)	Since 2019, thyssenkrupp has been testing the use of hydrogen in a blast furnace in Germany, replacing a portion of injected coal (thyssenkrupp, 2019).
DRI: Natural gas-based with high levels of electrolytic H_2 blending	7	2030 (High)	• In the 1990s, Tenova tested 90% hydrogen use in Mexico (scale of 9kt/yr DRI production) (Tenova, 2018). • Salzgitter steelworks is undertaking MW-scale electrolyser demonstration in Germany and conducting a feasibility study for integrating a hydrogen DRI plant into the existing site, as part of the SALCOS project (SALCOS, 2019). • thyssenkrupp is planning to build commercial DRI plants incorporating hydrogen by the mid-2020s (thyssenkrupp, 2020b).
DRI: Based solely on electrolytic H_2	5	2030 (Very high)	• Pilot plant began operation in August 2020 in Sweden as part of the HYBRIT project; targeting a 1 Mt/yr demo plant by 2025 (HYBRIT, 2020). • Pilot plant under design also in Hamburg lead by ArcelorMittal, to be built by 2030 (ArcelorMittal, 2019c). • Thyssenkrupp is also planning to transition towards eventually full hydrogen reduction (thyssenkrupp, 2020b).
Smelting reduction: H_2 plasma reduction	4	--- (Medium)	• SuSteel research project at voestalpine plant in Austria; currently in the process of upscaling a 100 g reactor to 50 kg batch operation, aiming for commissioning in 2020 (K1MET, 2018; Primetals, 2019). • Flash Ironmaking Technology under development at the University of Utah, with a mini pilot reactor commissioned (Sohn et al., 2017).
Ancillary processes: H_2 for high-temperature heat	5	2025 (High)	• In early 2020, Ovako and Linde completed a successful trial of using hydrogen to heat steel before rolling in Sweden (Ovako, 2020). • CELSA (a recycled steel producer), Statkraft and Mo industrial park in Norway signed an agreement in mid-2020 to produce hydrogen to replace fossil fuels used in steel production (Statkraft, 2020).
Direct electrification			
Electrolysis: Low-temperature alkaline	4	--- (Medium)	Siderwin project building on the ULCOWIN process (electrowinning), previously developed by the ULCOS programme; working towards developing a pilot-scale plant by the end of 2020 (Siderwin, 2019).
Electrolysis: High-temperature molten oxide	4	--- (Medium)	• ULCOS proposed a concept called MIDEIO during its 2004-12 work programme (Wiencke et al., 2018). • Research at Massachusetts Institute of Technology led to the founding of Boston Metal, which commissioned the first prototype cell in 2014 (more than 1 t of metal produced); now aiming for pilot-scale size plant (Boston Metal, 2019).
Bioenergy			
Blast furnace: Torrefied biomass	7	2025 (Medium)	The Torero partnership project is testing the use of bio-coal (torrefied waste wood) to partially substitute coal in ArcelorMittal's plant in Ghent, Belgium; the large-scale demonstration is expected to be operational by the end of 2020 (ArcelorMittal, 2019a).
Blast furnace: Charcoal	10	Today (Medium)	Charcoal is currently being used commercially to substitute for a portion of the coal used in blast furnaces, primarily in Brazil. Some development continues to further optimise charcoal production to improve its product specifications for steel production.

* Personal communication with Christian Boehm (2020), Primetals.

Notes: DRI = direct reduced iron. CCUS = carbon capture, utilisation and storage. For CO_2 capture technologies, the specified technology readiness level (TRL) refers to the whole carbon capture and utilisation or carbon capture and storage value chain applied within the iron and steel sector (whichever is at a higher TRL), rather than the TRL of the capture technology only.

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Other R&D projects are focused on reducing emissions by adapting technologies other than the blast furnace. CCS was applied commercially in steelmaking for the first time with the commissioning of a DRI plant with CCS in 2016 in Abu Dhabi, which stores the captured CO_2 via enhanced oil recovery. Oxygen-rich smelting reduction also presents a promising option for applying carbon capture, given that the off-gases have a very low nitrogen content (compared to a relatively high nitrogen content in typical blast furnace off-gases), which makes separation considerably more cost-efficient. The HIsarna project is developing a process of this kind that could lead to a 90% reduction in CO_2 emissions compared to conventional blast furnace production. A pilot plant is already operational in the Netherlands (TRL 7), although not yet connected to storage, and there are plans to build a demonstration-scale plant in India as well as a commercial-scale plant in the Netherlands during the period 2023-33.

Initial testing is also underway to integrate full carbon capture and storage into the already commercial COREX and FINEX smelting reduction technologies. These technologies currently incorporate physical CO_2 scrubbing using pressure swing adsorption in order to isolate higher ratios of CO and H_2 for recirculation to the smelting reduction process or for use in a subsequent direct reduction plant. Upgrading to an amine-based chemical CO_2 scrubbing capture system would lead to CO_2 concentrations in the tail gas that are suitable for CO_2 use or storage.

A number of efforts are also being made to integrate electrolytic hydrogen into DRI production, either through blending to replace a portion of natural gas, or more ambitiously through 100% hydrogen-based reduction. If zero-emission electricity were to be used to produce the hydrogen, the latter would lead to virtually zero-emission primary steel production. It is already possible to use electrolytic hydrogen to displace up to 30% of natural gas in commercial DRI furnaces, but blends involving more than 30% displacement require further development (TRL 7) and the use of 100% electrolytic hydrogen is still at the pilot stage (TRL 5). There is, however, a good deal of piloting and developmental work going on. The SALCOS project in Germany is demonstrating an electrolyser at the MW-scale alongside a feasibility study for integrating a hydrogen DRI plant into its existing site, while thyssenkrupp is planning to build commercial DRI plants incorporating hydrogen by the mid-2020s. In Sweden, the HYBRIT project began operation of a pilot plant in August 2020 using 100% electrolytic hydrogen from non-fossil fuel sources, and a demonstration plant is being targeted by 2025. A separate project led by ArcelorMittal is also aiming for a pilot plant with full hydrogen production in Germany by 2030.

Technologies currently at demonstration phase (i.e. TRL of 7 or more) start to be deployed within a decade in the Sustainable Development Scenario, while those currently in prototype phase (i.e. TRL of 5 to 6) are commercially deployed from the mid-2030s, with some initial ramp-up taking place earlier (Figure 4.11). Technologies

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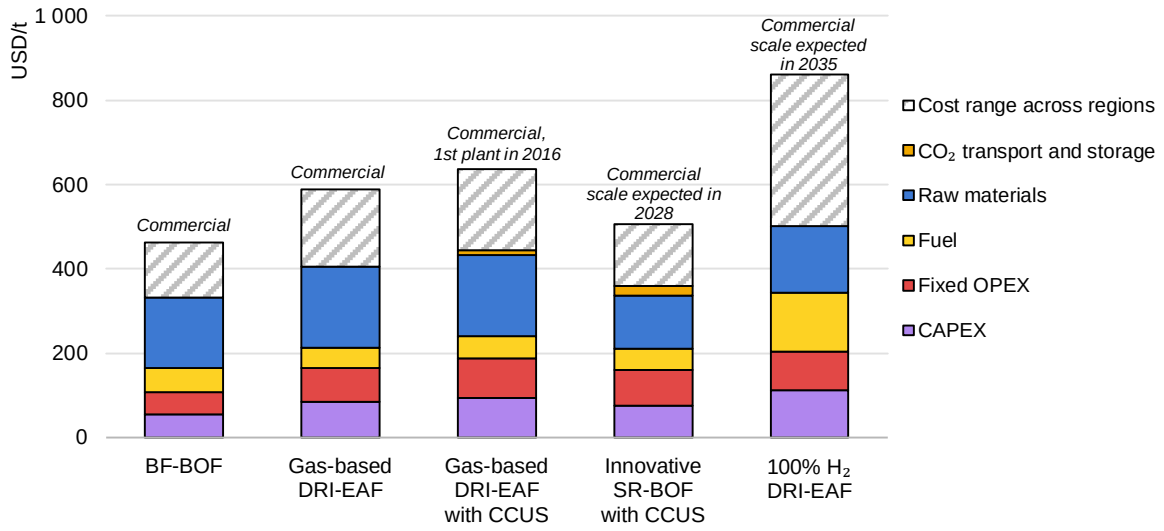
with a TRL of 4 and below, including direct iron ore electrolysis and hydrogen plasma reduction, are not factored into the Sustainable Development Scenario, given the lack of availability of reliable techno-economic information, but we nonetheless explore the potential of some of these early-stage technologies to deliver further emissions reductions across the energy system in Chapter 6.

Figure 4.13 Levelised cost of steel production for selected production routes when they reach commercialisation



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Notes: BF-BOF = blast furnace-basic oxygen furnace. DRI-EAF = direct reduced iron-electric arc furnace. CCUS = carbon capture, utilisation and storage. SR-BOF = smelting reduction-basic oxygen furnace. OPEX = operating expenditures. CAPEX = capital expenditures. Presented costs consider regional variation. Fuel costs: natural gas = USD 2-10/MBtu (million British thermal units), thermal coal = USD 35-80/tce (tonne coal equivalent), coking coal = USD 75-155/tce and electricity = USD 30-90/MWh. CO_2 streams are captured with a 90% capture rate. CO_2 transport and storage = USD 20/tCO_2 captured. CAPEX comprises process equipment costs (including air separation units, carbon capture equipment and electrolysers where applicable) plus engineering, procurement and construction costs. An 8% discount rate, 25-year lifetime and a 90% capacity factor are used for all equipment. Electrolyser CAPEX = USD 452/kW_e (kilowatt electrical capacity) and OPEX = USD 7/kW_e. No regulatory cost on emitting CO_2 is imposed in this analysis.

Innovative technologies for steel production are generally around 10-50% more expensive than their commercially available counterparts, with the gas-based DRI with CCUS and H_2 DRI being highly sensitive to the cost of natural gas and electricity respectively.

Cost will be crucial to determining which of the emerging innovative technologies for producing low-CO_2 steel are ultimately deployed. The innovative process routes considered within this analysis generally cost around 10-50% more than commercially available commercial counterparts within a given regional context, a cost increase significantly exceeding profit margins from steel production today (Figure 4.13). The future costs of CAPEX, OPEX, energy and raw material costs are all highly uncertain for all the emerging innovation technologies under consideration, so ranges are necessary to explore the key sensitivities. Among the emerging low-emissions technologies, the innovative smelting reduction route at present seems

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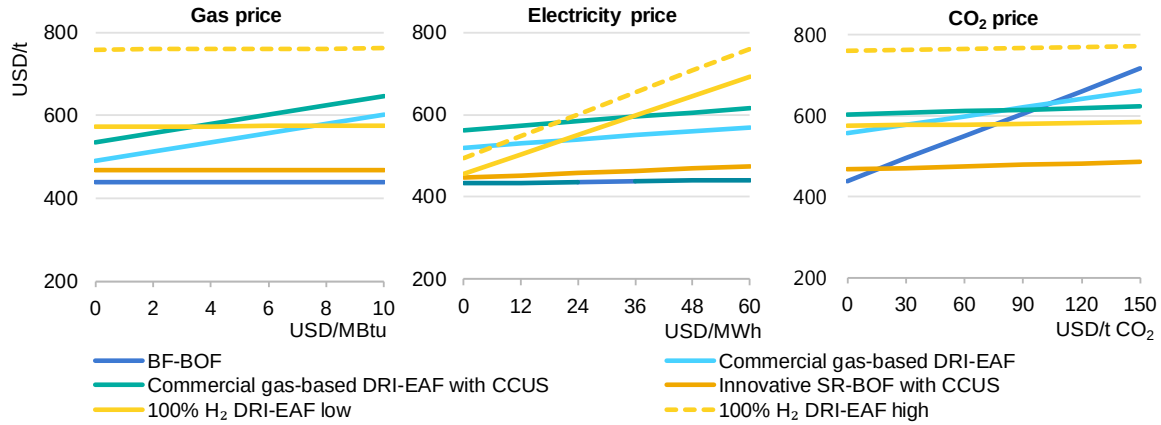
likely to have the lowest overall production cost in most regions on the basis of the typical ranges of energy prices seen today, and the lowest estimated capital and operating costs at commercial scale.

Figure 4.14 Levelised cost of steel production for selected production pathways at varying gas, electricity and CO_2 prices



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Notes: BF-BOF = blast furnace-basic oxygen furnace. DRI-EAF = direct reduced iron-electric arc furnace. CCUS = carbon capture, utilisation and storage. SR-BOF = smelting reduction-basic oxygen furnace. Fuel costs: natural gas = USD 6/MBtu, thermal coal = USD 70/tce, coking coal = USD 140/tce and electricity = USD 45/MWh. CO_2 streams are captured with a 90% capture rate. CO_2 transport and storage = USD 20/tCO_2 captured. Includes engineering, procurement and construction costs. "H_2 DRI-EAF low" corresponds to an electrolyser cost of USD 285/kW_e and lower heating value efficiency of 74%. "H_2 DRI-EAF high" corresponds to an electrolyser cost of USD 1 067/kW_e and lower heating value efficiency of 64%. Left- and right-hand side graphs use electricity costs of USD 60/MWh for "H_2 DRI-EAF high" and USD 30/MWh for "H_2 DRI-EAF low". An 8% discount rate, 25-year lifetime and a 90% capacity factor are used for all equipment.

At a gas price of USD 6/MBtu, the H_2 DRI route becomes competitive with its gas-based counterpart equipped with CCUS at electricity prices below USD 35/MWh.

The economics of the gas-based DRI with CCUS and H_2 DRI processes are particularly sensitive to the cost of gas and electricity respectively. In the absence of sufficiently high CO_2 prices, switching to hydrogen produced via electrolysis for DRI-EAF steel production would increase overall costs, making it less competitive with conventional gas-based DRI-EAF and BF-BOF routes, except where electricity prices are very low. To compete in the long term with its natural gas-based counterpart equipped with CCUS, the H_2 DRI would need reliable low-carbon electricity prices below USD 35/MWh, based on estimates of likely capital and operating costs at the time of commercialisation and a gas price of USD 6/MBtu (Figure 4.14). These prices may be achievable in certain regions with ample low-cost renewable resources, but those regions may not be well-endowed with reserves of iron ore and other input materials. Furthermore, there is an ongoing need to demonstrate the flexible operation of relevant near-zero emissions pathways for steelmaking (e.g. the H_2 DRI route) and other bulk materials, in combination with variable renewable electricity and buffer storage systems where applicable. Existing industrial hubs are likely to

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contribute significant inertia in the determination of where future production will take place. Ports, railways and other trade infrastructure take decades to develop and are not usually viable propositions on the basis of a single project.

While the additional cost of producing steel via innovative processes is considerable on a "per tonne of primary steel production" basis relative to conventional routes, this needs to be put into context. There is much uncertainty about future costs for a number of reasons, one of which is that the future prices of steel, iron ore and scrap are impossible to predict through to 2070. We estimate, however, that the average increase in the cost of steel production by 2070 in the Sustainable Development Scenario is around 15% relative to today, with the size of the uplift in the cost of primary production being partially cushioned by the much larger share of secondary production, which is substantially less energy-intensive than primary production and therefore less expensive. At the consumer end, it is worth noting that only a small fraction of the cost of most end-use goods is attributable to the cost of the steel embedded in them. We estimate that the construction cost of an average family home (costing USD 300 000) would be 0.4% higher, while an average mid-sized car (costing USD 25 000) would increase in cost by around 0.2%.

Cement production

Sector overview and demand outlook

The production of cement – the binding agent for making concrete[11] and a primary input to the construction industry – currently emits large amounts of CO_2, both from the combustion of fossil fuels used to generate process heat and from the chemical reaction that forms an integral part of the production process, the latter of which are known as process emissions. Concrete is the second-most consumed substance on Earth after water, with half a tonne of cement being used each year for every person on the planet, so reducing emissions from cement production could make a significant contribution to global efforts to tackle climate change. About half of all the cement used in the world goes to construction of residential and non-residential buildings, while the rest is used in making various types of infrastructure, including roads, railways and energy facilities.

Making cement requires large amounts of energy for process heat to produce a lumpy substance known as clinker – the key active ingredient in cement – from a mixture of limestone and clay in a kiln, which is then mixed with gypsum and sometimes other elements like slag, fly ash and limestone, and crushed and ground

[11] Concrete is made by mixing roughly 10-15% cement in terms of mass (depending on the end-use application) in conjunction with aggregates such as sand, gravel and crushed stone, as well as water and chemical additives.

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into a fine powder. Around 2.8 GJ (0.07 toe) of energy are needed to produce 1 t of cement on average, with energy typically accounting for between about 15% and 40% of total cement production costs. The production of 1 t of cement emits 0.5-0.6 tCO_2 on average. In 2019, the sector consumed 280 Mtoe of energy, accounting for 7% of total industrial energy use, and emitted 2.4 $GtCO_2$, or around 26% of total industrial emissions (about 7% of world energy sector emissions, including process emissions). Of those emissions, around two-thirds are process emissions.

Abating emissions from cement is difficult and costly for several reasons:

- **Process emissions:** Direct emissions from cement production occur through a chemical process called calcination, which occurs when limestone, which is made of calcium carbonate ($CaCO_3$), is heated, causing it to break down into calcium oxide (CaO) and CO_2. In practice, these emissions can only be reduced by capturing and ultimately storing the CO_2, by reducing the need for clinker by blending it with other cementitious materials (e.g. fly ash and blast furnace slag), or by using alternatives to limestone to produce binding agents that generate less CO_2. These technologies are generally either at a pre-commercial stage of development or are restricted by building regulations in many countries in the case of the latter two options.
- **Fossil fuel-based process:** The clinker production process is highly energy-intensive and tends to rely heavily on coal, which is generally the cheapest source of energy. While alternative fuels like bioenergy and waste are an option, sustainable biomass availability is limited and faces competition from other end uses, while the CO_2 footprint of non-renewable waste is very variable: in some cases, the emissions from such waste are higher than those of coal. Given the high temperatures, the large quantities of energy needed and the technical requirements of kilns, switching to direct electrification, hydrogen or direct heating from concentrated solar power would be technically challenging and very costly. Work on some of these switching options is underway, but it is at an early stage of development.
- **Regional constraints:** Cement plants are highly dispersed geographically, and are often located close to sources of raw materials and to centres of cement demand. They normally make use of locally available energy resources, which may mean limited access to cost-effective, low-carbon fuels (e.g. biomass). Furthermore, the limited regional availability of alternative constituents of cement may constrain the extent to which particular cement plants can lower emissions through reducing their clinker-to-cement ratio. While cement is less internationally traded than chemicals and steel, some trade of clinker is possible, and this means that large cost increases could well undermine competitiveness.

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- **Long-lived capital assets:** The fact that cement factories last a long time hinders the pace at which they can be replaced with new ones using lower emission technologies without early retirement. Many of these facilities have been added to the existing stock in the past decade or so, and further additional capacity is also expected to be added in developing regions in the coming decade. Retrofits of existing capacity with CCS technologies are therefore likely necessary (see Chapter 1), perhaps together with conversion of some assets to enable them to process alternative lower emission raw materials like calcined clay.

Cement and concrete naturally reabsorb CO_2 from the air throughout the lifecycle of the materials and building components of which they become a part. This process, known as recarbonation, occurs at very slow rates for in-use buildings and infrastructure, and at somewhat quicker rates for waste arising from cement kilns and during the construction and demolition of concrete structures. The amount of CO_2 absorbed can vary considerably depending on factors such as surface area and the intensity of atmospheric exposure. Studies suggest that about 10-30% of the emissions generated during the production of cement are typically reabsorbed within the subsequent 50-100 years of the material's lifecycle (Andersson et al., 2019; Cao et al., 2020). While these impacts on lifecycle CO_2 emissions are non-trivial, they cannot substitute the reductions in emissions required in the production phase – the focus of this energy system analysis.

Cement is indispensable for the construction of all types of buildings and infrastructure, including facilities in the energy sector, so demand for it is linked to economic activity and a region's stage of economic development. Despite the decline in demand of around 4% expected in 2020 due to the Covid-19 crisis, cement demand is projected to continue rising in the longer term, especially in emerging economies that have growing populations and infrastructure needs. In the more advanced developing economies that have already industrialised to a large degree, such as China, construction activity and, therefore, cement demand has already stabilised and is beginning to decline, as the huge wave of construction over recent years recedes. In advanced economies, cement is used largely for maintaining existing infrastructure and replacing it when it becomes non-repairable, so demand is much lower.

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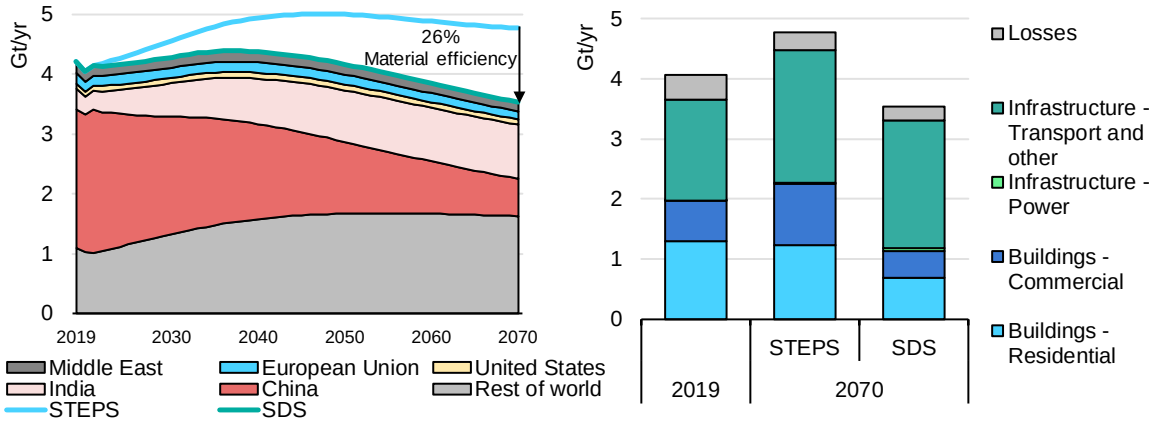
Figure 4.15 Global cement production by region and end use, 2019-70



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Losses represent onsite construction waste and other losses throughout the value chain.

Material efficiency gains have the potential to reduce global cement demand substantially, notably in China and the advanced economies.

As with other industrial sectors, there is considerable potential for material efficiency gains to curb the demand for cement and the need for energy to make it, while providing the same level of services from buildings and infrastructure. In the Sustainable Development Scenario, material efficiency measures cut global cement demand in 2070 by one-quarter compared with the Stated Policies Scenario (Figure 4.15). The main measures that yield these gains are higher renovation rates to extend the lifetime of existing buildings, lower levels of waste on construction sites and the optimisation of building designs to reduce the materials needed to construct the same floor area. In the Sustainable Development Scenario, global demand progressively falls to around 3.5 Gt by 2070 – about 15% lower than in 2019 – with a sizeable contraction in China and advanced economies more than offsetting growth in India and other developing economies. A more detailed discussion of material efficiency measures that could curb cement (and steel) demand in the buildings construction sector can be found below in the section "Bulk materials for construction".

Technology pathways towards net-zero emissions

In the Sustainable Development Scenario, global CO_2 emissions from cement production fall by more than 90%, from 2.4 Gt in 2019 to just 0.2 Gt in 2070 (Figure 4.16). The size of this reduction reflects a large role from CO_2 capture and storage, through which over 80% of the total CO_2 generated in 2070 is captured. In the Stated Policies Scenario, on the other hand, emissions are relatively constant over the modelling period, increasing slightly to a peak of 2.6 Gt in 2040 due to growth in

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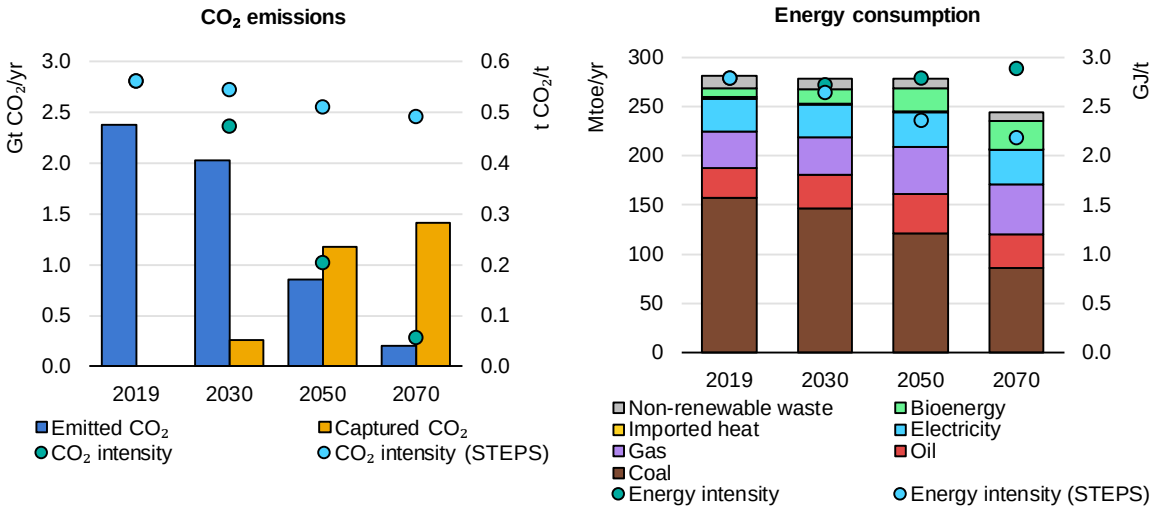
production before declining with a small drop in production to 2.3 Gt in 2070 – a level 12 times higher than in the Sustainable Development Scenario.

There is no silver bullet for decarbonising the cement sector: a range of technological solutions are needed to achieve the emissions trajectory of the Sustainable Development Scenario, and their relative contributions vary over time according to their maturity and relative costs. Reductions in demand levels facilitated by the adoption of material efficiency strategies contribute a quarter of cumulative reductions to 2070 (Figure 4.17). Many measures that reduce demand are already mature from a technology standpoint, and they play a particularly large role over the next decade, accounting for about 40% of reductions to 2030. Over time, demand reduction strategies that are currently at earlier stages of development also play an increasingly important role.

Figure 4.16 Global cement sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70



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Notes: STEPS = Stated Policies Scenario. Energy intensity here includes all energy used per tonne of cement, including additional energy needs for some strategies deployed in the Sustainable Development Scenario – chemical absorption carbon capture and storage, calcined clay use and alternative fuel use. This explains the increasing overall energy intensity by 2070.

CO_2 emissions from the cement sector fall by around 90% between 2019 and 2070 in the Sustainable Development Scenario, largely due to material efficiency and the large-scale deployment of CCUS.

In addition to the cement demand reduction measures discussed above, about 35% of material efficiency-related emissions reductions and 14% of total cumulative emissions reductions for cement come from a fall in the clinker-to-cement ratio. This strategy reduces the need for emissions-intensive clinker through the addition of other less energy-intensive materials to blended cement mixes. In 2019, clinker made

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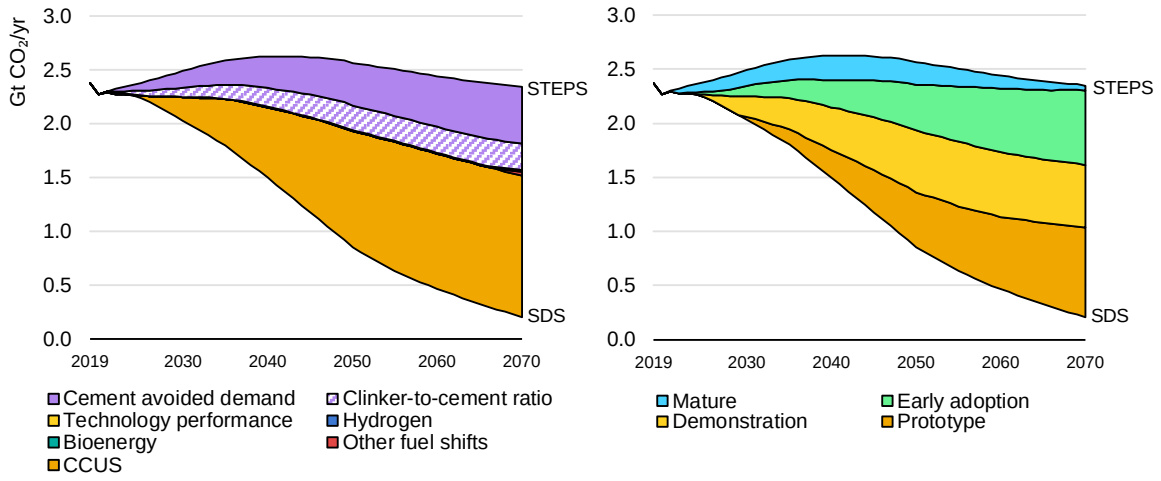
up about 71% of cement on average worldwide, with blast furnace slag and fly ash from coal plants accounting for a significant proportion of the rest. The supply of these materials falls significantly in the Sustainable Development Scenario, which increases reliance on alternatives like limestone and calcined clay (Figure 4.18). While the availability of these materials is constrained in some parts of the world, global reserves of raw clay are more than adequate to meet projected demand.

Figure 4.17 Global CO_2 emissions reductions in the cement sector by mitigation strategy and current technology maturity category, 2019-70



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. Cement avoided demand and clinker-to-cement ratio both fall within the broader category of material efficiency. The thermal energy used by chemical absorption CCUS deployment is subtracted from the CCUS contribution, and thus does not impact the efficiency contribution. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

Material efficiency and CCUS together play the leading role in reducing cement sector emissions in the Sustainable Development Scenario. Over 60% of cumulative reductions come from technologies that are not yet commercially available.

Incremental gains in technology performance play a minor role, as most of the potential has been exploited in recent decades, mainly due to the phase-out in most regions of wet kilns and traditional vertical kilns.[12] The most efficient kiln commercially available today is the dry kiln with a precalciner and a staged cyclone preheater.[13] It has already been deployed extensively, including in China and India, which are the largest cement-producing countries. Some CO_2 reduction measures deployed in the Sustainable Development Scenario require more energy inputs, partially offsetting the energy savings from switching to modern kilns and resulting

[12] Wet kilns involve adding water to the slurry fed into the kiln and thus require more energy for drying. Vertical kilns are less efficient in heating the slurry.

[13] The precalciner and staged cyclone preheater are units that heat the raw materials before they enter the kiln.

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in a higher energy intensity compared to the Stated Policies Scenario. For example, using calcined clay requires considerable energy for processing even after recent energy efficient improvements, while using bioenergy and waste leads to somewhat higher energy needs for pre-treatment to ensure uniform composition and optimum combustion, as well as to minimise the content of potentially problematic substances. In addition to thermal energy intensity improvements, switching to more efficient grinding technologies, such as from ball mills to high-pressure grinding rolls and vertical roller mills for the grinding process, leads to a reduction in electricity intensity, while efficiency is also improved by onsite power generation using excess heat recovered from the kiln. However, much of the remaining potential for technology performance improvements is already exploited in the Stated Policies Scenario, leading to minimal additional gains in the Sustainable Development Scenario.

Fuel switching – mainly from coal to natural gas, hydrogen, biomass and renewable waste (including waste wood, sawdust and sewage sludge) – makes a relatively minor contribution to emissions reductions in the Sustainable Development Scenario, accounting for about 1% of cumulative reductions. Both renewable waste and non-renewable waste (including tyres, waste oil, plastics and municipal solid waste) are in use today. Use of non-renewable waste, which can have CO_2 intensities higher than coal in some cases, is reduced by 35% by 2070. Rigorous emissions accounting of mixed renewable and non-renewable wastes needs to be undertaken to determine in what instances its use leads to emission reductions.

Use of hydrogen plays a very small role via the blending of hydrogen into natural gas grids. Larger scale use of hydrogen faces considerable technical challenges and would require big changes to equipment and practices. The challenges include the high combustion velocity and non-luminous flame of hydrogen, which makes it difficult to monitor optically; the comparatively lower radiation heat transfer, which requires other media to be introduced into the fuel stream, necessitating redesign of burners to deal with the new media; the corrosiveness of hydrogen when in contact with some metals, necessitating new coatings inside kilns; and the intermittency of hydrogen sourced from variable renewables, which leads to a requirement for storage facilities (IEA, 2019). Given these challenges, as well as the early TRL and expected high costs of hydrogen use in kilns, hydrogen is likely to play a much smaller role in the cement sector than in the chemicals and steel sectors. Direct electrification is also at too early a stage of development to play a role in cement in the Sustainable Development Scenario.

The leading source of emissions reductions is CCUS, which accounts for 60% of cumulative reductions to 2070. While it begins to play a role in the mid-2020s as the most advanced capture types become commercially available, its role increases particularly after 2030 as additional capture types are commercialised and costs fall

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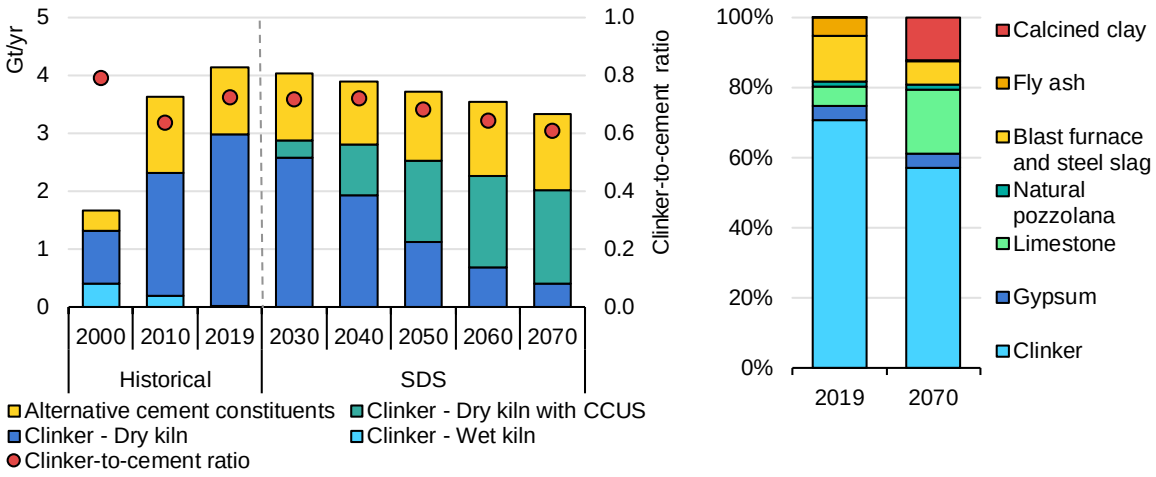
with economies of scale and technological learning. The projected pace of deployment is equivalent to an average of 41 new 2 Mt annual capacity cement plants (existing or new-build) around the world being equipped with CO_2 capture equipment every year – or nearly one every week – over the period 2030-70. By 2070, 80% of clinker production is equipped with CCUS, and a total of over 40 $GtCO_2$ is captured cumulatively. The extent to which different CO_2 capture technologies are used changes over time as their performance and cost change with scaling up and learning.

Figure 4.18 Global cement production by technology and material composition in the Sustainable Development Scenario, 2000-70



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Notes: SDS = Sustainable Development Scenario. CCUS = carbon capture, utilisation and storage. While historically vertical shaft kilns were considerably less efficient than dry kilns, recent technology improvements have brought their efficiency towards the level of dry kilns (Tsinghua University, 2008). Thus, inefficient shaft kilns are grouped with wet kilns while efficient shaft kilns are grouped with dry kilns. Wet kilns include semi-wet/semi-dry.

Adoption of CCUS technologies in the cement sector, along with a reduction in the clinker-to-cement ratio, is needed in the long term to achieve the Sustainable Development Scenario emissions trajectory.

The deployment of CO_2-reduction technologies in the cement industry is broadly similar across regions in the Sustainable Development Scenario. Nonetheless, there are some differences in the contribution made by reductions in the clinker-to-cement ratio as its potential is highly dependent on the local availability of the materials that are capable of replacing clinker, as well as on the required properties of the final concrete product, which are determined by local standards and end-use applications. The potential also varies according to the extent to which it has already been exploited. For example, China already has a comparatively low clinker-to-cement ratio (0.65 in 2019), and based on raw material availability and current building standards, its ratio is expected to remain relatively low (it could fall further with technological advances). Brazil is expected to remain a leader in calcined clay

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production, having produced about 2 Mt per year since the 1970s. Regions like Italy that have good availability of natural pozzolana – an alternative cement constituent – rely more on that to lower cement-related emissions. Regions that move to concrete standards that are not prescriptive and do not require pre-specified amounts of clinker could facilitate increased uptake of blended cements without compromising safety and performance.

Readiness and competitiveness of emerging technologies

Most of the technologies that are deployed in the cement industry over the near term in the Sustainable Development Scenario are already mature or on the verge of large-scale commercialisation. Achieving the required emissions reductions in the longer term hinges on efforts over the next decade to develop technologies that are still being piloted or are at demonstration stage today, and then to use them to replace or retrofit the overwhelming bulk of existing production capacity over the second half of the modelling period. Near-term enhanced support for projects underway may be needed to ensure that the Covid-19 crisis does not hinder progress towards long-term goals. The emerging technology categories with the highest TRLs (above 6) that offer potential for deep emissions reductions include CCUS and alternative cement constituents and binding materials (Table 4.3).

Among CO_2 capture technologies, chemical absorption and calcium looping are the closest to large-scale commercialisation (TRL 7). The first commercial chemical absorption facility opened in 2014 in Texas, although with only partial capture rates of about 15% of emissions. A pilot plant with a much higher capture rate began operation in Wuhu, China in 2018. A large-scale demonstration plant is expected to start operations in 2023 or 2024. Following successful demonstration of calcium looping technologies at pilot scale, a pre-commercial demonstration plant is expected to begin operation in Italy soon, and a commercial-scale plant is expected in Chinese Taipei by 2025. Other capture technologies – including oxy-fuelling, direct separation and novel physical adsorption approaches – are also in the testing phase. The relative contribution of these capture technologies will depend on their success in reaching commercialisation and achieving cost reductions.

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Table 4.3 Status of main emerging technologies in the cement sector

Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Carbon capture, utilisation and storage			
Chemical absorption (partial capture rates, <20%)	8	Today (Medium)	• Commercial facility opened in 2014 at Capitol Aggregates plant in Texas, capturing 15% of emissions (75 $ktCO_2$/yr) for use in materials like baking soda, bleach and hydrochloric acid (Capitol Aggregates, 2020; Global Cement, 2014).
Chemical absorption (full capture rates)	7	2024 (Very high)	• Successful industrial-scale feasibility study in 2016 at the Norcem plant in Norway; operations of full-scale plant (0.4 $MtCO_2$/yr) expected in 2023/24 (Norcem, 2020). • Industrial-scale feasibility study being conducted at the Lehigh Cement plant in Canada (0.6 $MtCO_2$/yr) (Lehigh Hanson, 2019; Voorhis, 2019). • Dalmia Cement will undertake large-scale demonstration (0.5 $MtCO_2$/yr) at plant in India (Perilli, 2019). • Anhui Conch pilot plant (50 $ktCO_2$/yr) began operation in 2018 in China (Global CCS Institute, 2018b).
Calcium looping	7	2025 (Very high)	• Testing at Heping Plant by Taiwan Cement since 2017, pilot-scale trials successfully completed; aiming for commercial scale (0.45 $MtCO_2$/yr) by 2025 (Taiwan Cement, 2020; Cemnet, 2019). • Pilot-scale demonstration completed by CEMCAP in Germany; pre-commercial retrofit demonstration (1.3 Mt cement/yr) in Italy by CLEANKER project expected to begin in 2020 (Buzzi Unicem, 2019; Hornberger, Sporal and Scheffknecht, 2017; Jordal, 2018).
Oxy-fuel	6	2030 (High)	• Successful pilot in kiln precalciner in Denmark (Davison, 2014). • The European Cement Research Association aims to develop oxy-fueling; however, its two proposed pilot plants appear to be on hold due to funding challenges (ECRA, 2020a). • A joint research initiative by four European cement producers, formed in late 2019, is planning to build a semi-industrial oxy-fuel test facility in Germany (Beumelburg, 2019).
Novel physical adsorption (using silica or organic-based adsorption)	6	2035 (High)	• The CO2MENT project in Canada launched trials in 2019 of Svante's CO_2 capture technology at a LafargeHolcim cement plant; it will trial using the CO_2 for low-carbon fuels and concrete (LafargeHolcim, 2019; Financial Post, 2019). • In early 2020, several companies announced a joint study to assess the design and cost of a commercial facility (0.725 $MtCO_2$/yr) at the Holcim Portland cement plant in Colorado, United States (Total, 2020).
Direct separation	6	2030 (High)	• Successful pilot-scale demonstration at the Heidelberg Cement plant in Belgium by the LEILAC project in 2019, targeting large-scale demonstration in 2025 (0.1 $MtCO_2$/yr) (LEILAC, 2019; Perilli, 2020).
Other capture technologies	4-5	--- (Medium)	• Various other capture technologies could be applied to cement, including membrane separation, chilled ammonia process and cryogenics. Some laboratory and small-scale trials have taken place, but these technologies remain in relatively early development stages (ECRA, 2017; Sayre et al., 2017; Pérez-Calvo, 2018).
Sequester/ mineralise CO_2 in concrete and other inert carbonate materials	9	Today (Medium)	• Multiple commercial-scale plants using CO_2 for producing aggregates or in concrete curing (Carbon8, 2020; CarbonCure, 2020; Blue Planet, 2020). • Sinoma International and CNBM completed a project in 2016 in China that uses CO_2 to produce precipated barium carbonate (50 kt/yr).* • CO2Min, led by HeidelbergyCement and RWTH Aachen University, has proven the ability of olivine and basalt to absorb CO_2 (Beumelburg, 2017; Stopic et al., 2019). • The FastCarb project in France is investigating accelerated carbonation in recycled concrete aggregates; research is currently at the lab scale (FastCarb, 2020).

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Technology	TRL	Year available (importance for net-zero emissions)	Deployment status
Raw material substitution			
Calcined clay	9	Today (High)	• Currently used in a limited number of countries in low proportions; developed by collaboration between researchers in Cuba, India and Switzerland (Scrivener et al., 2018; UNEP, 2016). • A large-scale flash calciner that would considerably improve the energy efficiency of calcinating clay is under development in China, with two 300 t/day lines already built (Sui, 2020).
Carbonation of calcium silicates	8	Today (Medium)	• First produced in 2014 by Solidia Technologies at a Lafarge plant in the United States, with production now at an additional plant in Hungary; in 2019, a first commercial venture was announced to supply a paver plant (Aggregates Business, 2019).
Magnesium silicates (MOMs)	3	--- (Medium)	• R&D largely remains in university labs; at present, largely on hold after a venture (Novacem in the United Kingdom) ended in 2012 due to lack of funding (Majcher, 2015).
Alkali-activated binders (geopolymers)	9	Today (Medium)	• Some cements already commercially available, but primarily used in non-structural applications. An example is Vertua Ultra Zero developed by CEMEX in Switzerland (CEMEX, 2020). Others are at earlier stages of development.
Direct electrification or heating			
Direct electrification	4	--- (Medium)	• A Feasibility study, beginning in 2017 by the CemZero project in Sweden, has shown that electrification of cement kilns is technically possible; currently exploring the possibility to build a pilot plant (Cementa, 2019; Vattenfall, 2020). • The ELSE project initiated in Norway in 2018 found in a technical feasibility study that electrification of precalciners is probably possible (Norcem, 2018; Tokheim et al., 2019).
Concentrated solar power direct heating	6	--- (Medium)	• The SOLPART project in France successfully commissioned a pilot-scale calcination solar reactor in mid-2019; it aims to open a partially solar-powered cement plant by 2025 (SOLPART, 2019). • US-based start-up Heliogen proved in 2019 at its test facility in the Mojave desert the possibility of generating heat above 1 000°C using concentrated solar power (Heliogen, 2019). • The Paul Scherrer Institute, ETH Zurich and LafargeHolcim are performing a study using concentrated solar power in kilns (LafargeHolcim, 2015).
Hydrogen			
Partial use of hydrogen	4	--- (Medium)	• The Mineral Products Association has received funding to conduct physical trials in the United Kingdom using hydrogen and biomass in combination in a kiln (another trial will test electrical plasma and biomass in combination), aiming for completion by mid-2021 (MPA, 2020).
Decarbonating calcium carbonate	3	--- (Medium)	• Electrolyser-based concept proven through laboratory-scale testing at Massachusetts Institute of Technology, with results published in late 2019 (Ellis et al., 2019).
Technology performance			
Advanced grinding	6-9	Today (Medium)	• Various technologies are at different stages of development, some nearing commercialisation (ECRA, 2017; 2020b).

* Personal communication with T. Sui (2020), Sinoma.

Notes: TRL = technology readiness level. This table aims to include key emerging technologies with good potential to achieve considerable CO_2 emissions reductions. Various other alternative cement constituents and binding materials may also contribute to reducing emissions in cement. This table does not include alternative cement constituents that are already commonly used or do not require considerable further development (e.g. steel slag, fly ash, ground limestone) and alternative binding materials that achieve only moderate emissions reductions and/or may face considerable challenges related to material availability or structural properties. For a full discussion of all alternative cement constituents and binding materials, please see the IEA *Cement Technology Roadmap* (IEA, 2018). For CO_2 capture technologies, the specified TRL refers to the whole carbon capture and utilisation or carbon capture and storage value chain applied within the cement sector (whichever is at a higher TRL), rather than the TRL of the capture technology only.

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CO_2 mineralisation involves the absorption and storage of CO_2 in inert carbonate materials such as concrete or concrete aggregates. As mentioned above, this recarbonation process happens naturally at very slow rates over the lifetime of concrete as it reacts with CO_2 in air. Various methods can be used to accelerate the absorption of CO_2, most of them involving the use of concentrated exhaust streams: this makes mineralisation a CO_2 utilisation technology and a potential source of revenue for captured CO_2. In the case of curing – the process of maintaining adequate moisture and temperature while concrete is being formed by adding water to cement – CO_2 enrichment can actually improve the strength of the concrete. Accelerated CO_2 mineralisation is already used commercially in concrete curing and with aggregates and other inert minerals like barium carbonate. Additional research and development is underway to enable the storing of CO_2 in other mineralised forms, including in recycled concrete aggregates and in olivine and basalt that could be used as concrete aggregates. The amount of CO_2 stored and thus the potential for emissions reductions can vary considerably by process, and total demand for materials with mineralised CO_2 has an upper limit, so storage sites for captured CO_2 from cement production will also be needed.

Alternative cement constituents – materials that reduce the clinker-to-cement ratio of blended cements – also have the potential to bring about near-term emissions reductions. As alternative cement constituents like blast furnace slag and fly ash which are currently used become scarcer in the Sustainable Development Scenario (fewer coal power plants and blast furnaces), other materials will be required. Limestone calcined clay cement is one option that is already being used in some countries to a limited extent and could be further deployed. The technology, which was developed through a partnership among research institutes in Cuba, India and Switzerland, reduces CO_2 emissions by replacing up to 50% of clinker with limestone and calcined clays. Calcining clay does require considerable energy, but research efforts are underway to reduce the energy it requires: these include a large-scale flash calciner under development in China. Natural pozzolana (e.g. rice husk ash, silica fume) and limestone are also likely to play an increasing role.

Cements based on alternative binding materials – in which conventional Portland Cement clinker is fully replaced by binding agents derived from raw materials with different mineralogical compositions but with the same or similar processes and facilities – offer further potential to reduce process emissions. Some alternative binding agents are in commercial use now, but their CO_2 reduction potential is relatively limited and a number of them are facing technical challenges or are applicable only to specific applications (for more information see IEA [2018]). Innovation may help to bring forward options with greater process emissions reductions. Cement based on carbonation of calcium silicates is perhaps one of the most promising alternative binding agent technologies, and a commercial plant is now under development (TRL 8). It can be produced in conventional cement plants

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by modifying the raw material mix, greatly increasing its potential deployment, and it can capture CO_2 during curing (see discussion on CO_2 mineralisation above), potentially leading to zero process emissions in net terms. However, its application is limited to pre-cast applications, as curing needs a controlled environment, and it only works effectively with thin slabs of concrete, because of the slow kinetics of CO_2 during curing.

Magnesium oxides derived from magnesium silicates have strong potential to lower CO_2 intensity by absorbing CO_2 during curing, and have the potential to absorb more CO_2 than the amount released in manufacturing, but this technology is at a much earlier stage of development (TRL 3). Various cements based on alkali-activated binders are under development, with some commercially used today (TRL 9), primarily in non-structural applications, and others at much earlier stages of development. Their CO_2 savings potential is highly variable – ranging from 10% to as high as 97% – and depends on the materials and processes used to produce them (Provis, 2017). Raw material availability may limit their application in some regions, and it may be more efficient in any case to use the raw materials in blended cements than for alkali-activated binders.

In the longer term, other currently less-advanced technologies could play a role in decarbonising the cement industry. Direct electrification of cement kilns, for example, is currently under investigation in Sweden – the concept of using electrical plasma has been proven and the possibility of building a pilot plant is being explored (TRL 4). The partial use of hydrogen in combination with biomass, as well as use of electrical plasma in combination with biomass, is being investigated in early trials in the United Kingdom (TRL 4). Using concentrated solar power to provide high-temperature heat for cement kilns has reached pilot stage (TRL 6), with research projects underway in Europe and the United States, but faces the challenge of solar energy's intermittency and would be limited to areas with sufficiently high solar irradiance. If successfully developed, these various fuel-switching technologies would eliminate fuel combustion emissions, and while they wouldn't address process emissions directly, they would at least result in a purer CO_2 stream of process emissions, making the CO_2 easier to capture. Another early-stage technology proven at the lab scale (TRL 3) is use of an electrolyser to electrochemically decarbonate calcium carbonate prior to clinker production in the kiln: this would produce a concentrated stream of CO_2 that could be captured, together with hydrogen that could be used in subsequent stages of production.

A number of initiatives are examining new techniques for recycling cement and concrete. Today, concrete is recycled by crushing it and reusing it as aggregate, but this is a form of "down-cycling" as the aggregate does not form a substitute for the use of cement. Several projects are aiming to recover concrete fines (particles with grain size of less than 4 mm) produced while recycling concrete, and to use the

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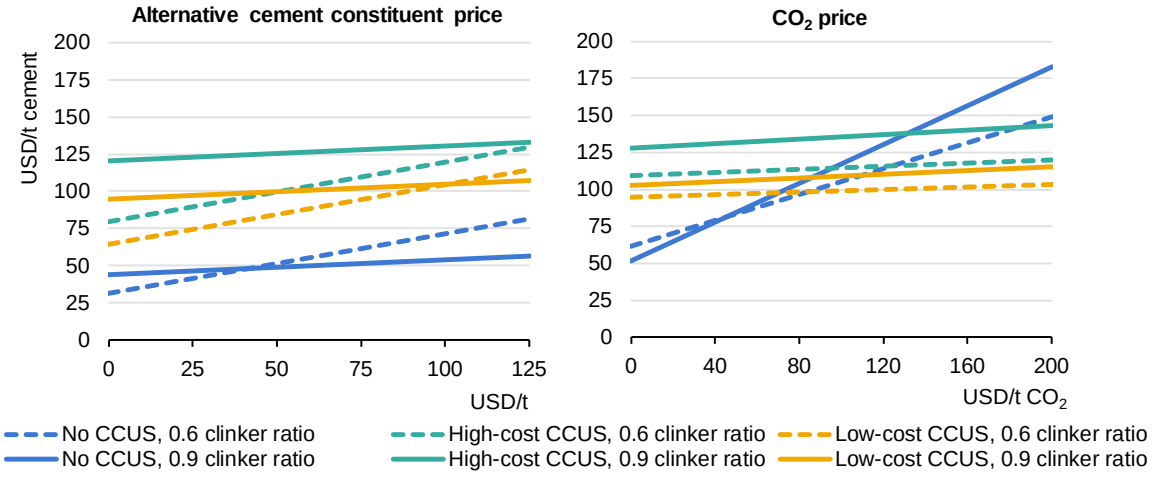
calcium oxide present in place of a portion of limestone in cement kilns, which could reduce process emissions by about a factor of three (University of Lorraine, 2018; VEEP, 2020; Oksri-Nelfia et al., 2015; Lotfi and Rem, 2017). Another initiative has developed a new concrete crushing technology that recovers unhydrated cement (cement that does not come in contact with water during cement curing) from end-of-life concrete for direct use as new cement, thus displacing new production (SmartCrusher, 2020).

Figure 4.19 Levelised cost of cement production under varying techno-economic assumptions



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Notes: CCUS = carbon capture, utilisation and storage. CCUS costs are the expected costs once commercialised, assuming full capture rates (90% of CO_2 captured). CO_2 transport and storage costs of USD 20/tCO_2 captured are included, as are engineering, procurement and construction costs. Assumes best available technology efficiency for kilns of 2.9 GJ/t clinker; fuel mix: 60% coal, 25% natural gas and 15% biomass-based fuels; raw material (limestone) cost for clinker production = USD 4/t; cost for alternative cement constituents in the right-hand graph = USD 75/t. An 8% discount rate, 25-year lifetime and 90% capacity factor are used for all equipment.

At a CO_2 price of about USD 80/tCO_2, CCUS starts to become a cost-competitive option for cement production.

The competitiveness of the different technologies and pathways for reducing CO_2 emissions from cement will vary according to factors such as the level of cost reductions achieved for innovative technologies and regional raw material availability (Figure 4.19). Given their higher TRL levels relative to other options for cement, CCUS and the increased use of alternative cement constituents in order to reduce the clinker-to-cement ratio are currently two of the main competing options. The cost of alternative cement constituents varies by type and according to regional availability. At costs of less than USD 100/t, they are competitive with low-cost CCUS. In other words, it is less expensive to increase alternative constituent blending to the extent possible, thereby lowering the clinker-to-cement ratio, than to produce the additional clinker required in the absence of alternative constituents in a CCUS-equipped

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facility. However, neither technology competes on cost with unabated kilns. For CCUS to be competitive with an unabated kiln, a CO_2 price of between about USD 80/t and USD 130/t would be required (depending on the clinker-to-cement ratio and cost of CCUS). The actual costs of CCUS will depend on the type of technology, and could fall significantly once commercialised on a large scale. Policies such as CO_2 performance standards, minimum market share regulations or market pull incentives could make CCUS competitive in the absence of an adequate CO_2 price.

In the Sustainable Development Scenario, the cost of cement in 2070 is on average 55% higher than in the Stated Policies Scenario in that year, and 60% higher than it is now. This cost increase is sensitive to parameters such as the clinker-to-cement ratio, the eventual cost of CCUS and energy prices, all of which are uncertain and could vary by region. The cost increase in 2070 compared to the Stated Policies Scenario could therefore be as low as 35% or as high as 115%. Fortunately, this cost increase has a minimal effect on end-user prices, given that materials account for a relatively small proportion of the costs of construction projects. For an average detached concrete-framed home in the United States (costing USD 300 000), the construction cost would be only about 0.6% more in 2070 in the Sustainable Development Scenario than in the Stated Policies Scenario due to the increase in cement costs, assuming that material efficiency measures were not adopted. The adoption of material efficiency measures might well nearly eliminate the difference between the construction costs in the two scenarios, as reduced demand for cement would offset most of the increased cost per tonne of cement.

Bulk materials for construction

Overview

The construction sector, as well as being a major industrial consumer of energy, is also a large consumer of raw and intermediate materials, the production of which involves large amounts of energy and, therefore, CO_2 emissions. Global demand for these bulk materials for construction and renovation has been rising rapidly in recent decades in parallel with economic and demographic growth. Despite improvements in manufacturing processes, the emissions related to construction materials are therefore rising, especially in emerging economies. Curbing this rise through material efficiency measures could make a major contribution to wider efforts to cut emissions in hard-to-abate materials sectors. This section assesses the technological options for improving material efficiency in the construction of residential and commercial buildings, focusing on steel and cement (technologies to reduce direct emissions in those industries, as well as in the chemicals industry, are discussed in the first part of this chapter).

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The manufacturing, transportation and use of all construction materials for buildings resulted in energy and process CO_2 emissions of 3.5 Gt in 2019, or 10% of all energy sector emissions. For the construction sector, these embodied emissions are categorised in the standard emissions accounting framework as scope-3, i.e. indirect emissions from sources not owned or directly controlled by construction companies but related to their activities, such as those arising from the extraction and production of purchased materials, the transportation of purchased fuels, and the use of products and services. Scope-1 emissions are direct emissions from energy and other sources that are owned or controlled by those companies, while scope-2 emissions are indirect emissions from the production of electricity and heat purchased and used by them. Worldwide, the sector consumes over 2 Gt of cement and 0.5 Gt of steel, which corresponds to around 50% and 30% of total cement and steel demand respectively. Those two materials are primarily responsible for the emissions embodied in the construction materials used for buildings. Glass accounts for the bulk of the rest in the form of flat glass for windows and glass fibres for insulation, alongside aluminium, plastics and other insulation materials (e.g. rock fibres).

The primary driver of demand for cement and steel for buildings construction historically is floor area (Figure 4.20). Since 2000, the total floor area of all types of buildings worldwide has expanded by almost 60%, adding 90 billion m^2 globally. Cement and steel usage per unit floor space has also tended to increase over that period because reinforced concrete and steel framing have come to account for a growing proportion of buildings construction materials, especially in Asia. One secondary cause of this is an increase in the average height of buildings. Since 2000, the number of new buildings more than 150 m high has increased around fivefold, and their average height has increased from 170 m to 230 m (CTBUH, 2018).

Global historical trends hide important differences across regions. Most advanced economies have experienced only a moderate increase in the embodied emissions of buildings construction materials in recent decades, reflecting decelerating rates of increase in population and income, well-established non-energy buildings construction codes and continuity in basic construction techniques. By contrast, booming construction on the back of rising population, urbanisation and rising income levels have resulted in a very large increase in embodied emissions from construction materials in developing and emerging economies in Asia and elsewhere. In China, those emissions increased by around threefold between 2000 and 2019 as total floor area increased by 30 billion m^2 (or almost today's built surface in the United States) and as the percentage of reinforced-concrete and steel-frame buildings rose from 10% to 45%, increasing demand for more carbon-intensive materials (Wang et al., 2015). Chinese growth has, however, slowed since 2015 as a result of market saturation and slower economic growth, and India is now emerging

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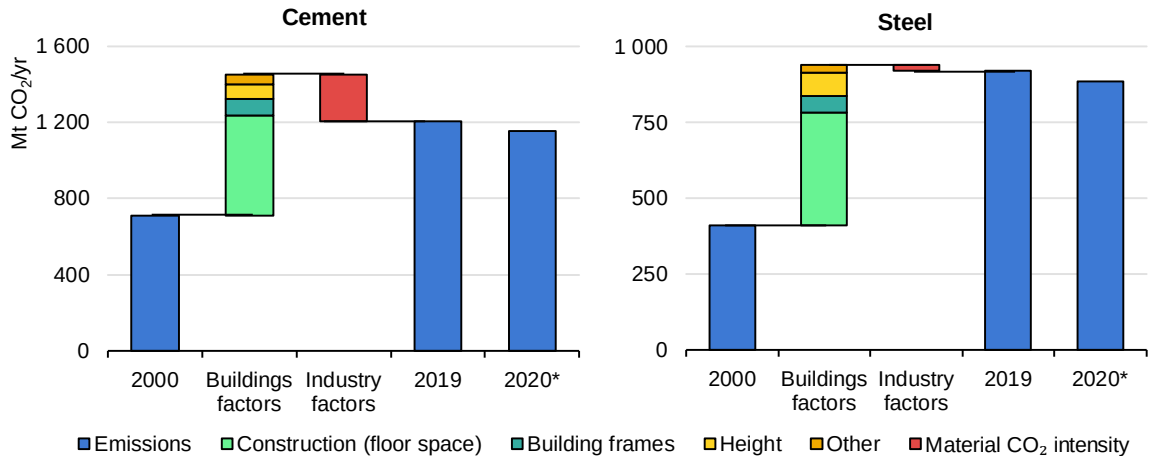
as a primary driver of global demand for construction materials and the primary source of growth in embodied emissions (NBS, 2018).

Figure 4.20 Decomposition of embodied cement and steel sector CO_2 emissions in buildings construction, 2000-20



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* Projected emissions for the year 2020 account for construction activity indicator for the first half of 2020 followed by an assumed economic recovery facilitated by no further major lockdowns for the second half of 2020.

Notes: This figure is based on a logarithmic mean divisia index which compares each influencing factor contributing to embodied emissions in 2019 relative to 2000 to assess their contribution to the change in emissions. *Other* includes increased material use per unit of new floor area related to changes in building code enforcement and construction practices, as well as the effect of existing floor area renovation.

Embedded emissions in the cement and steel used in buildings have increased sharply since 2000, with increased construction and other factors outweighing the effect of a fall in the carbon intensity of both materials – particularly cement.

Since the beginning of 2020, most countries have experienced a significant slowdown in construction activity. Buildings completions in January-April 2020 decreased by 14.5% in China (NBS, 2020) year-to-year, but picked up soon after and will likely only be about 5% lower in 2020, relative to 2019 (Figure 4.21). There are strong regional differences in how the Covid-19 crisis has impacted the construction market across the world, and the situation remains very dynamic. While the European Union registered a 25% drop in buildings construction in April 2020 relative to April 2019, it bounced back to a 10% drop in May 2020 relative to May 2019 (Eurostat, 2020), suggesting that construction rates will go back to pre-Covid-19 levels over the course the remainder of 2020 in the absence of new lockdowns. Construction for small businesses and services buildings appears to have been impacted the most markedly, although this segment has also seen a resumption in activity in May 2020 and close to pre-crisis levels in June. In developing economies such as India and Indonesia, housing construction growth in 2020 is likely to be modest, and well below the typical annual increases before the crisis.

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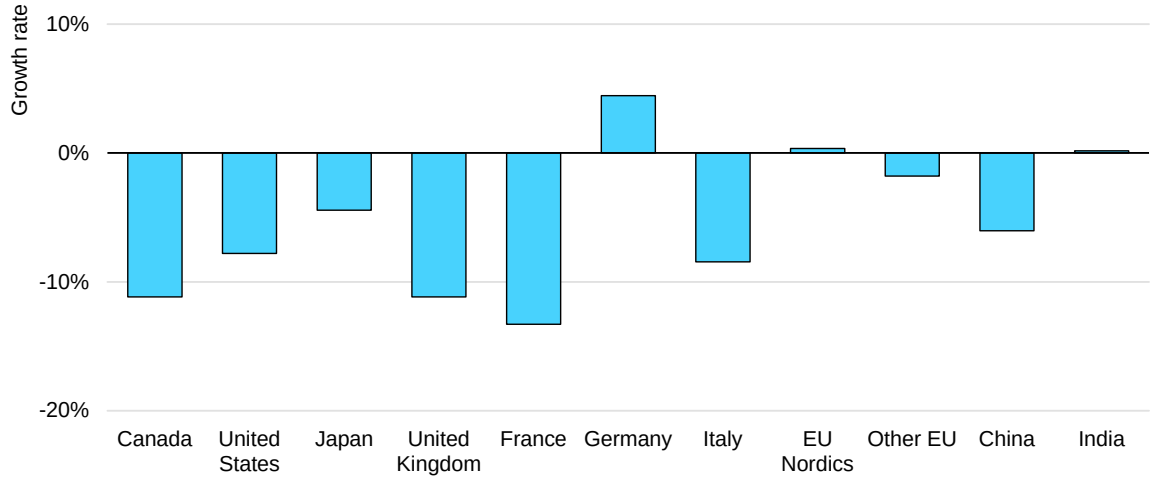
Figure 4.21 Projected year-to-year growth of residential construction activity in 2020 relative to 2019



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Notes: Buildings construction activity is estimated based on the average number of square metres under active construction for a given year, itself derived from construction starts and housing completions data. The EU Nordics country grouping includes Demark, Finland and Sweden.

Material demand sectors are strongly affected by the Covid-19 pandemic, as residential construction activity could decline by up to 10-15% in 2020 relative to 2019 at the country level.

Should local outbreaks be limited geographically and temporally during the second half of 2020, embodied emissions from buildings construction are expected to be about 5% lower in 2020 than in 2019 (Figure 4.20). A 5% decrease in CO_2 emissions is less than the annual average increase since 2000.

Material efficiency pathways towards net-zero embodied emissions

The endorsement of the World Green Buildings Council's Bringing Embodied Carbon Upfront campaign by 80 public and private entities calls for co-ordinated action to decarbonise the buildings construction value chain by 2050 (WorldGBC, 2019), on top of decarbonising buildings operations by 2030. Material demand sectors will need to play a major role in achieving net-zero embodied emissions in buildings construction because clean material manufacturing technologies are at early stages of deployment, under demonstration or even at the prototype phase (see above) and because current manufacturing assets are long-lived: while investment cycles are typically around 25 years long, cement kilns and blast furnaces are typically operated for around 40 years (see Chapter 1).

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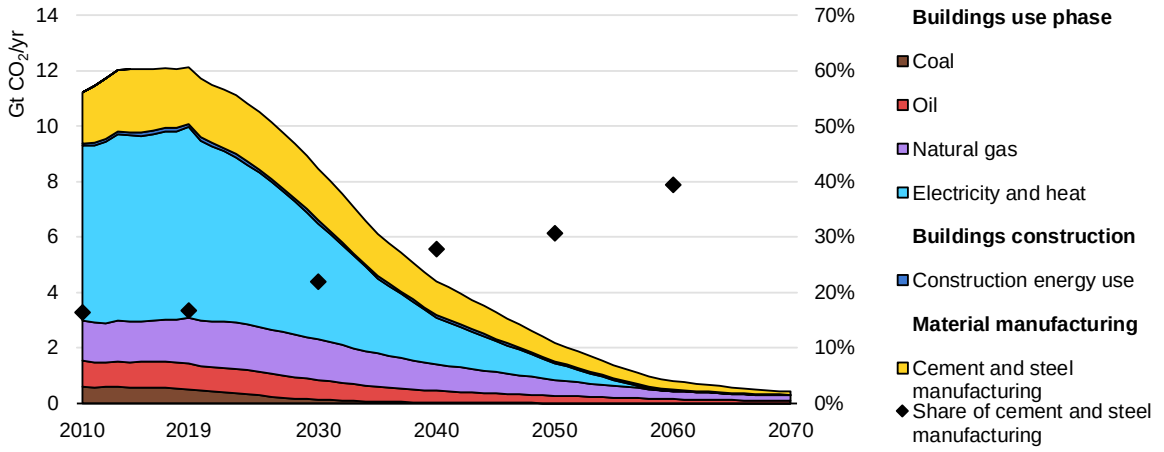
Figure 4.22 CO_2 emissions in the buildings and construction value chain in the Sustainable Development Scenario, 2010-70



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Despite gains in material efficiency, the share of cement- and steel-related emissions in total buildings emissions jumps from less than a fifth today to 40% by the 2060s.

Material efficiency strategies also have a major part to play. Despite a range of measures to improve material efficiency, the share of cement- and steel-related emissions in total buildings emissions jumps from under 20% in 2019 to about 30% by 2040, and keeps increasing to 2070 in the Sustainable Development Scenario. This happens because, while emissions related to the manufacturing of cement and steel fall by 40% by 2040, emissions from fossil fuel consumption in buildings fall faster, by around 55%, thanks mainly to switching to electricity and renewables. Likewise, emissions associated with the electricity and heat purchased and used by buildings fall to zero with the complete decarbonisation of the power sector supported by efficiency and flexibility measures in buildings and other end-use sectors (Figure 4.22).

Notwithstanding the rise in their share of overall cement- and steel-related buildings emissions by 2070, measures to improve material efficiency play an essential part in achieving the CO_2 emissions reductions from materials used for buildings construction that are required in the Sustainable Development Scenario. They contribute around a third of the total reduction in global emissions related to cement and steel use in 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario (Figure 4.23), with lower carbon intensity manufacturing of cement and steel accounting for the other two-thirds. Material efficiency measures covering cement and steel reduce emissions in the buildings construction sector by around 900 Mt in 2070. In volume terms, material efficiency measures for cement contribute to a larger emissions reduction than for steel because of its larger size; in relative terms, their impact on emissions from steelmaking is greater.

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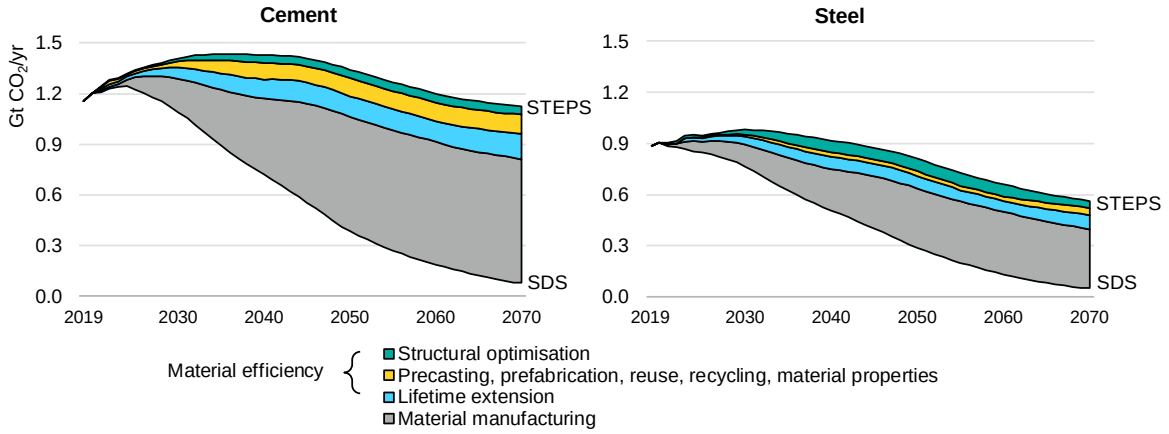
Figure 4.23 World cement- and steel-related CO_2 emissions in the buildings construction sector by scenario and driver, 2019-70



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Notes: STEPS = Stated Policies Scenario. SDS = Sustainable Policy Scenario. *Structural optimisation* refers to innovative design or composite framing that reduce material overuse while ensuring that buildings elements fulfil their structural functions. *Material properties* refers to the use of best available steel and concrete to reduce overall material use. *Lifetime extension* includes renovation and construction strategies.

Material efficiency measures contribute to around a third of the total reduction in emissions by 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario.

The projected declines in emissions follow uneven paths. The contribution of material efficiency to emissions grows rapidly until 2050, in large part because building lifetime extensions have a cumulative impact on reducing the need for materials for constructing new buildings. In the period from 2050 to 2070, the contribution of material efficiency strategies increases only marginally: by 2050, most of the existing building stock has been renovated, and other strategies start to have a wider impact. From 2050 onwards, most of the additional reduction in the emissions embodied in buildings comes from materials manufacturing, as innovative low-carbon cement and steel production technologies, including CCUS, are deployed on a massive scale, although material efficiency continues to play an important role in reducing the need for costly low-carbon material manufacturing processes. As a result of these various measures, the level of embodied carbon in the Sustainable Development Scenario in 2070 is reduced by 95% from today's levels.

Reducing the underlying need for cement and steel in construction through material efficiency is central to achieving these emissions reductions. Total cement and steel demand for buildings construction worldwide peaks between 2025 and 2030 and falls to well below 2010 levels by 2070 in the Sustainable Development Scenario. Total cumulative material demand to 2070 is lower by roughly 30 Gt for cement and 7 Gt for steel relative to the Stated Policies Scenario. That is a roughly equivalent to a reduction of 20% over a 50-year timeframe.

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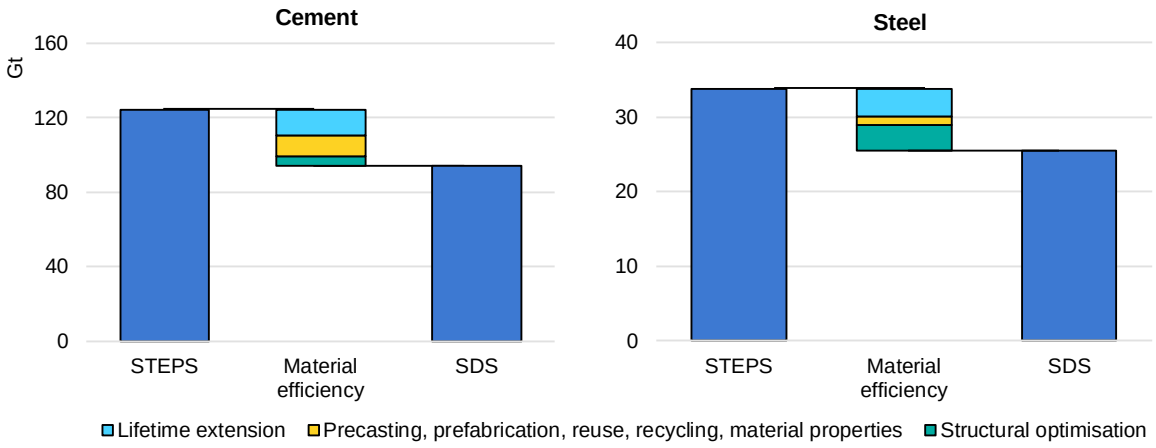
Figure 4.24 Contribution of material efficiency to reducing cumulative cement and steel demand for buildings construction in the Sustainable Development Scenario, 2019-70



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Notes: *Lifetime extension* includes renovation and construction strategies. *Material properties* refers to the use of best available steel and concrete to reduce overall material use. *Structural optimisation* refers to innovative design or composite framing that reduce material overuse while ensuring that buildings elements fulfil their structural functions.

Material efficiency measures contribute to reducing cumulative cement and steel demand by 20% to 2070, with the main contribution coming from lifetime extensions.

The principal material efficiency measures that drive these demand and emissions reductions are extensions to buildings lifetimes, structural optimisation and enhanced material properties. Using fewer structural elements and optimising design could reduce concrete and steel use by 20-25% and 35% respectively (Ghayeb, Razak and Sulong, 2020), but lifetime extensions make the biggest contribution, accounting for more than 40% of the cumulative fall in cement and steel demand over 2019-70 relative to the Stated Policies Scenario. There are multiple ways of extending the lives of buildings, including by using better materials and construction techniques to make them last longer, by creating more flexible and modular spaces to facilitate repurposing at a later date, and by renovating or refurbishing old buildings so as to delay their demolition.

Renovation offers the biggest potential for material savings from lifetime extensions. Renovating a building, as a general rule, involves the use of 40-80 times less material resources in terms of mass than reconstruction from scratch (Leonardon et al., 2019). The material savings are even higher for steel and cement, as most renovations require very little of either material. Generally, a newly refurbished commercial or industrial building lasts 70-100% as long as a new one, while renovations typically prolong the life of a residential building by 30-60%. Yet renovations can be costly. For certain types of buildings, such as high-rise office buildings, refurbishment costs can be of the same order of magnitude as those for demolition and reconstruction.

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Structural optimisation refers to innovative design or composite framing that reduces material overuse while ensuring that buildings are structurally sound. Structural engineers have the opportunity to work with other design disciplines to include whole life carbon as an additional criterion, and the scope for this to bring about material savings in construction is significant: structural optimisation reduces cement demand by about 15% and steel demand by about 25% in 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario, mainly from improved modelling and planning.

Voided concrete slabs, either cast onsite or prefabricated, are one example of a material-efficient building component. Post-tensioning of floor slabs is another commercially available example: it offers material savings of around 15%, and can be combined with voiding. Unreinforced funicular floors and concrete shell roofs are now being tested in the NEST HiLo experimental building in Switzerland (Block et al., 2017). For new, tall and commercial buildings, the 3for2 design uses façade and floor-integrated mechanical and electrical elements to improve ventilation and reduce heating and cooling needs. In addition to their potential for operational energy efficiency gains of up to 75%, voided concrete slabs can save over 15% in material mass (Schlueter et al., 2016). Building layouts can also be designed in ways that reduce material needs, including by optimising the shape of buildings and reducing the length of perimeter walls (D'Amico and Pomponi, 2019). Holistic approaches, digital design and digital manufacturing could enable wider adoption of these types of designs (Box 4.3).

Enhancing material properties can be an effective way of reducing the amounts of materials needed for construction, yielding potentially large emission savings. Quality standards avoid the use of low-grade concrete that would lead to a building's early demolition. Optimising structural element size, concrete strength and concrete mix further reduce cement demand while delivering the same performance. Light-weighted elements also reduce lifecycle emissions, particularly from transportation. For example, cold-formed steel framing, which has been widely adopted since the 1990s for interior, non-loadbearing partition walls in commercial construction, is now starting to be adopted for structural applications in mid-rise and multi-housing buildings, aided by technological advances such as panellised systems. Such components are relatively light to transport and assemble, and can support heavier loads than hot-rolled alternatives.

Other material efficiency measures could also help lower cement and steel demand in construction. Precasting and prefabrication provide greater control over the size, shape and manufacturing of buildings components, and help to speed up construction processes. Concrete precast also allows lower cement-to-water ratios, enhancing product durability. The centralisation of best practices in dedicated workshops would help to reduce the risk of wasting materials, while digital processes

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such as additive manufacturing (3D printing) could also make a contribution, though digitalisation has yet to demonstrate its practical and economic viability at a large scale and for broad applications.

The reuse and recycling of cement and steel components can also reduce material needs. Steel-based elements, including structural elements and cold-formed steel framing, may be reused without harming their material properties, safety and overall sustainability. When steel elements cannot be reused, collection for recycling and use in secondary steel production can help achieve lower production emissions for new steel elements than production from iron ore (see the iron and steel section above). Opportunities for cement reuse and recycling are more limited, partly because of the costs of transporting heavy blocks over long distances. There may be potential for recovery and reuse of unhydrated cement from used concrete, but technologies for this have yet to reach the commercial stage. Recycling concrete aggregates is possible, though the potential emissions savings are small due to transport needs, the non-carbon-intensive nature of aggregates and the potential need to add cement to facilitate recycling (Zhang et al., 2017).

Box 4.3 How digital technologies can support material efficiency

The digitalisation of construction and renovation along their value chains could contribute to various aspects of improving material efficiency in the use of cement and steel in construction:

- **At the planning stage:** Some digital tools can optimise material use through better component design, while others such as thermal imaging systems can identify poor-performance buildings and renovation strategies.
- **Prefabrication and precasting:** Digitalisation could standardise off-site component design and manufacturing processes, saving an estimated 20-35% of concrete relative to cast-in-place concrete. 3D printing has potential to enhance structural optimisation further by ensuring the use of only the exact amount of cement and steel that is needed, reducing construction waste by 30-60% (Zhang et al., 2019).
- **During construction:** A number of new businesses are creating new digital construction management platforms to help construction companies monitor progress, the use of resources and material reporting. These tools for tracking material use could provide significant opportunities to quantify a building's embodied carbon, serve as a basis for mandatory or voluntary certifications, and optimise concrete delivery (Gurmu, 2018).

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- **At the end of a building's life**: Data from material tracking tools could be used to create a repository of building components that will be available for reuse or recycling prior to a building's demolition. Banking on construction materials could allow construction companies to save costs on materials costs, reduce expenditure on transportation and logistics, and reduce the carbon footprint of the buildings they construct, which could enhance the value of the buildings through certification (EC, 2020).

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References

ADNOC (Abu Dhabi National Oil Company) (2017), ADNOC and Masdar's Carbon Capture Facility Holds Key to Limiting Industrial CO2 Emissions, press release, ADNOC, https://www.adnoc.ae/en/news-and-media/press-releases/2017/adnoc-and-masdars-carbon-capture-facility-holds-key-to-limiting-industrial-co2-emissions.

Aggregates Business (2019), LafargeHolcim Expands Reduced CO_2 Cement Offering, press release, Aggregates Business, https://www.aggbusiness.com/ab9/news/lafargeholcim-expands-reduced-co2-cement-offering.

Allwood, J.M. and J.M. Cullen (2012), Sustainable Materials: With Both Eyes Open, UIT Cambridge, Cambridge, United Kingdom.

Andersson, J. and J. Lundgren (2014), Techno-economic analysis of ammonia production via integrated biomass gasification, Applied Energy, Vol. 130, pp. 484-490, https://doi.org/10.1016/j.apenergy.2014.02.029.

Andersson, R. et al. (2019), Carbonation as a method to improve climate performance for cement based material, Cement and Concrete Research, Vol. 124, https://doi.org/10.1016/j.cemconres.2019.105819.

ArcelorMittal (2019a), Climate Action Report 1, ArcelorMittal, Luxembourg, https://storagearcelormittaluat.blob.core.windows.net/media/3lqlqwoo/climate-action-report-2019.pdf.

ArcelorMittal (2019b), Launch of the "3D" Project for the Capture and Storage of CO_2, press release, ArcelorMittal, Luxembourg, https://automotive.arcelormittal.com/news_and_stories/news/2019DMXproject.

ArcelorMittal (2019c), Hydrogen-based Steelmaking to Begin in Hamburg, ArcelorMittal, Luxembourg, https://corporate.arcelormittal.com/media/case-studies/hydrogen-based-steelmaking-to-begin-in-hamburg.

ArcelorMittal (2017), 2017 Integrated Annual Review, ArcelorMittal, Luxembourg, https://annualreview2017.arcelormittal.com/our-progress/sustainability-review/carbon-and-energy.

Arena (2019), Renewable Hydrogen Could Power Moranbah Ammonia Facility, press release, Australian Renewable Energy Agency, https://arena.gov.au/news/renewable-hydrogen-could-power-moranbah-ammonia-facility.

Arne, M. (2017), Naphtha Catalytic Cracking: Process Economics Program Report 29K, IHS Chemical, https://cdn.ihs.com/www/pdf/RP29K-toc.pdf.

Asiachem (2018), Inventory: What Progress Has Been Made in 2018 of China's CCUS Projects?, webpage, Asiachem, http://www.asiachem.org/en/2018CO2-1005.

BASF (2019), BASF Develops Process for Climate-friendly Methanol, press release, BASF, https://www.basf.com/global/en/media/news-releases/2019/05/p-19-218.html.

IEA. All rights reserved.

Beumelburg, C. (2019), Cement Producers Have Founded an Oxyfuel Research Corporation, press release, HeidelbergCement, https://www.heidelbergcement.com/en/pr-11-12-2019.

Beumelburg, C. (2017), HeidelbergCement and RWTH Aachen Investigate in Binding CO_2 in Minerals, press release, HeidelbergCement, https://www.heidelbergcement.com/en/pr-29-06-2017.

BioBTX (2020), The Sustainable BioBTX Technology, webpage, BioBTX, https://biobtx.com/sustainable-technology.

Biorizon (2018), ALIGN Project Launched: Developing Bio-aromatics from Lignin, press release, Biorizon, https://www.biorizon.eu/news/align-project-launched-developing-bio-aromatics-from-lignin.

Block, P. et al. (2017), NEST HiLo: Investigating lightweight construction and adaptive energy systems, Journal of Building Engineering, Vol. 12, pp. 332-341, https://doi.org/10.1016/j.jobe.2017.06.013.

Bloomberg (2020), China's Recovery Continues But Wary Consumers Show Vulnerability, Bloomberg News, https://www.bloomberg.com/news/articles/2020-06-15/china-s-industry-led-recovery-from-virus-slump-continued-in-may.

Blue Planet (2020),Blue Planet, webpage, Blue Planet, http://www.blueplanet-ltd.com/.

BMWi (Germany Federal Ministry of Economic Affairs and Energy) (2020), Winner of the Ideas Competition "Real Laboratories of the Energy Transition" – Profiles (in German), BMWi, https://www.bmwi.de/Redaktion/DE/Downloads/P-R/reallabore-der-energiewende-gewinner-ideenwettbewerb-steckbriefe.pdf?__blob=publicationFile&v=9.

Borealis (2019), Petrochemical Companies Form Cracker of the Future Consortium and Sign R&D Agreement, press release, Borealis, https://www.borealisgroup.com/news/petrochemical-giants-form-consortium-cracker-of-the-future-and-sign-agreement.

Boston Metal (2019), Metal Oxide Electrolysis, webpage, Boston Metal, Woburn, MA, https://www.bostonmetal.com/moe-technology.

Brown, T. (2017), Comparative Studies of Ammonia Production, Combining Renewable Hydrogen with Haber-Bosch, Ammonia Industry, https://ammoniaindustry.com/comparative-studies-of-ammonia-production-combining-renewable-hydrogen-with-haber-bosch.

Buzzi Unicem (2019), The Cleanker Project for Capturing CO_2: SmartCity is Talking About it, press release, Buzzi Unicem, Casale Monferrato, Italy, https://www.buzziunicem.it/media/news/il-progetto-cleanker-per-la-cattura-della-co2-ne-parla-smartcity?languageId=en_US.

Cao, Z. et al. (2020), The sponge effect and carbon emission mitigation potentials of the global cement cycle, Nature Communications, Vol. 11/3777, https://doi.org/10.1038/s41467-020-17583-w.

Capitol Aggregates (2020), Capitol Skymine: Pro-business, Pro-environment, webpage, Capitol Aggregates, http://www.capitolaggregates.com/s/Sustainability-SkyMine.

IEA. All rights reserved.

Carbon4PUR (2020), At a Glance, webpage, Carbon4PUR, https://www.carbon4pur.eu/about/at-a-glance.

Carbon8 (2020), Carbon8, webpage, http://c8s.co.uk.

CarbonCure, (2020), CarbonCure, webpage, https://www.carboncure.com.

Cementa (2019), Cementa and Vattenfall Take the Next Step Towards a Climate Neutral Cement, press release, Cementa, https://www.cementa.se/sites/default/files/assets/document/d3/3a/20190130-cementa_and_vattenfall_take_the_next_step_towards_a_climate_neutral_cement.pdf.

CEMEX (2020), CEMEX Launches UK's First Net Zero Ready Mixed Concrete Product, press release, CEMEX, https://www.cemex.co.uk/-/cemex-launches-uk-s-first-net-zero-ready-mixed-concrete-product.

Cemnet (2019), Taiwan Cement Co Sets CO_2 Capture Targets, press release, Cemnet, https://www.cemnet.com/News/story/166756/taiwan-cement-co-sets-co2-capture-targets.html.

CRI (Carbon Recycling International) (2020), Our Projects, webpage, CRI, https://www.carbonrecycling.is/projects.

CTBUH (Council on Tall Buildings and Urban Habitat) (2018), Tall Buildings in Numbers: 2018 Year in Review, CTBUH, https://www.skyscrapercenter.com/year-in-review/2018.

D'Amico, B. and F. Pomponi (2019), A compactness measure of sustainable building forms, Royal Society Open Science, Vol. 6, https://doi.org/10.1098/rsos.181265.

Davison, J. (2014), Pilot plant trial of oxy-combustion at a cement plant, IEAGHG Information Paper 2014-IP7I, IEAGHG, https://ieaghg.org/docs/General_Docs/Publications/Information_Papers/2014-IP7.pdf.

EC (European Commission) (2020), Banking on Construction Materials for Eco-benefits, EC, Brussels, https://ec.europa.eu/research/infocentre/article_en.cfm?artid=48396.

EC (2019), From Residual Steel Gasses to Methanol, EC, Brussels, https://cordis.europa.eu/project/id/727504.

EC (2014), ULCOS Top Gas Recycling Blast Furnace Process, Publications Office of the European Union, Brussels, https://op.europa.eu/en/publication-detail/-/publication/0371a7f6-3e10-40aa-a8ec-16c1bfabdc38.

ECRA (European Cement Research Academy) (2020a), CCS – Carbon Capture and Storage, webpage, ECRA, Duesseldorf, Germany, https://ecra-online.org/research/ccs.

ECRA (2020b), Future Grinding Technologies, webpage, ECRA, Duesseldorf, Germany, https://ecra-online.org/research/future-grinding-technologies.

ECRA (2017), Development of state of the art techniques in cement manufacturing: Trying to look ahead, CSI/ECRA Technology Papers, ECRA, Duesseldorf, Germany, https://ecra-online.org/fileadmin/redaktion/files/pdf/CSI_ECRA_Technology_Papers_2017.pdf.

Ellis, L. et al. (2019), Toward electrochemical synthesis of cement: An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams, PNAS, Vol. 117/23, pp. 12584-12591, https://doi.org/10.1073/pnas.1821673116.

IEA. All rights reserved.

Enerkem (2020), Methanol, webpage, Enerkem, Montreal, Canada, https://enerkem.com/products/methanol.

Enhance Energy Inc., Wolf Carbon Solutions and North West Redwater Partnership (2019), Knowledge Sharing Report, Enhance Energy Inc., https://open.alberta.ca/dataset/e61e2157-9260-4fc4-b5fd-e206de00f7b5/resource/95f6f6c6-3437-4b51-950b-98d17b727570/download/actl-knowledge-sharing-2018-summary-report-updated-july-23.pdf.

ETSAP and IRENA (2013), Production of bio-ethylene, Technology-Policy Brief I13, ETSAP and IRENA, https://iea-etsap.org/E-TechDS/PDF/I13IR_Bioethy_MB_Jan2013_final_GSOK.pdf.

Eurostat (2020), Impact of Covid-19 Crisis on Construction, Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Impact_of_Covid-19_crisis_on_construction#Development_of_construction_production_in_May_2020.

FAO (Food and Agricultural Organisation of the United Nations) (2011), Global Food Losses and Food Waste: Extent, Causes and Prevention, FAO, Rome, www.fao.org/3/mb060e/mb060e.pdf.

FastCarb (2020), Axis 1 – Experimental Approach in the Laboratory, webpage, FastCarb, https://fastcarb.fr/en/program/experimental-approach-in-the-laboratory.

Financial Post (2019), Inventys – A Leading Developer of Commercially Viable, Economically Scalable Carbon Capture Technology – Changes Name to Svante Inc., press release, Financial Post, https://business.financialpost.com/pmn/press-releases-pmn/business-wire-news-releases-pmn/inventys-a-leading-developer-of-commercially-viable-economically-scalable-carbon-capture-technology-changes-name-to-svante-inc.

FReSMe (2020), About, webpage, FReSMe, http://www.fresme.eu/about.php.

FXEmpire (2020), Cement Production Across the Globe, FXEmpire, https://www.fxempire.com/macro/indicators/cement-production.

Geyer, R., J.R. Jambeck and K.L. Law (2017), Production, use, and fate of all plastics ever made, Science Advances, Vol. 3/7, e1700782, https://doi.org/10.1126/sciadv.1700782.

Ghayeb, H. H., H. A. Razak and N. H. R. Sulong (2020), Evaluation of the CO_2 emissions of an innovative composite precast concrete structure building frame, Journal of Cleaner Production, Vol. 242, https://doi.org/10.1016/j.jclepro.2019.118567.

Global CCS Institute (2018a), Carbon Capture and Storage in De-carbonising the Chinese Economy, Global CCS Institute, https://www.globalccsinstitute.com/news-media/insights/carbon-capture-and-storage-in-de-carbonising-the-chinese-economy.

Global CCS Institute (2018b), World's Largest Capture Pilot Plant for Cement Commissioned in China, Global CCS Institute, https://www.globalccsinstitute.com/news-media/insights/worlds-largest-capture-pilot-plant-for-cement-commissioned-in-china.

Global CCS Institute (2016), Yanchang CO_2 EOR: Unique Geology, Unique Challenges, Global CCS Institute, https://www.globalccsinstitute.com/news-media/insights/yanchang-co2-eor-unique-geology-unique-challenges.

Global Cement (2020), Update on South America, Global Cement, https://www.globalcement.com/news/item/11090-update-on-south-america.

IEA. All rights reserved.

Global Cement (2014), Skyonic Opens Commercial-scale Carbon Capture Unit at Capitol Aggregates Cement Plant, press release, Global Cement, https://www.globalcement.com/news/item/2980-skyonic-opens-commercial-scale-carbon-capture-unit-at-capitol-aggregates-cement-plant.

GPIC (Gulf Petrochemical Industries Co.) (2020), Implementing CDR – Milestones, webpage, GPIC, https://www.gpic.com/responcibility/CDRmoved/ImplementingCDRMilestones/ImplementingCDRMilestones.aspx.

Green Car Congress (2009), Mitsui Chemicals Begins Operations of Pilot Plant for Methanol Synthesis for CO_2, Green Car Congress, https://www.greencarcongress.com/2009/05/mitsui-co2-methanol-20090531.html.

Gurmu, A. (2018), Tools for measuring construction materials management practices and predicting labor productivity in multistory building projects, Journal of Construction Engineering and Management, Vol. 145/2, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001611.

Heliogen (2019), Heliogen Achieves Breakthrough Temperatures From Concentrated Sunlight for Industrial Processes, press release, Heliogen, https://heliogen.com/press-release-heliogen-achieves-breakthrough-temperatures-from-concentrated-sunlight-for-industrial-processes-with-momentum-toward-commercial-hydrogen-fuel-creation.

Hornberger, M., R. Sporal and G. Scheffknecht (2017), Calcium looping for CO_2 capture in cement plants – pilot scale test, Energy Procedia, Vol. 114, pp. 6171-6174, https://doi.org/10.1016/j.egypro.2017.03.1754.

HYBRIT (2020), HYBRIT – Fossil-free Steel, webpage, HYBRIT, www.hybritdevelopment.com.

IEA (International Energy Agency) (2020), Sustainable Recovery, IEA, Paris, https://www.iea.org/reports/sustainable-recovery.

IEA (2019), The Future of Hydrogen, IEA, Paris, https://www.iea.org/reports/the-future-of-hydrogen.

IEA (2018), Technology Roadmap – Low-Carbon Transition in the Cement Industry, IEA, Paris, https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

IMF (International Monetary Fund) (2020), World Economic Outlook Update, June 2020, IMF, Washington, DC, https://www.imf.org/en/Publications/WEO/Issues/2020/06/24/WEOUpdateJune2020.

JISF (The Japan Iron and Steel Federation) (2011), Outline of COURSE 50, JISF, https://www.jisf.or.jp/course50/outline/index_en.html.

Jordal, K. (2018), CEMCAP-Project: Tech Options for Cement CO_2-capture Need a Plant Specific Assessment, Sintefblog, https://blog.sintef.com/sintefenergy/the-final-cemcap-event-the-ecra-cemcap-cleanker-workshop-i-brussels-october-17-2018.

K1MET (2018), Energy in Future Steelmaking, https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=80BB405C-DA08-56D3-800BC46FC9A6F350&DOC_ID=604E51C2-BF68-0811-55466D1CB8DE995D&type=CMTY_CAL.

IEA. All rights reserved.

LafargeHolcim (2015), Solar Energy in Cement Manufacturing, press release, LafargeHolcim, https://www.lafargeholcim.com/solar-energy-cement-manufacturing.

Lake Charles Methanol (2020), Frequently Asked Questions, Lake Charles Methanol, https://www.lakecharlesmethanol.com/faqs.

LanzaTech (2019), World First Products made from Recycled Pollution Reduce Emissions and Keep Carbon in the Ground!, https://www.lanzatech.com/2019/10/07/world-first-products-made-from-recycled-pollution-reduce-emissions-and-keep-carbon-in-the-ground/.

LanzaTech (2018), World's First Commercial Waste Gas to Ethanol Plant Starts Up, https://www.lanzatech.com/2018/06/08/worlds-first-commercial-waste-gas-ethanol-plant-starts/.

Lehigh Hanson (2019), Lehigh Cement and the International Knowledge Centre Pioneering a Feasibility Study of Full-scale Carbon Capture Storage (CCS) on Cement, press release, Lehigh Hanson Heidelberg Cement Group, https://www.lehighhanson.com/resources/news/news/2019/11/28/lehigh-cement-and-the-international-knowledge-centre-pioneering-a-feasibility-study-of-full-scale-carbon-capture-storage-(ccs)-on-cement.

LEILAC (2019), Successful Demonstration of CO_2 Separation at Project LEILAC in Belgium, webpage, LEILAC, https://www.project-leilac.eu/successful-co2-separation.

Leonardon, P. et al. (2019), Prospectives 2035 et 2050 de consommation de matériaux pour la construction neuve et la rénovation énergétique BBC, ADEME, Paris, https://www.ademe.fr/prospectives-2035-2050-consommation-materiaux-construction-neuve-renovation-energetique-bbc.

Levi, P.G. and J.M. Cullen (2018), Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products, Environmental Science & Technology, Vol. 52/4, pp. 1725-1734, https://doi.org/10.1021/acs.est.7b04573.

Lotfi, S. and P. Rem (2017), Recycling of end of life concrete fines (0-4 mm) from waste to valuable resources, in: Hordijk, D. and M. Luković (eds), High Tech Concrete: Where Technology and Engineering Meet, pp. 224-232, Springer, https://doi.org/10.1007/978-3-319-59471-2_28.

Majcher, K. (2015), What happened to green concrete?, MIT Technology Review, https://www.technologyreview.com/s/535646/what-happened-to-green-concrete.

Methanol Institute (2019), Methanol Price and Supply/Demand, webpage, Methanol Institute, www.methanol.org/methanol-pricesupply-demand.

MHI (Misubishi Heavy Industries) (2020), CO_2 Recovery Plants: Commercial Experiences, webpage, MHI, https://www.mhi.com/products/environment/carbon_dioxide_recovery_process_commercial.html.

MIT (Massachusetts Institute of Technology) (2016a), Enid Fertilizer Fact Sheet: Commercial EOR Using Anthropogenic Carbon Dioxide, MIT, Cambridge, MA, https://sequestration.mit.edu/tools/projects/enid_fertilizer.html.

IEA. All rights reserved.

MIT (2016b), Coffeyville Fact Sheet: Commercial EOR Using Anthropogenic Carbon Dioxide, MIT, Cambridge, MA, https://sequestration.mit.edu/tools/projects/coffeyville.html.

Mohsenzadeh, A., A. Zamani and M. Taherzadeh (2017), Bioethylene production from ethanol: A review and techno-economical evaluation, ChemBioEng Reviews, Vol.4/2, pp. 75-91, https://doi.org/10.1002/cben.201600025.

MPA (Mineral Products Association) (2020), MPA Wins £6.02 Million BEIS Award for Ground-breaking Fuel Switching Decarbonisation Demonstration Projects, press release, MPA, https://mineralproducts.org/20-release09.htm.

NBS (National Bureau of Statistics of China) (2020a), Monthly Statistics: Output of Major Industrial Products, NBS, Beijing, https://data.stats.gov.cn/english/easyquery.htm?cn=A01.

NBS (National Bureau of Statistics of China) (2020b), National Real Estate Development and Sales in the First Four Months of 2020, NBS, Beijing, http://www.stats.gov.cn/english/PressRelease/202005/t20200518_1745962.html.

NBS (National Bureau of Statistics of China) (2019), Floor Space of Buildings Constructed by Construction Enterprises, NBS, Beijing, http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm.

Nextant (2015), Methanol to Aromatics – Global Impact of a New Technology, Nextant, https://thinking.nexant.com/sites/default/files/report/field_attachment_prospectus/201602/STMC15_Methanol%20to%20Aromatics_BROCHURE_R4.pdf.

Norcem (2020), CCS at Norcem Brevik: Background, webpage, Norcem Heidelberg Cement Group, https://www.norcem.no/en/CCS%20at%20Brevik.

Norcem (2018), Norcem Starts Innovation Project on Electrification of Cement Production (in Norwegian), Norcem Heidelberg Cement Group, https://www.norcem.no/no/ELSE-elektrifisering-sementproduksjon.

OCI (2020), BioMCN, OCI, https://www.oci.nl/operations/biomcn.

OGCI (Oil and Gas Climate Initiative) (2019), OGCI Climate Investments, the Oil and Gas Climate Initiative's Investment Arm, Announces a New Investment in Carbon Capture and Sequestration (CCS) Project to Create the World's First Ammonia Produced With Near Zero Carbon Footprint, press release, OGCI, https://oilandgasclimateinitiative.com/ogci-climate-investments-announces-a-new-investment-in-wabash-valley-resources-carbon-capture-and-sequestration-project.

Oksri-Nelfia, L. et al. (2015), Reuse of recycled crushed concrete fines as mineral addition in cementitious materials, Materials and Structures, Vol. 49, pp. 3239-3251, https://doi.org/10.1617/s11527-015-0716-1.

Ovako (2020), First in the World to Heat Steel Using Hydrogen, press release, Ovako, https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen.

IEA. All rights reserved.

Oxford Economics (2019), The Global Chemical Industry: Catalyzing Growth and Addressing Our World's Sustainability Challenges, International Council of Chemical Associations, Washington, DC, https://www.oxfordeconomics.com/recent-releases/the-global-chemical-industry-catalyzing-growth-and-addressing-our-world-sustainability-challenges.

Pérez-Calvo, J.-F. (2018), Chilled Ammonia Process (CAP) Optimization and Comparison with Pilot Plant Tests, CEMCAP, https://www.sintef.no/globalassets/project/cemcap/2018-11-14-deliverables/d10.3_cap-optimization.pdf.

Perilli, D. (2020), Innovation in Industrial Carbon Capture Conference 2020, press release, Global Cement, https://www.globalcement.com/news/item/10379-innovation-in-industrial-carbon-capture-conference-2020.

Perilli, D. (2019), Dalmia Cement Takes Steps Towards Carbon Capture, press release, Global Cement, https://www.globalcement.com/news/item/9887-dalmia-cement-takes-steps-towards-carbon-capture?utm_source=newsletter&utm_medium=email&utm_content=493885&utm_campaign=gcw424.

Platts (2020), Olefins Outlook [purchased], Platts, London.

Primetals (2019), Primetals Technologies Develops Breakthrough Technology for Carbon-free, Hydrogen-based Direct Reduction for Iron Ore Fines, press release, Primetals, https://www.primetals.com/press-media/news/primetals-technologies-develops-breakthrough-technology-for-carbon-free-hydrogen-based-direct-reduction-for-iron-ore-fines.

Provis, J.L. (2017), Alkali-activated materials, Cement and Concrete Research, Vol. 114, pp. 40-48, https://doi.org/10.1016/j.cemconres.2017.02.009.

Qiu, S. and R. Woo (2020), Chinese Factories to Face Headwinds in Next Phase of Post-lockdown Rcovery, press release, Reuters, https://www.reuters.com/article/us-china-economy-industrial-production/chinese-factories-to-face-headwinds-in-next-phase-of-post-lockdown-recovery-idUSKBN2490NG.

Saarstahl (2019), Sustainable Steel Production at the Saar: Dillinger and Saarstahl Are for the First Time Using Hydrogen in Blast Furnaces to Reduce Carbon Emissions, press release, Saarstahl, https://www.saarstahl.com/sag/en/group/media/press/sustainable-steel-production-at-the-saar-dillinger-and-saarstahl-are-for-the-first-time-using-hydrogen-in-blast-furnaces-to-reduce-carbon-emissions-88595.shtml.

SALCOS (2019), Salzgitter Low CO_2 Steelmaking, webpage, SALCOS, https://salcos.salzgitter-ag.com/en.

Sayre, A. et al. (2017), Field Testing of Cryogenic Carbon Capture, Carbon Management Technology Conference, https://www.osti.gov/servlets/purl/1412681.

Schlueter, A. et al. (2016), 3for2: Realizing spatial, material, and energy savings through integrated design, CTBUH Journal, Issue 2, pp. 40-45, https://global.ctbuh.org/resources/papers/download/2783-3for2-realizing-spatial-material-and-energy-savings-through-integrated-design.pdf.

IEA. All rights reserved.

Scrivener, K. et al. (2018), Calcined clay limestone cements (LC3), Cement and Concrete Research, Vol. 114, pp. 49-56, https://doi.org/10.1016/j.cemconres.2017.08.017.

Sharman, P. (2019), Pathways to a Low-carbon China – MIT Study Shows Key Role for CCS, International Flame Research Foundation, https://ifrf.net/ifrf-blog/pathways-to-a-low-carbon-china-mit-study-shows-key-role-for-ccs.

Siderwin (2019), Development of New Methodologies for Industrial CO2-free Steel Production by Electrowinning, Siderwin, https://www.siderwin-spire.eu.

SmartCrusher (2020), Smartcrusher, webpage, https://www.slimbreker.nl/smartcrusher.html.

Sohn, H.Y. et al. (2017), Status of the development of flash ironmaking technology, in: Wang, S. et al. (eds), Applications of Process Engineering Principles in Materials Processing, Energy and Environmental Technologies, The Minerals, Metals & Materials Series, https://doi.org/10.1007/978-3-319-51091-0_2.

Solidia (2020), Solidia: Impact, webpage, Solidia, https://www.solidiatech.com/impact.html.

SOLPART (2019), About Us, webpage, SOLPART, https://www.solpart-project.eu/about-us.

Statkraft (2020), Hydrogen Production and Green Steel in Mo Industrial Park, press release, Statkraft, https://www.statkraft.com/newsroom/news-and-stories/archive/2020/hydrogen-og-stal.

Steelanol (2016), Ethanol Production Successfully Tested on Live Steel Waste Gas Stream of ArcelorMittal Gent, press release, Steelanol, http://www.steelanol.eu/en/news/ethanol-production-in-gent-successfully-tested-on-real-steel-waste-gas-stream.

STEPWISE (2020), STEPWISE: A H2020 Project, webpage, STEPWISE, https://www.stepwise.eu.

Stopic, S. et al. (2019), Synthesis of nanosilica via olivine mineral carbonation under high pressure in an autoclave, Metals, Vol. 9/6, pp. 708, https://doi.org/10.3390/met9060708.

Sui, T. (2020), Progress of low carbon cement in China, ICT Yearbook 2019-2020, 24th edition, The Institute of Concrete Technology, pp. 21-27.

Taiwan Cement (2020), Circular Economy, webpage, Taiwan Cement, https://www.taiwancement.com/en/circular1.html.

Tata Steel (2017), Hisarna: Game Changer in the Steel Industry, Tata Steel, https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf.

TCMB (Turkish Cement Manufacturers' Association) (2020), Statistics: Monthly Data, TCMB, https://www.tcma.org.tr/en/statistics/monthly-data.

Tenova (2018), HYL News, December 2018, Tenova, https://www.tenova.com/fileadmin/user_upload/HYL_News_-_December_2018.pdf.

IEA. All rights reserved.

Ternium (2018), Low Carbon Energy Cases at Ternium, presentation at the American Steel Expert's Dialogue in the Framework of the IEA Global Sustainable Technology Roadmap for Iron & Steel, Ternium, https://iea.blob.core.windows.net/assets/imports/events/64/LowcarbonenergycasesatTernium.pdf.

The Economist (2020), Covid-19 has led to a pandemic of plastic pollution, The Economist, 22 June 2020, https://www.economist.com/international/2020/06/22/covid-19-has-led-to-a-pandemic-of-plastic-pollution.

thyssenkrupp (2020a), The Carbon2Chem® Project, webpage, thyssenkrupp, Essen, Germany, https://www.thyssenkrupp.com/en/newsroom/content-page-162.html.

thyssenkrupp (2020b), Targeting a Future Without CO_2: Our Climate Strategy for Sustainable Steel Production, webpage, thyssenkrupp, Essen, Germany, https://www.thyssenkrupp-steel.com/en/company/sustainability/climate-strategy/?gclid=EAIaIQobChMIgL2O88zv6AIV1O5RCh2W2wacEAAYASAAEgI08PD_BwE.

thyssenkrupp (2019), World First in Duisburg as NRW Economics Minister Pinkwart Launches Tests at thyssenkrupp into Blast Furnace Use of Hydrogen, press release, thyssenkrupp, Essen, Germany, https://www.thyssenkrupp.com/en/newsroom/press-releases/world-first-in-duisburg-as-nrw-economics-minister-pinkwart-launches-tests-at-thyssenkrupp-into-blast-furnace-use-of-hydrogen-17280.html.

Tokheim, L. et al. (2019), Combined calcination and CO_2 capture in cement clinker production by use of electrical energy, in: CO_2 Capture, Transport and Storage Conference Proceedings, SINTEF Academic Press, https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2637654.

Tsinghua University (2008), Report of Energy Saving and CO2 Emission Reduction Analysis in China Cement Industry, Tsinghua University, http://ccap.org/assets/Energy-Saving-and-CO2-Emission-Reduction-Analysis-in-China-Cement-Industry_CCAP-Nov-2008.pdf.

Total (2020), Svante, LafargeHolcim, Oxy Low Carbon Ventures and Total Launch Study for Commercial-scale Carbon Capture and End-use at U.S. Plant, press release, Total, https://www.total.com/en/media/news/press-releases/svante-lafargeholcim-oxy-low-carbon-ventures-and-total-launch-study-commercial-scale-carbon-capture.

UNEP (United Nations Environment Programme) (2016), Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry, UNEP, https://wedocs.unep.org/handle/20.500.11822/25281.

United States Census Bureau (2020), New Residential Construction, United States Census Bureau, https://www.census.gov/construction/nrc/index.html.

University of Lorraine (2018), Recycling of Construction and Demolition Waste in Cement, webpage, NWEurope, Lille, France, https://www.nweurope.eu/projects/project-search/seramco-secondary-raw-materials-for-concrete-precast-products/news/recycling-of-construction-and-demolition-waste-in-cement.

IEA. All rights reserved.

USGS (United States Geological Survey) (2020), Mineral Industry Surveys: Cement in May 2020, US Department of the Interior, Washington, DC, https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mis-202005-cemen.pdf.

VärmlandsMetanol Ltd (2017), In Short About VärmlandsMetanol Ltd, VärmlandsMetanol Ltd, Hagfors, Sweden, www.varmlandsmetanol.se/dokument/Folder%20VM%20nov%202017%20eng.pdf.

Vattenfall (2020), Cementa and Vattenfall Are Pioneering the Production of Fossil-free Cement, webpage, Vattenfall, Stockholm, Sweden, https://group.vattenfall.com/what-we-do/roadmap-to-fossil-freedom/industry-decarbonisation/cementa.

VEEP (2020), News, webpage, VEEP, www.veep-project.eu/Page.aspx?CAT=NEWS&IdPage=67a58a1d-ea59-4f54-934b-6a1b83868da7.

Vito (2018) Linovalue Pilot Launched, press release, Vito, Mol, Belgium, https://vito.be/en/news/lignovalue-pilot-launched.

VoltaChem (2020), Electric Cracking, webpage, VoltaChem, https://www.voltachem.com/projects/electric-cracking.

Voorhis, S. (2019), Canada producer plans global cement sector's first carbon capture system, Engineering News-Record, https://www.enr.com/articles/48373-canada-producer-plans-global-cement-sectors-first-carbon-capture-system.

Wang, T. et al. (2015), Concrete transformation of buildings in China and implications for the steel cycle, Resources, Conservation and Recycling, Vol. 103, pp. 205-215, https://doi.org/10.1016/j.resconrec.2015.07.021.

Wiencke, J. et al. (2018), Electrolysis of iron in a molten oxide electrolyte, Journal of Applied Electrochemistry, Vol. 48, pp. 115-126, https://doi.org/10.1007/s10800-017-1143-5.

World Steel Association (2020), Crude Steel Production Monthly, World Steel Association, https://www.worldsteel.org/steel-by-topic/statistics/steel-data-viewer/MCSP_crude_steel_monthly.

WorldGBC (World Green Building Council) (2019), Bringing Embodied Carbon Upfront, press release, WorldGBC, London, https://www.worldgbc.org/news-media/bringing-embodied-carbon-upfront.

Yara (2020), Yara Pilbara Renewable Ammonia, Yara, https://www.yara.com.au/siteassets/about-yara/pilbara-documents-other/renewable-ammonia-factsheet-ver-01.pdf.

ZeroCO$_2$ (2016), QPC Quimica Methanol Plant, webpage, ZeroCO$_2$, http://www.zeroco2.no/projects/metanol-plant-prosint.

Zhang J. et al. (2019), A review of the current progress and application of 3D printed concrete, Composites Part A: Applied Science and Manufacturing, Vol. 125, https://www.sciencedirect.com/science/article/pii/S1359835X19302829.

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Chapter 5. Technology needs in long-distance transport

- In 2019, transport accounted for nearly 30% of global final energy use and 23% of total energy sector direct CO_2 emissions. Reducing oil use and CO_2 emissions in long-distance transport modes – heavy-duty trucking, maritime shipping and aviation, the focus of this chapter – is particularly difficult because of their energy and power density requirements: technically viable alternative fuel technologies are not yet very advanced and are also likely to initially cost more than oil-based fuels.
- Each of the three sub-sectors have been hit hard by the Covid-19 pandemic; aviation most of all with passenger volumes in 2020 expected to be half of 2019 levels. In the longer term, however, rising incomes and population growth are expected to continue to drive up demand, exacerbating the decarbonisation challenge.
- In the Sustainable Development Scenario, operational and technical innovations unlock energy efficiency gains in the short to medium term, while switching to low-carbon fuels and electric powertrains drives emissions reductions in the long term. Yet none of the three sub-sectors is decarbonised by 2070 when collectively they emit 1.0 $GtCO_2$.
- In trucking, electricity and hydrogen dominate the fuel mix in 2070, powering vehicles that no longer rely on internal combustion engines. This hinges on rapid developments in batteries and fuel cells, as well as massive investment in new infrastructure, including hydrogen refuelling stations, fast chargers for electric trucks and electric road systems (which power vehicles as they drive).
- In maritime shipping, biofuels, ammonia and hydrogen meet more than 80% of fuel needs in 2070, using around 13% of the world's hydrogen production. Energy efficiency also makes a significant contribution. These changes require further tightening of efficiency targets and low-carbon fuel standards to close the price gap with fossil fuels and de-risk investment.
- In aviation, where technical fuel requirements are most stringent, biofuels and synthetic fuels account for three-quarters of the fuel demand in 2070. Synthetic fuels, which do not face the same supply constraints as biofuels, increase from about 2030 to meet almost half of demand by 2070. Policies will need to manage demand growth and promote new aircraft and engine technologies.
- The decarbonisation of these sub-sectors will require long-term planning and government support. R&D of alternative powertrains and fuels is needed to reduce costs and improve performance, and measures to develop associated infrastructure. More than 60% of the emissions reductions in 2070 come from technologies that are not commercially available today.

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Introduction

The transport sector encompasses all forms of mobility and freight services ranging from road and rail transport to travel by river, sea and air. It plays a vital role in our lives and it uses a lot of energy, particularly in the form of oil: it accounted for around 55 million barrels of oil per day (mb/d) in 2019, or more than half of total global oil demand. Transport is a major source of emissions, accounting for nearly one-quarter of energy sector carbon dioxide (CO_2) in 2019. In addition, transport is a major source of air pollution. Steps have been taken in recent years to mitigate the impacts of transport on the environment, in particular from cars. Regulations to reduce harmful local pollutants and fuel economy standards to cut fuel consumption have become the norm in practically all major car markets, and the application of fuel economy standards for heavy-duty vehicles is expanding.

More and more countries and regions are now going further by promoting zero tailpipe emissions technologies through zero-emission vehicle (ZEV) mandates and announcing bans of internal combustion or diesel engines.[1] Countries with an ambition to phase out internal combustion engine (ICE) cars between 2025 and 2050 together accounted for close to one-quarter of global car sales in 2019. Cities around the world are looking to reduce traffic congestion and to do more to tackle air pollution. In 2019, 2.1 million electric cars were sold accounting for 2.6% of global car sales. The pace of electric vehicle (EV) sales is set to accelerate and to shake up global car markets. Analysis of market trends to date in 2020 indicate that sales of EVs are likely to be more resilient than those of conventional cars in the wake of the Covid-19 pandemic, with many EV sales bolstered by policy support measures, especially in Europe and the People's Republic of China ("China" hereafter) (IEA, 2020a).

Electrification, accompanied by a shift to low-carbon electricity generation, will undoubtedly play a central role in reducing emissions from the transport sector. There are limitations to the possibilities that electrification offers for long-distance forms of transport, and in particular for heavy-duty trucks, maritime shipping and aviation, which together were responsible for 45% of both global energy demand for transport and CO_2 emissions from the sector in 2019. The limitations reflect the practical difficulties that come with the energy and power density requirements of long-distance transport, as well as the fact that ocean-going vessels and aircraft are very long-lived assets.

Patterns of freight transport have been dramatically altered in the Covid-19 crisis, with lockdowns and plant closures leading logistics companies to reconfigure global supply chains in response to supply disruptions and rapid changes in demand.

[1] For more details on these announcements, see *Global EV Outlook 2020*, Chapter 2 (IEA, 2020a). Further, that report covers recent trends, current status and the future prospects for transport electrification, with focus chapters on battery technologies, battery end-of-life and EV-grid integration.

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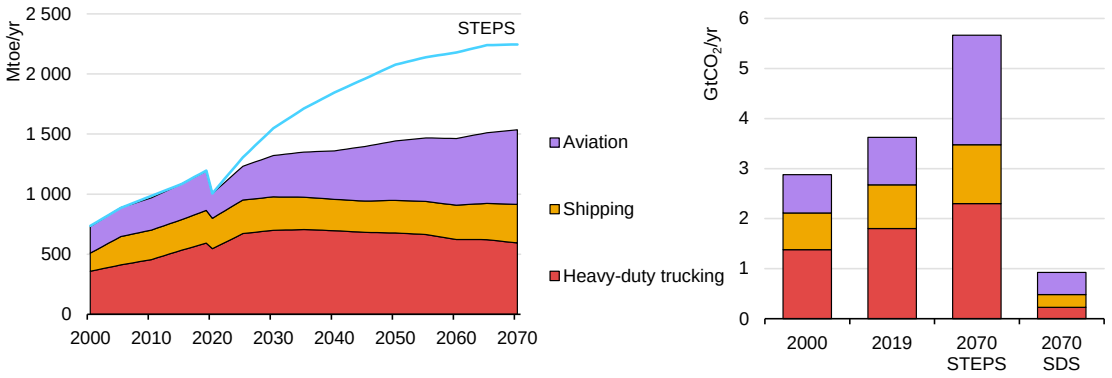
Reduced activity has led to a sharp reduction in energy use across all three long-distance transport modes (Figure 5.1). Sourcing patterns of raw materials and finished goods, as well as energy commodities, have been disrupted, while some are beginning to recover in mid-2020, the return of cargo trade will vary substantially by country, mode and product. Vehicle supply chains have been among the hardest hit. Commercial passenger aviation has been hit particularly hard: current industry expectations are for a full demand recovery only sometime between late 2022 and 2025. As discussed in more detail in the following sections, some of the adjustments to global trade and passenger aviation activity will be transitory, but others are likely to be longer lasting.[2]

Figure 5.1 Global energy consumption and CO_2 emissions in long-distance transport by sub-sector in the Sustainable Development and Stated Policies scenarios



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Note: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

In 2019, heavy-duty trucking, shipping and aviation consumed nearly 25 mb/d of oil and accounted for about 45% of energy demand and CO_2 emissions from the transport sector.

In the Sustainable Development Scenario, the heavy-duty trucking, maritime shipping and aviation sub-sectors reduce CO_2 emissions in 2070 by three-quarters from 2019 levels, despite a significant increase in energy demand. Though not fully decarbonised, together they emit nearly 1.0 gigatonnes (Gt) of CO_2 in 2070, or about 40% of total remaining energy sector emissions at that time. The challenge of decarbonising these sub-sectors is not one of technology availability alone; it also encompasses resource availability and costs, including the costs of new infrastructure. Various production pathways for biofuels, for example, are commercially available and the resulting biofuels can be made compatible with

[2] For a more detailed analysis of the impacts of the Covid-19 crisis on transport, see *Covid-19 Crisis and Clean Energy Progress* (IEA, 2020b).

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existing vehicles and infrastructure, but they face limitations on the availability of sustainable feedstock supplies due to demand from other sectors and cost barriers (see Chapter 2).

Heavy-duty trucking

Overview and outlook in the wake of Covid-19

Road freight is a vital component of global economic activity. Trucks deliver all kinds of commodities from their points of production to the factories that use or transform them and on to their final points of sale. The types of trucks used, and their implications for energy use and emissions vary by size, weight and power according to the nature of the goods transported (Box 5.1). In recent years, three-quarters of road freight activity measured in tonne-kilometres (tkm) has been carried out by heavy-freight trucks, which can be rigid body or articulated tractor-trailers.

While overall road freight volumes were not hit as hard as maritime shipping or aviation by the Covid-19 crisis, specific activities such as regional and long-distance trucking were hit in the early period of the pandemic, though at the time of writing in mid-2020 are showing signs of recovery. Volumes in China, for example, dropped to 15% of 2019 levels for a month in early 2020. They have now recovered to levels above those of 2019 (IFC, 2020), but in many places long-distance trucking is continuing to suffer. Social distancing to ensure the safety of truckers and warehouse workers, border checkpoints (especially in Europe) and other operational constraints have led to bottlenecks, delays, congestion, long queues and other logistical challenges. These matters have increased the rates that shippers charge for road freight, maritime shipping and cargo aviation. These rate increases, together with a reduction in activity on passenger rail lines, in some regions have led to an increase in the demand for rail services for freight, improving the position of some rail corridors, such as those between Europe and China.

The impact of simultaneous supply and demand shocks on small trucking operations has been severe. As in other sectors, some consolidation is likely. This has immediate short-term implications for fleet wide efficiency: it will result in an accelerated retirement of older and less efficient trucks, and provide an opportunity for bigger fleets to exploit operational and technical efficiency measures. While large logistics operations, such as Amazon, DB Schenker, DHL, FedEx, Kenco Group, UPS and XPO logistics, are certainly not immune to the economic impacts, they are better able to withstand the pressures. Indeed, against an economic backdrop where many companies continue to struggle, companies such as Amazon with a strong digital presence and data analytic capabilities have seen stock prices surge. Policies that require and assist companies that emerge stronger from the crisis to invest capital in

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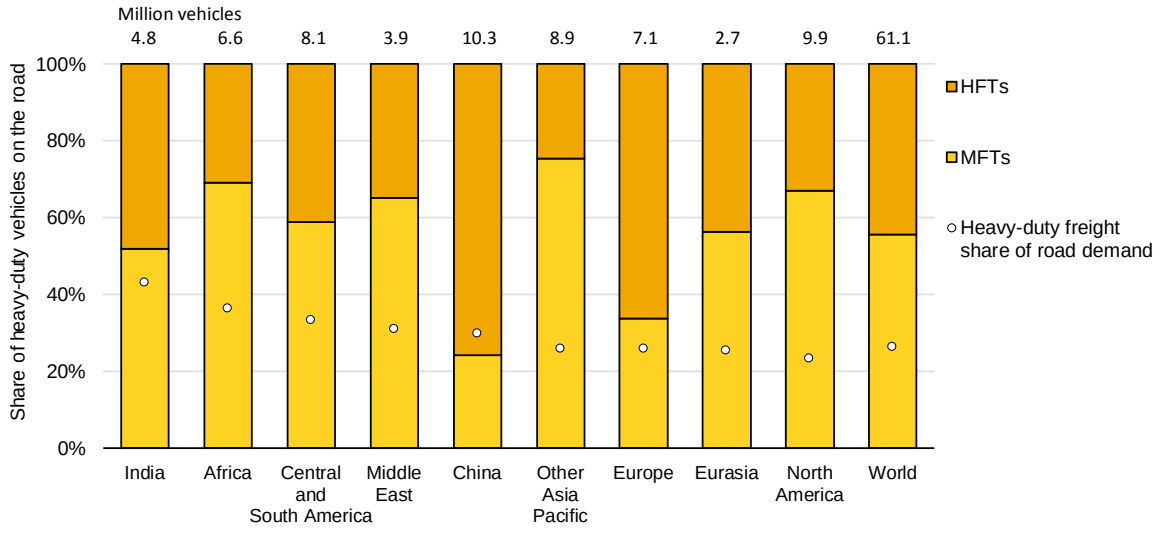
efficiency and emissions-reducing technologies could help to ensure that the Covid-19 crisis does not delay emission reductions, or even help to accelerate them.

The global fleet of heavy-duty trucks (referred to here simply as trucks) – was less than 6% of the size of the global car fleet in 2019. Trucks include medium-freight trucks (MFTs) and heavy-freight trucks (HFTs), which are differentiated on the basis of gross vehicle weight (GVW) (Box 5.1). In 2019 there were 33 million MFTs and 27 million HTFs, which is much smaller than the passenger light-duty vehicle fleet of 1 billion cars on the road today. China has the world's largest truck fleet, with more than 10 million HFTs on the road. The next largest fleets were in the United States (7.8 million trucks) and Europe (7.1 million trucks). Despite these relatively small numbers, trucks account for about 30% of total road fuel consumed in the world. In many regions this share is much higher. In India, for instance, trucks accounted for over 40% of road fuel used in 2019 (Figure 5.2). On average, per unit of cargo (tonne-kilometre [tkm]) moved, heavy-duty road freight is more energy-intensive (using about 2.5 litres of diesel/100 tkm) than rail or maritime freight: trains use about 30% as much energy as trucks, while maritime ships use about 10% as much.

Figure 5.2 Heavy-duty truck fleet and share of road fuel demand, 2019



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Note: HFTs = heavy-freight trucks; MFTs = medium-freight trucks.

Heavy-duty trucks account for less than 6% of vehicles on the road worldwide, but they consume about 30% of all the fuel and about two-thirds of the diesel used in road transport.

Today virtually all trucks run on oil-based fuels. Globally, trucks consumed more than 12 mb/d in 2019, equivalent to 12.5% of global oil demand and total oil production of the United States in that year. Oil demand from trucks is only outstripped by demand from passenger cars, which accounted for around 22% of total oil demand in 2019. More than 90% of the fuel consumed by trucks is in the form of diesel due to its higher

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energy density relative to gasoline, the reliability and efficiency of diesel engines in heavy-duty applications, and the higher torque for a given size of diesel versus spark-ignition engines. Gasoline provides around 6% of final energy demand for heavy-duty trucks, mostly in regions where fuel prices favour gasoline over diesel, in cases where fleet operators are capital constrained, and in operations with lower mileage and lower load and torque requirements. Alternative fuels currently play a minor role in fuelling trucks at a global level. Biofuels, usually blended into conventional diesel or gasoline, contribute nearly 3% of final energy use in heavy-duty trucks. Many cities in the United States and Europe have switched municipal fleets (e.g. transit buses and garbage trucks) to run on biomethane produced from municipal solid waste. Sweden leads the world in shares of blended biodiesel (fatty acid methyl esters [FAME] and hydrotreated vegetable oils [HVO]). Natural gas, in compressed or liquefied form, supplies less than 1% of energy for trucking.

While oil use in passenger cars had begun to plateau and decline in a growing number of industrialised countries, oil consumption in trucking continued to rise strongly prior to the Covid-19 crisis. Over the past decade, worldwide growth in fuel use has risen faster for trucks than it has for passenger cars. While this trend began in developed economies like Germany, it has become more widespread and is now visible in some developing economies such as India. Since 2000, worldwide fuel use by trucks has risen by about 50%, and trucks have been responsible for half of the global net increase in diesel demand in the transport sector. Today trucking accounts for about half of total global diesel demand. Rising road freight activity, which is broadly linked to economic growth, is the underlying driver of increasing energy use and emissions in trucking.

Heavy-duty road freight is a big contributor to CO_2 emissions. In 2019, it accounted for 22% of all transport-related CO_2 emissions and over 5% of total energy-related CO_2 emissions. Road freight is also a leading cause of transport-related pollutant emissions, which can have detrimental impacts on human health, particularly in urban areas. Trucks contribute more than one-third of total transport-related emissions of nitrogen oxides (NO_X) and nearly half of total transport-related emissions of fine particulate matter ($PM_{2.5}$). The sulphur dioxide (SO_2) share is much lower, at 7% of transport-related emissions, largely because fuel quality standards for automotive diesel fuel in most major economies mandate low concentrations of sulphur and because emissions from international shipping are much larger, though the sulphur cap that came into force in 2020 will change this picture going forward (IEA, 2016). Trucks that use internal combustion engines need to use costly after-treatment systems to reduce pollutant emissions. As pollutant emissions standards across world continue to ramp up, after-treatment costs will continue to increase, giving an advantage to zero-emission powertrain technologies.

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Box 5.1 Types of trucks and their energy and emission implications

One way to categorise trucks is by their gross vehicle weight (GVW) – the maximum rated curb weight of the vehicle plus its maximum rated payload.

Heavy-freight trucks (HFTs) have a GVW of more than 15 tonnes and are typically used for long-haul delivery of goods. In some cases, multiple trailers are pulled by a single tractor unit (called a "road train"). In regional and long-haul operations, the heaviest HFTs often cover more than 100 000 kilometres (km) per year and, in some instances, twice this distance. HFTs account for three-quarters of road freight activity, measured by tonne-kilometres, and more than half of total truck energy use and CO_2 emissions.

Medium-freight trucks (MFTs) are commercial vehicles with a GVW of 3.5-15 tonnes. They include small trucks, rigid trucks and tractor-trailers as well as large vans. They tend to be used in regional and urban operations but also include public and commercial service vehicles, such as garbage trucks or firefighting vehicles. In countries with a less-developed highway network, the function of some MFTs mimics that of HFTs, i.e. they carry out long-haul operations and transport goods from central distribution hubs (warehouses and ports) to their final destinations or transport bulk building materials and resources. MFTs consume around one-quarter of total energy used in road freight and an equivalent share of emissions. Together, HFTs and MFTs are categorised as heavy-duty trucks.

Light-commercial vehicles (LCVs) have a GVW of less than 3.5 tonnes and are used for a variety of tasks, including small-scale postal and commercial "last-mile" deliveries, transporting industrial goods and building materials to and from work sites, and providing other non-freight commercial services (e.g. by plumbers and electricians). Their mostly urban operations and lower total weight make LCVs good candidates for electrification (Chapter 2), with range extenders or additional power systems (e.g. fuel cells) in the case of very intensive use. Hence, while the spread of LCVs will help with the deployment of alternative fuelling infrastructures, they are not considered "hard to abate" like heavy-duty trucks, and so are not considered in this chapter.

Despite the sizeable contribution to global oil demand and CO_2 emissions, road freight historically has not been the focus of policy as much as passenger vehicles. Although policies to curb air pollution emissions from road freight vehicles exist in many countries, only five countries – Canada, China, India, Japan and United States – and one regional block, the European Union, have adopted regulations for fuel economy/CO_2 standards for heavy-duty vehicles (trucks and buses). However, this is starting to change, with more countries planning to introduce standards for heavy-duty vehicles. In 2019, while more than 85% of global light-duty vehicle (LDV) sales

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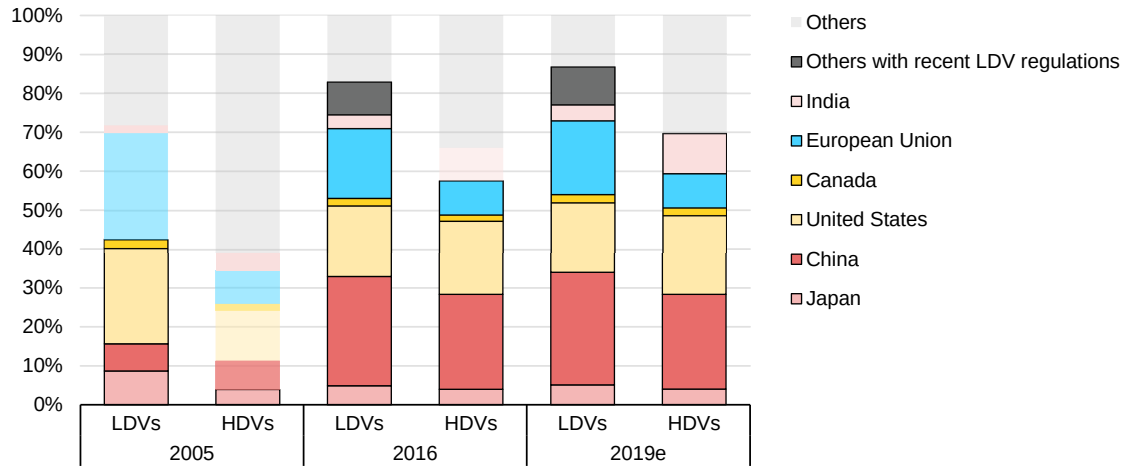
were covered by fuel economy/CO_2 standards, less than 70% of heavy-duty vehicles sales were in regions where such standards have been put in place (Figure 5.3).[3]

Figure 5.3 Share of vehicle sales covered by fuel economy and/or CO_2 emissions standards by vehicle type and country/region



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Notes: LDVs = light-duty vehicles; HDVs = heavy-duty vehicles; e= estimated. Countries and regions shown without outline and in transparent colours have not adopted standards. India put new HDV fuel economy standards in place in April 2018. Mandatory reporting of fuel consumption and CO_2 emissions began in the European Union in January 2019, and binding standards will come into force for four classes of heavy-duty trucks in July 2025.

Vehicle efficiency and CO_2 emissions standards for heavy-duty vehicles are catching up with those for light-duty vehicles.

Reducing CO_2 emissions from road freight to zero is hampered by several factors. There is limited scope for decoupling road freight activity from economic activity, given that there are few practical alternatives to trucks for transporting goods inland. Railways and inland waterways could take a larger share of the freight market, but the infrastructure is not always in place, nor is it always feasible to build it. Alternative low-carbon fuels, including biofuels and renewables-based electricity and hydrogen, could displace oil-based diesel and gasoline, but there are constraints on supply in the case of biofuels, while electricity and hydrogen are not yet either technically or economically viable for many truck operations, and in particular for regional and long-haul operations. Major advances in all these technologies will be needed for them to play a leading role in decarbonising road freight in the long term. While

[3] Fuel economy / CO_2 emission standards do not yet cover all the heavy-duty truck sales, as they have yet to come into effect in some regions. For instance, in the European Union, CO_2 emission standards will come into effect as from 2025.

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improved fuel economy could reduce fuel use in the near term, trucks tend to be used for more than a decade, slowing the pace at which they can be replaced.[4]

The market for trucks is highly regional and specialised. There are fewer manufacturers of heavy-duty trucks than cars in both the North American and European Union markets, and most of them are national or regional. Elsewhere, original equipment manufacturers (OEMs) in China and India are increasing sales of low cost trucks in the Middle East, Africa, some Asian countries and Latin America, where markets are more price sensitive. In the case of rigid trucks and, to a lesser extent, tractor-trailers, one or two vehicle platforms tend to dominate sales for each manufacturer. Truck manufacturing plants tend to be more flexible than car manufacturing plants in terms of being able to customise vehicle variants on an assembly line. Engines, powertrains and other components (e.g. the axle configuration and, in the case of tractors, the trailer type) can be fitted onto one or two vehicle platforms, making it possible to produce hundreds or even thousands of variants capable of operating according to specific mission profiles and applications. OEMs are more flexible than other manufacturers in accommodating customer needs, not only in terms of loads and power, but also in terms of fitting diverse powertrain options. This flexibility enables truck OEMs to customise the powertrains ordered by clients on a single production line, including plug-in, battery and fuel cell electric trucks, as well as fuel cell range extended trucks.

Limited model offers, together with higher purchase prices and limited infrastructure, are the main barriers to adoption of zero-emission trucks. Nevertheless, some logistic companies are responding to the growing pressure to work towards net-zero emissions in their operations by either retrofitting to electric trucks on their own (e.g. Schenker AG, Climategroup and UPS), or placing large orders from start-ups that are developing electric trucks in which they hold shares (e.g. Amazon) (Table 5.1). However, most of the retrofits and orders to date have been in the light-commercial vehicle segment (i.e. less than 3.5 tonnes GVW).

[4] They are typically operated for less than a decade by the first owner before being sold, either within the country or exported (often from a developed economy to a developing one) where they may be used for another decade.

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Table 5.1 Logistic companies and electric trucks

Company	Target / action
Amazon	All last-mile delivery to customers by ZEVs and 50% of all logistics to be net-zero carbon by 2030. In 2019, ordered 100 000 battery electric delivery vehicles from the start-up Rivian.
FedEx	In 2018 acquired 1 000 commercial electric vehicles from Chanje.
Ingka Group (Ikea)	Last-mile delivery to costumers to be fully electric by 2025. For Paris, Los Angeles, Amsterdam, New York by 2020. It was achieved in Shanghai in 2019.
Schenker AG	Retrofitting existing diesel trucks to run on electricity due to a lack of models available from automakers.
Deutsche Post DHL Group	Net-zero emissions logistics by 2050 and delivery of mail and parcels to be delivered by electric vehicles powered by renewables-based electricity in the medium term.
UPS	Ordered 10 000 electric trucks in 2020.

Technology pathways towards net-zero emissions

In the Sustainable Development Scenario, global CO_2 emissions from the road freight sub-sector fall by 90% from around 1.8 Gt in 2019 to just 200 million tonnes (Mt) in 2070 (Figure 5.4). Net-zero emissions are not achieved until after 2070 due to the high cost of fully decarbonising road freight relative to other options to reach net-zero emissions in the energy system as a whole. In the Stated Policies Scenario, emissions continue to increase through 2045, peaking at 2.7 Gt around mid-century, before gradually declining to around 2.3 Gt in 2070, about a 40% increase from 2019 levels.

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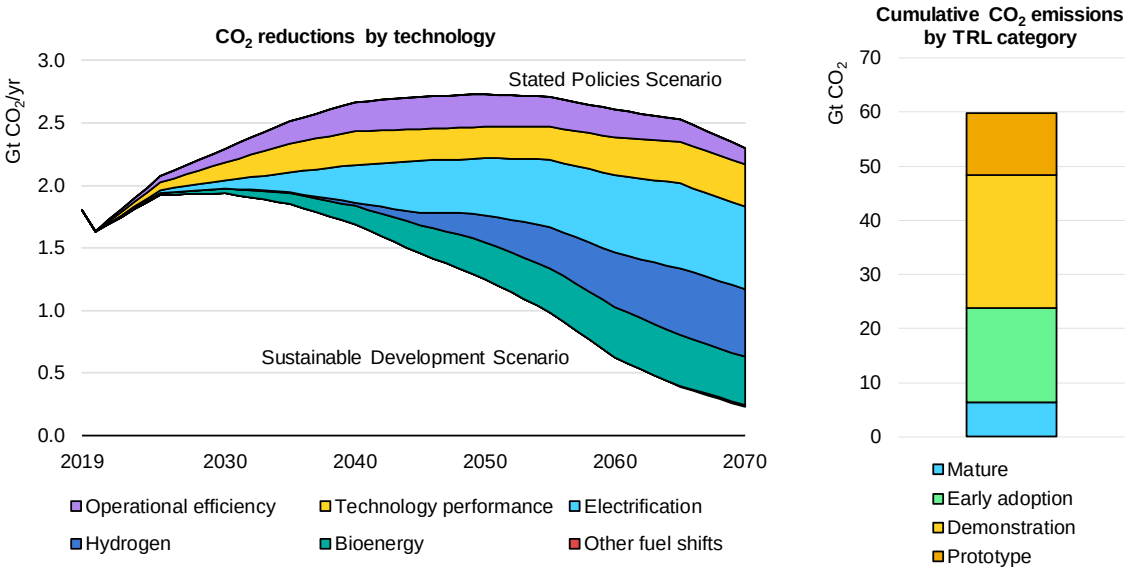
Figure 5.4 Global CO_2 emissions from trucks by abatement measure (left) and technology readiness level (right) in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-70



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Notes: Some operational efficiency technologies and measures, such as platooning and retiming urban deliveries, improve technical vehicle efficiency. The effects of switching to biofuels, electricity and hydrogen (fuel cell electric) vehicles are distinguished from other fuel switching, which are primarily from diesel to natural gas and synthetic fuels. TRL = technology readiness level. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

For heavy-duty trucks, operational and technical efficiency together contribute nearly 45%, electricity an additional 31%, and hydrogen and biofuels together almost 35% of cumulative CO_2 emission reductions in the Sustainable Development Scenario.

The kinds of action envisaged to reduce CO_2 emissions from heavy-duty trucks in the Sustainable Development Scenario fall into three main categories:[5]

- *Systemic improvements in road freight operations and logistics*. Such improvements, akin to material efficiency improvements in the industrial sector, can help to curb the growth in road freight trucking activity and improve the on-road efficiency of trucking. These include near-term measures with low barriers to adoption (e.g. retiming urban deliveries to periods of the day when congestion is low, driver fuel efficiency training and a wide range of measures to improve the utilisation of vehicles to maximise load).[6] Mid-term measures with more significant technological or institutional barriers to adoption (e.g. platooning or

[5] For further discussion of the three key strategies for decarbonising road freight, see: *The Future of Trucks: Implications for Energy and the Environment* (IEA, 2017).

[6] Operational efficiency measures, such as maximising loads (e.g. via digital freight matching or backhauling), routing or driver training, as well as vehicle efficiency retrofits, can have an immediate impact on road freight emissions, thereby making attractive targets for elements of economic recovery packages to respond to the Covid-19 crisis.

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broader adoption of high-capacity vehicles) that could transform road freight operations entirely, but for which eventual adoption and impacts are uncertain, for example measures involving the use of autonomous trucks. Companies in China and the United States (e.g. MangBang Group, Uber Freight), have taken the lead in adopting new information and communication technologies, including digital freight matching which helps to ensure that trucks operate closer to their full weight or volume loads in order to increase operational efficiency. Such business models are likely to catch on in other regional markets.

- *Improved fuel efficiency*. For the existing stock of trucks, aerodynamic retrofits can yield immediate improvements in fuel economy. For new trucks, other technologies, such as the use of lightweight materials and improvements to truck engines, transmissions and drivetrains can increase vehicle efficiency.[7]
- *Adoption of low-carbon alternative fuels*. These include biofuels, synthetic fuels, natural gas, electricity and hydrogen. Under stringent regulatory and technical regimes, they can all contribute to reducing air pollution and, in the case of electricity and hydrogen, do not directly emit CO_2.[8] Biofuels account for most of the increase in the use of alternative fuels in the Sustainable Development Scenario, though electricity and hydrogen make a growing contribution, especially in the second half of the projection period (Figures 5.4 and 5.5). The consumption of biofuels jumps more than six-fold from 13 million tonnes of oil equivalent (Mtoe) in 2019 to 80 Mtoe in 2070.

In the near term in the Sustainable Development Scenario, technical and operational efficiency (including hybridisation) contribute most to reducing the carbon intensity of heavy-duty truck operations, though electric trucks begin entering the fleet in small but growing numbers in the 2020s. Driven by favourable economics in some regions, truck operations that require large vehicles and are heavily utilised (typically more than 100 000 km/year) shift to liquefied natural gas (LNG), while smaller trucks with lower mileage and less regular operations adopt compressed natural gas (CNG). Natural gas consumption growth by trucks is modest, reflecting its limited potential to reduce CO_2 emissions on a well-to-wheel basis. The share of biofuels also increases in the 2030s, including biofuels that can be blended directly with gasoline and diesel, as well as biomethane, which is virtually indistinguishable in chemical properties from conventional natural gas.

[7] Many of the improved fuel efficiency measures that can be retrofitted in the existing fleet or are available in new trucks are not taken up, despite the attractive financial savings they can bring. Some reasons include capital constraints, uncertainty on payback period, misalignment of economic incentives and inconsistent regulations and enforcement across jurisdictions. Hurdles to efficiency technologies are particularly pronounced in the case of individual truck owner-operators or small fleets, which account for a large share of road freight operators, even in such countries as Canada, members of the European Union and the United States.

[8] IEA accounting of direct combustion emissions of fossil fuels treats emissions from the production of synthetic fuels separately (as upstream emissions) and treats biofuels as net-zero emissions. Hence it excludes the emissions considered by analytical frameworks and regulations based on well-to-wheel accounting for non-fossil based fuels.

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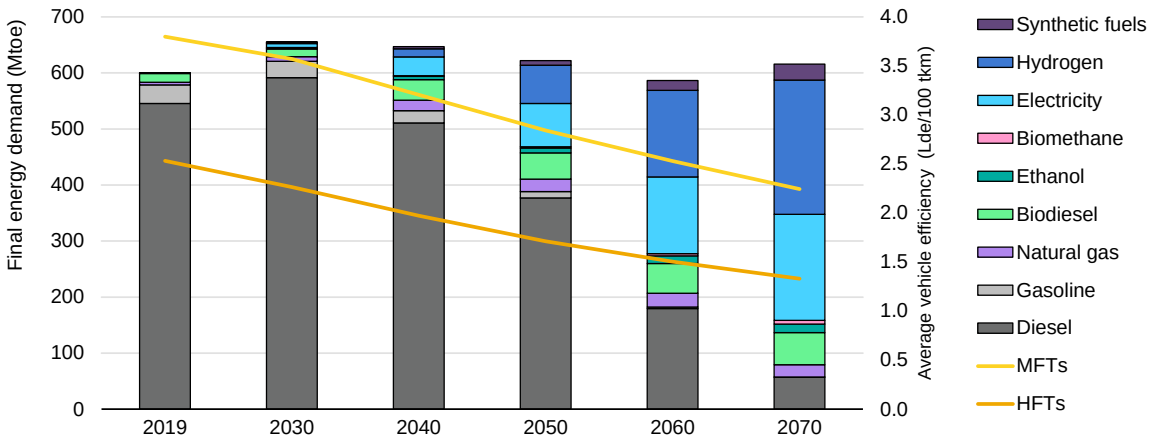
In the longer term, decarbonising trucks requires a transition to powertrains that rely on electricity and hydrogen. The scaling up of plug-in and battery electric trucks in the projections starts with medium-freight trucks in the 2020s in urban operations, and then extends to broader regional operations. Fuel cell electric MFTs as well as HFTs begin to diversify the fuel mix away from fossil and liquid alternative fuels starting in the late 2030s and operations extend to long-haul routes (Figures 5.5 and 5.6). As battery, plug-in, and fuel cell electric trucks penetrate road freight their more efficient powertrains drive improvements in the energy intensity of trucking. By 2070, in the Sustainable Development Scenario, the equivalent of more than 33 Tesla gigafactories are needed to equip heavy-duty trucks with batteries for energy storage. Hydrogen and electricity together account for around 70% of global final energy use from trucks in the Sustainable Development Scenario, requiring nearly 2 400 terawatt-hours (TWh) of electricity (equivalent to the current combined electricity use of the Russian Federation and India) and 83 Mt of hydrogen (more than 15% of total hydrogen used in 2019).

Figure 5.5 Global heavy-duty trucking energy demand by fuel and average vehicle efficiency in the Sustainable Development Scenario, 2019-70



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Notes: Lde = litres of diesel equivalent; tkm = tonne-kilometres; MFTs = medium-freight trucks (3.5-15 tonnes GVW); HFTs = heavy-freight trucks (> 15 tonnes GVW). Efficiency improvements more than offset activity growth in the 2030-60 time period, but after 2060 activity demand growth overwhelms efficiency improvements, leading to increases in final energy demand.

Biofuels, electricity, hydrogen and synthetic fuels progressively displace oil-based fuels for trucks in the Sustainable Development Scenario.

Market entry in the 2020s of electric trucks in plug-in hybrid, fuel cell electric, and battery electric powertrains is accelerated by policies such as zero-emission vehicles (ZEV) mandates for medium- and heavy-duty trucks, as pioneered by California and other US states, and by the co-ordinated roll out of supporting infrastructure. Installation of fast, ultra-fast and mega charging (from 100 kilowatts minimum to as high as 1-2 megawatts or more) on regional and long-haul routes enables long-

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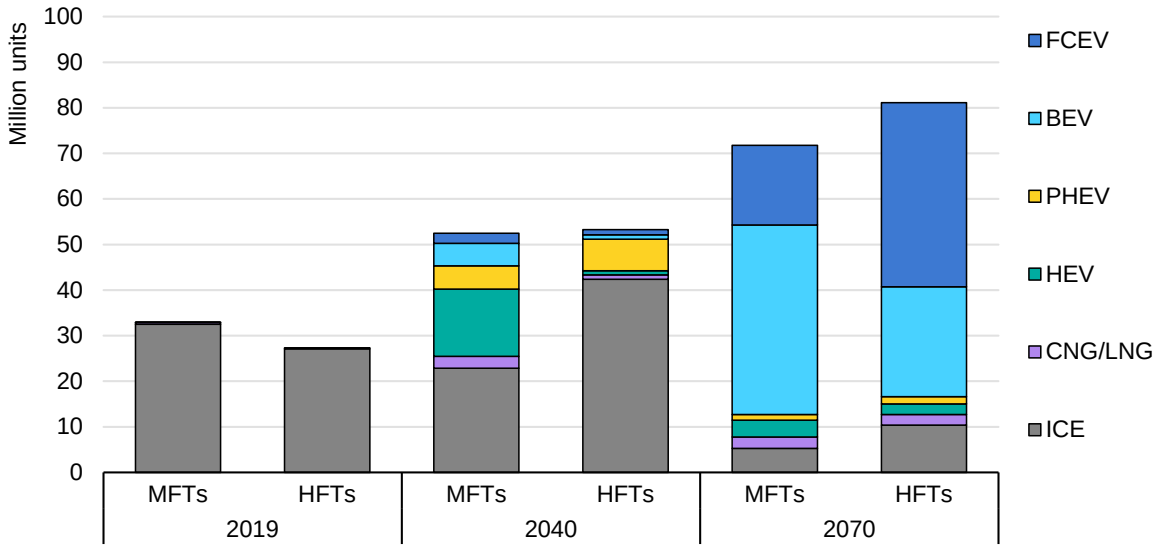
distance electric trucking operations. Hydrogen refuelling stations, which to date mostly serve LDVs, will need to be designed and equipped to serve MFTs and HFTs. Electric road systems, which enable vehicles equipped with batteries and electric motors to draw power and charge while driving – and so are capable of charging plug-in-, battery-, and fuel cell electric trucks – expand their operations. Initial roll out is likely to be in the most heavily trafficked road freight corridors.

By around 2040, fuel cell electric trucks using hydrogen begin to enter the fleet in significant numbers as the cost of fuel cells and hydrogen storage tanks decline as economies of scale are achieved in the LDV sub-sector. This requires the development of supply and refuelling infrastructure capable of delivering hydrogen at competitive prices, particularly for long-haul intensive use on regular routes and operations (IEA, 2019a).

Figure 5.6 Heavy-duty truck fleet by powertrain in the Sustainable Development Scenario



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Notes: FCEV = fuel cell electric vehicle; BEV = battery electric vehicle; PHEV = plug-in electric vehicle; HEV = hybrid electric vehicle; CNG/LNG = compressed natural gas/liquefied natural gas vehicle; ICE = internal combustion engine; MFTs = medium-freight trucks; HFTs = heavy-freight trucks.

Nearly half of medium-freight trucks have hybrid or full electric powertrains by 2040, while most medium- and heavy-freight trucks operate with batteries or hydrogen fuel cells in 2070 in the Sustainable Development Scenario.

As late as 2050, most trucks in the global fleet continue to rely on internal combustion engines, although hybrid powertrains become more common in MFTs and a growing numbers of medium- and heavy-freight trucks begin to electrify. Countries that roll out charging/fuelling infrastructure in a timely manner while promoting the adoption of these vehicle technologies are the first to transition to zero-emission trucks. Broadly speaking, this implies that early deployment of zero-emission trucks is likely in China, Japan, Korea, EU countries and North America.

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The lower technology readiness level of zero-emission powertrain technologies for road freight suggests that their uptake will take time to reach cost competitiveness for long-haul operations. This has two main implications: first, it suggests that future uptake in particular of hydrogen- and electricity-based trucks is very uncertain and the balance of long-term technology uptake might shift depending on progress on relevant technologies and the supporting infrastructure as well as policy support over the next decade. Second, it means that some HFTs with ICE powertrains using a mix of bio- and fossil-based diesel, natural gas and methane and synthetic fuels are likely to still be in operation at the time the energy sector as a whole reaches net-zero emissions. Alternative low-carbon liquid fuels will be crucial to facilitate a faster transition away from high-carbon fuels. Biofuels, particularly biodiesel (but also ethanol and biomethane), are a key alternative to fossil fuels for trucks in the Sustainable Development Scenario. Policy frameworks that encourage R&D of biofuel production pathways with low or net negative lifecycle greenhouse gas (GHG) emissions can foster their deployment and help address the entry hurdles of higher costs than conventional fuels and limited production volumes. Cellulosic and lipid-based feedstocks feed repurposed biorefineries (e.g. via biomass-to-liquids and alcohol-to-jet pathways) and transition to this new, highly specialised fuel pool. Synthetic fuels enter the fuel mix for heavy-duty transport in the 2040s, and while the share of these synthetic "drop-in" diesel substitutes remains low, it grows steadily. As with biofuels, synthetic fuel production also has the potential to transition from the road freight sub-sector to aviation, which continues to require liquid fuels throughout the second half of the century.

Readiness and competitiveness of emerging technologies

As discussed, the three categories of technology-related measures – systematic improvements in operations and logistics, better fuel efficiency and uptake of low-carbon fuels – plays an important part in decarbonising trucks in the Sustainable Development Scenario. In the near term, technologies are available to improve logistical, operational and energy efficiency which contribute to system-level improvements and lower trucks' fuel consumption, while efforts are ongoing to develop cleaner fuels and the powertrains capable of running on them (Table 5.2). In the longer term, progress is needed to enable the use of electricity and hydrogen in road freight operations, including the infrastructure to produce, transport and provide power to fuel cell EVs and BEVs as they displace trucks burning fossil fuels. There are many emerging technologies that may be able to contribute. They are at various stages in the development process and which ones succeed and to what extent depends on a variety of factors.

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Table 5.2 Status of the main emerging technologies in heavy-duty road freight

Technology	TRL	CO_2 reduction means	Year available (Importance for net-zero emissions)	Deployment status
System and logistics efficiency				
Platooning	8-9	Reduction in aerodynamic drag	Present -2025 (Low-medium)	2008: Japan *Energy ITS* demonstration of CAV platoons. 2011: California *PATH* programme. 2014: NREL *SmartTruck* demonstrations. 2016: European *Truck Platooning Challenge*. United States Caltrans/Volvo, Auburn/Peterbilt demonstrations. 2017: European Union *SARTRE* project demonstration of V2V.
Autonomous trucks	5-8	Energy and fuel efficiency	2025-35 (High)	2019: Plus.ai made an autonomous truck trip across the United States. 2020: Einride recruits remote operators for autonomous trucks.
Energy efficiency				
Lithium-ion batteries	5-9	Electrification	Present -2050 (High)	Various chemistries and designs are available. Li-ion batteries with various chemistries installed on cars (NMC, NCA), and buses and trucks (also LFP) are continuously improving. Other lower TRL chemistries, such as solid-state Li-metal, could make battery electric trucks commercially viable in the mid to long term.
PEM fuel cells	7-9	Hydrogen	Present -2030 (High)	The US Department of Energy, through its national laboratories, together with Toyota, Ballard, and Hyundai, are leading in basic and applied PEM research and commercialisation.
Alternative fuels and powertrains				
ED95 engines	8-9	Fuel switching	Present (High)	Scania has pioneered compression ignition engines that can run on 95% ethanol. Hundreds of trucks are operating in Sweden.
Electric HDTs	8-9	Electrification	Present (High)	2019: cumulative global deliveries of electric HDTs totalled more than 23 000, more than 95% in China. Most of these were battery electric trucks, and most were MFTs. BYD, Cummins, Daimler, Emoss and Fuso were the earliest manufacturers. The Tesla Semi model will soon be on the market.
FCEV HDTs	8-9	Hydrogen	Present (High)	Daimler, Fuso, Toyota, Hyundai, Scania, Volkswagen and PSA are developing FCEV trucks, ranging from prototypes to commercial models. The start-up Nikola has secured substantial funding and many pre-orders for its semi-trucks. FedEx and UPS are testing fuel cell range-extender Class 6 delivery vehicles. In Europe, the *h2Share* Project is demonstrating several heavy trucks over 12 tonnes.

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Technology	TRL	CO_2 reduction means	Year available (Importance for net-zero emissions)	Deployment status
Alternative fuels infrastructure				
Megachargers / HPCCV	5-6	Electrification	Present - 2030 (High)	Tesla is developing prototype super-fast chargers (1.2-2 MW). Daimler is working on a charger with a rate of up to 3 MW.
Hydrogen refuelling stations	9	Hydrogen	Present (High)	2019: more than 400 HRS stations, most of which are in Japan, Germany, United States and China, supply H_2 to road vehicles. More large stations dispensing H_2 at 700 bar are being built.
Electric road systems	6-9	Electrification	Present (High)	Siemens has built a handful of demonstration catenary systems on highways, totalling more than 30 km, in Sweden and Germany. In-road conductive and inductive designs are also being tested.

Notes: TRL = technology readiness level. BEV = battery electric vehicle. PHEV = plug-in hybrid electric vehicle. FCEV = fuel cell electric vehicle. HDT = heavy-duty truck. CAV = Connected and autonomous vehicles. NREL = National Renewable Energy Laboratory. V2V = Vehicle-to-vehicle. NMC = Nickel manganese cobalt. NCA = Nickel manganese aluminium. LFP = Lithium iron phosphate. PEM = Polymer electrolyte membrane. HPCCV = High power charging for commercial vehicles. HRS = Hydrogen refuelling stations. A broader list of technologies compatible with a low-carbon transition for the heavy-duty road freight sub-sector is presented in the technology mapping portion of *The Covid-19 Crisis and Clean Energy Progress* (IEA, 2020b).

Cost-effective and technically viable **energy efficiency** technologies for trucks and trailers, engines, transmissions and drivetrains are capable of reducing the specific fuel consumption of road freight trucks by 15-25% in 2025 and by 25-35% in 2035 relative to a 2015 baseline – improvements that are achieved in the Sustainable Development Scenario.[9] This represents a marked acceleration compared with recent trends. Vehicle efficiency standards that effectively mandate adoption of technologies at or near the limit of economic viability would be needed to achieve this acceleration. Technical and operational barriers to efficiency improvements, such as imperfect information, can be addressed in various ways, particularly through green freight programmes.[10]

The adoption of **alternative fuels** and the **powertrains** that are designed to use them is a critical factor in the longer term, particularly for heavy-duty trucks that make regional and long-haul journeys. The eventual mix of low-carbon and, eventually,

[9] Techno-economic analyses of the cost-effective potential for technical efficiency improvements vary by truck type and mission profile, and according to differing methodologies and baselines. The range presented here reflects analyses undertaken by: Dünnebeil et al., 2015; Norris and Escher, 2017; Verbeek et al., 2018; US EPA & NHTSA, 2016; Krause and Donati, 2018; ICCT 2018.

[10] Green freight programmes are consortia of public and commercial stakeholders that share technical and operational efficiency information and promote technologies and practices across the freight sub-sector by combining carbon emissions accounting and disclosures with action plans to reduce emissions and improve operational and technical efficiency.

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zero-emission trucks that will be rolled out is highly uncertain and will depend on the pace of technology development in competing – and sometimes complementary – options on the fuel supply side and in batteries and fuel cells. The high costs of biofuels reflect feedstock harvesting, collection and processing, each of which involves considerable expense and requires substantial energy inputs (ICCT, 2011; Holland et al., 2015). In addition to costs, biofuels face concerns about sustainability, competition with food production and the extent to which they can deliver meaningful reductions in GHG emissions. Today synthetic fuels are far less technologically advanced and commercially viable than biofuels, though they have many potential advantages. For example, using hydrogen produced by electrolysis or via steam reforming of natural gas or biomethane with carbon capture, utilisation and storage (CCUS) to produce drop-in substitute diesel via Fischer-Tropsch technologies may prove to be more attractive than using many types of biofuels in terms of sustainability, availability and emissions impacts and eventually more competitive in terms of the total cost of vehicle ownership.

Battery electric and fuel cell electric vehicles – the only vehicles with no exhaust emissions – are both promising options to reduce CO_2 and air pollution emissions from the transport sector. Relative to LDVs, the challenges to electrify freight trucks are high due to vehicle weight, haulage weight and volume, hours in service and distances driven. Notably though an increasingly wide selection of all-electric trucks is entering the market in the less than 15 tonnes category.

The most promising fuel and vehicle platforms for decarbonising long-distance road freight – electricity and hydrogen – are crucially dependent on the development of supporting infrastructure. In the case of electricity, the rapid deployment of light-duty EVs, including LCVs and urban buses, requires growing networks of charging infrastructure. In the case of hydrogen, the deployment of fuel cell EVs depends on hydrogen refuelling stations (HRS). Japan, Germany, California, China and Korea have each deployed between 60 and 120 HRS, which primarily serve cars. China has taken the lead in deploying fuel cell electric buses and trucks, and it may benefit as the first mover in learning from successes and failures in co-ordinating the roll out of HRS with fuel cell electric and range extended fuel cell heavy-duty trucks.

Led by Sweden and Germany, European Union members and the United States are leading in pre-commercial demonstration of electric road systems (ERS).[11] Over the past decade, the United States and Sweden have built small-scale prototypes and demonstrations of both conductive and inductive ERS. These trials together with a growing body of academic and industry research suggest that the capital costs of ERS systems can be quickly amortised on heavily trafficked freight corridors. For the truck owner/operator, the additional costs of vehicle systems that are needed to

[11] Electric road systems provide power to vehicles while driving which enables dynamic charging. The simplest version of ERS uses catenary (overhead) cables and a pantograph, and is essentially a higher speed version of trolley bus systems. Conductive and inductive systems built into a roadway ('in-road' systems) at technology readiness level 6-7 also have been demonstrated.

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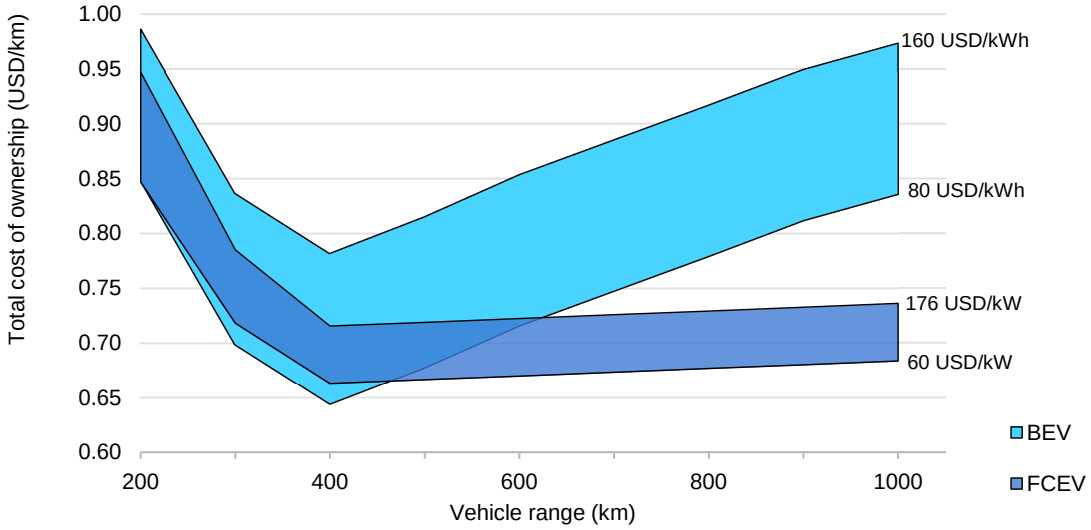
enable dynamic charging, e.g. a pantograph, in the case of overhead catenary systems, can be recovered through reduced fuel expenditure for hybridised electric powertrains, which can include plug-in hybrid trucks and fuel cell or range extended trucks, or through reduced battery capacity of pure battery electric or fuel cell electric trucks operating on an ERS. If such research and demonstration projects are successful in improving the economic, environmental, and operational benefits of ERS, it may provide a strategic opportunity to stimulate ZEV truck adoption for heavily trafficked freight corridors. There may be scope for ERS to expand and accelerate the application of ZEV trucks for drayage (i.e. short-distance moving of freight in the shipping and logistics industries), regional and long-haul journeys. Overall, ERS can serve as a near-term bridge to catalyse commercialisation of ZEV powertrains in a wide range of applications.

The future mix of low-carbon fuels and powertrains will be determined by cost reductions and performance improvements, including in energy and power density, durability of batteries and fuel cells, and the cost of delivering electricity and hydrogen. Assuming that the costs of delivering hydrogen at the pump can be brought down to less than USD 5 per kilogramme (kg), and also assuming that fuel cells can be mass produced to meet performance targets envisioned by OEMs and government, fuel cell trucks would compete favourably against battery electric trucks at vehicle ranges above 500 km, opening a niche in regional and long-haul trucking (Figure 5.7) (IEA, 2019a).

Figure 5.7 The effect of battery and fuel cell prices on total cost of ownership of heavy-duty trucks in long-haul operations



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Notes: kWh = kilowatt-hour; kW = kilowatt; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. The delivered price of hydrogen is assumed to be USD 5/kg, with about USD 4/kg related to the cost of hydrogen production (via centralised steam methane reforming with CCUS or electrolysis), and, in the case of off-site production, of transporting the hydrogen to the refuelling station. An additional 1 USD/kg mark-up comes from the amortised capital and operating costs of the hydrogen refuelling station itself.

The prospects for competing powertrain options hinge on improvements in the cost and performance of batteries and fuel cells.

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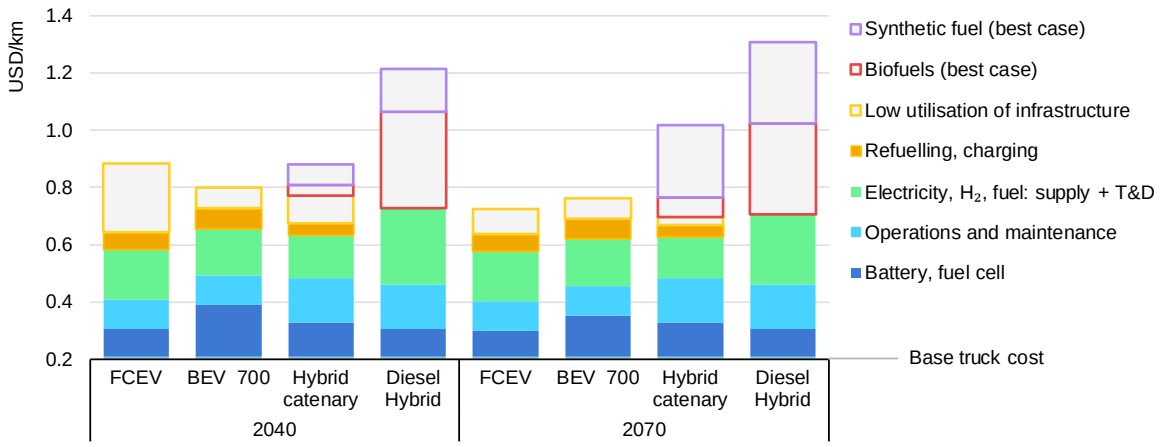
Installing hydrogen refuelling stations, EV fast chargers and ERS will be very expensive. Plus they need to be deployed as to ensure high utilisation in order to keep costs down. Depending on infrastructure utilisation, the total costs of owning and operating fuel cell electric trucks are lower than those of battery electric trucks at daily mileages of 500-700 km. In the medium term, the utilisation rate of hydrogen refuelling stations has a bigger impact on the total cost of ownership than the utilisation rate for fast chargers.

In the medium term, hybrid electric trucks using biofuels or synthetic fuels may well be able to compete on a total cost of ownership basis with oil-based diesel in some cases, particularly in regions with high diesel taxes. In the longer term, once the necessary infrastructure has been rolled out and more efficient zero-emission powertrains are available, alternative electric powertrains (i.e. battery and fuel cell electric trucks) look likely to become more competitive than internal combustion engines, assuming higher fuel taxes based on local pollutant and CO_2 emissions, as in the Sustainable Development Scenario, or an approach which has an equivalent effect (Figure 5.8).

Figure 5.8 Total cost of ownership of heavy-duty trucks by low-carbon fuel in the Sustainable Development Scenario, 2040 and 2070



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Notes: T&D = transmission and distribution losses; FCEV = fuel cell electric vehicle; BEV = battery electric vehicle. The Y-axis intercept of the right-hand side figure corresponds to the cost of the vehicle glider (i.e. the vehicle base without the powertrain) plus minor component costs. Infrastructure covers stations, charging points and catenary lines. Fuel supply costs include all upstream costs in the case of conventional fuels, biofuels and synthetic fuels, but include only the costs of producing and transporting electricity and hydrogen for these two energy carriers. For electricity and hydrogen, the additional costs of dedicated infrastructure are broken out explicitly in the items shown in yellow. These reflect the price mark-up for hydrogen and electricity that is determined by how quickly the infrastructure provider is able to amortise the capital and operating costs of hydrogen refuelling stations (for fuel cell electric trucks), fast charging (for battery electric trucks) and catenary lines, as the representative technology for the electric road system (for hybrid diesel trucks with 25 km of all-electric range). The speed of this amortisation depends on the frequency of infrastructure of utilisation; the yellow boxes in the figure show the variability arising from representative assumptions of this frequency. In the case of hydrogen stations, the utilisation ranges from 10-50% in 2040 and 20-50% in 2070. In the case of fast charging, the range is 10-15% both in 2040 and 2070. For catenary systems, the utilisation ranges shown reflect daily truck traffic of 600 - 2 000 vehicles in 2040, and 1 000 - 2 000 vehicles in 2070, reflecting the current range of heavily utilised truck corridors. For biofuels and synthetic fuels, costs reflect the lower threshold of potential production costs in 2040 and 2070 (for a mix of biomass-to-liquids [BtL] and hydrotreated vegetable oil [HVO] in the case of biofuels), plus taxation (33%) to reflect the detrimental impacts of local pollutant emissions.

Prospects for competing powertrain options hinge on the future costs and performance of batteries and fuel cells as well as accompanying infrastructure.

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Strong policy intervention will be needed to drive the needed technological changes. Policy approaches should support and promote technology demonstrations to test the cost competitiveness, performance and emission impacts of the various fuel and powertrain options in diverse contexts. Earmarking a share of fuel taxes to fund public-private cost-sharing for the infrastructure required for alternative fuels has accelerated deployment of fast charging stations and hydrogen refuelling stations in California and could be adopted elsewhere. Schemes that prohibit or adequately price emissions of air pollutants (i.e. zero- and low-emission zones) can promote the deployment of ZEV infrastructure and vehicles in cities and ports. Government support has also been of critical importance in the development of first-of-a-kind Electric Road Systems demonstration projects in Sweden and Germany, and has played a major role in enabling recent and on-going development of hydrogen refuelling stations in California, China, France and Japan, which are only beginning to be designed and equipped to fuel heavy-duty vehicles.[12] Programmes such as California's Low Carbon Fuel Standard, which ensures that the overall carbon intensity of fuel declines at a clearly defined pace, could provide an effective incentive to invest in the fuels that are needed to power the transition to low-carbon road freight transport.

Continued support for R&D – from basic research through to demonstration and market deployment – is needed to accelerate battery and fuel cell advances, and to integrate electrochemical energy storage technologies with motors and powertrains. Supply-oriented policies such as ZEV mandates[13] would help to ensure that, once market ready, alternative fuelled vehicles hit the road (see Chapter 7).

Given the various strengths and weaknesses of competing fuel and powertrain technologies, a range of low-carbon fuel and powertrain options may emerge and co-exist in markets, as projected in the Sustainable Development Scenario. In contrast to the case of LCVs operating in urban environments, where fully electric powertrains (perhaps relying on fuel cells or fuel cell range extenders) look likely to dominate, at the current point it is too early to be able to discern a winner (or winners) for heavy-duty trucks for long-distance and more intensive applications among known options such as biofuels, plug-in hybrids, battery electric vehicles and fuel cell

[12] Hydrogen refuelling stations servicing heavy-duty vehicles need to be equipped to handle storage pressures of greater than 350 bar (typically 700 bar), precooling for hydrogen to be dispensed, and other equipment (e.g. valves and nozzles) that enable faster flow rates and hence deliver hydrogen at acceptably short fueling times, among other additional requirements beyond what is needed to provide hydrogen to light-duty fuel cell electric vehicles.

[13] The US state of California has highly successful ZEV mandates for LDVs to accelerate electrification and other zero-emission technologies. In July 2020 it took steps to pave the way to extend that scope to heavy-duty trucks. Spurred by the passage of California's Advanced Clean Trucks rule, which requires original equipment manufacturers that produce trucks for the California market to sell increasing shares of ZEV trucks in each segment starting in 2024. Fifteen other US states and the District of Colombia have joined California to sign a memorandum of understanding that aims to boost the ZEV truck market.

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electric trucks. More demonstrations and deployment are needed to learn, gain experience and see which technologies and fuels can evolve to deliver zero-emission heavy-duty trucking.

Maritime shipping

Overview and outlook in the wake of Covid-19

Maritime shipping is a critical part of international trade and the primary means by which physical goods are transported over long distances. For many countries it accounts for a significant portion of national freight movements.[14,15] Maritime shipping (referred to as shipping in this section) accounts for about three-quarters of total freight transport activity (including inland transport) worldwide as measured by tonne-kilometres. Shipping is the least energy-intensive way to carry goods: despite the size of its share of total freight transport activity, it is responsible for about one-fifth of the energy used for freight transport and just 8% of total transport energy use. The vast majority of energy used in shipping relies heavily on oil-based fuels and is carbon intensive. Maritime shipping consumed 221 Mtoe in 2019, of which almost 180 Mtoe (about 3.7 mb/d) was heavy (residual) fuel oil and 45 Mtoe (about 1 mb/d) was distillate oil products (maritime diesel oil and maritime gas oil). Gas, mainly liquefied natural gas, accounted for 0.1 Mtoe. CO_2 emissions from shipping in 2019 totalled 710 Mt – equal to one-fifth of total CO_2 emissions from freight transport, almost 10% of total transport emissions and around 2% of total energy sector emissions.

The Covid-19 pandemic has hit the maritime shipping sub-sector hard. Global trade fell by about 3% in the first-quarter of 2020 and estimates suggest that it fell by more than 20% in the second-quarter (CCSA, 2020). Maritime shipping typically accounts for three-quarters of global trade: shipping volumes have plunged as a result of sharply reduced demand and supply constraints caused by the closure of industrial facilities and critical trade routes across borders during the lockdown. In ports located in Asia, Europe and North America, cargo and container trading volumes were 10-17% lower in the first half of 2020 than the same period in 2019; at major Chinese hubs they were 20-50% lower at the peak of the pandemic in China in the first-quarter of 2020 (Shanghai International Shipping Institute, 2020). Large

[14] The data and projections in this section refer to international maritime shipping. National shipping, which accounts for around 5% of fuel consumption and CO_2 emissions from freight transport (2% of total transport), faces similar technology challenges as international shipping, except for generally shorter trips.

[15] The IEA's international shipping CO_2 emissions estimates, which are based on national statistical data on fuel delivered to internationally registered vessels, are lower than those estimated by the International Maritime Organization (IMO), which are based on ship activity and associated fuel consumption. For instance, for 2012 the IEA estimates international shipping emitted about 600 $MtCO_2$, while the IMO estimates that it emitted about 800 $MtCO_2$. The analysis presented in this section is calibrated to IEA's statistics.

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shipping operators, particularly of container ships, have responded to reduced trade with blank sailings.[16] On some important shipping route container ship capacity was reduced for a time by up to 50% (Agility, 2020). At the third-quarter 2020, shipping volumes have started to recover, and estimates suggest that shipping activity in 2020 as a whole is set to be about 7% lower than in 2019. A recovery to pre-Covid-19 activity levels in 2021 is possible, but this ultimately will depend on the duration of the pandemic and the speed of economic recovery.

The maritime shipping sector is at a crossroads. There are a growing number of regulations requiring ships to reduce their GHG and air pollutant emissions. This poses a real challenge for the industry. Shipping by its nature mostly involves large vessels travelling long distances, and existing alternatives to oil-based fuels are either impractical or very costly. Moreover ships have a long lifetime of 20-35 years, which inhibits the uptake of new low-carbon technologies. The extent of the challenge varies according to the type of vessel. Reducing emissions from large transoceanic ships will be particularly onerous, requiring large investments and co-ordinated efforts among fuel suppliers, ports, shipbuilders and shippers, (especially so-called tramp shipping) (Box 5.2).

Various short term and longer term decarbonisation options for shipping are available. In the short term, there is considerable potential for curbing fuel consumption with energy efficiency, measures to optimise supply chains and slow steaming. In the medium to longer term, significant emissions reductions could be achieved by switching to low-carbon fuels such as biofuels and emissions-free hydrogen-based fuels (ammonia and hydrogen), which look likely to be particularly important for long-range transoceanic travel. Larger ships that carry freight over long distances need fuels with high energy density. Coastal short-distance ships can use less energy-dense fuels, making a switch to battery electric power technically feasible.

Box 5.2 Types of ships and their energy and emissions implications

Ships come in many types and sizes, each designed for specific cargos, routes or purposes and each with differing fuel consumption characteristics. The main categories by types of cargo are:

[16] A scheduled sailing that has been cancelled by a carrier or shipping line so that a vessel skips certain ports or even the entire route.

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- **Tankers:** liquid or gaseous bulk commodities. Oil tankers and chemical tankers are the most common. The fleet of LNG tankers has been expanding rapidly in recent years (DNV-GL, 2020a).
- **Bulk carriers*:*** non-liquid unpackaged bulk cargo such as grain, ore or coal.
- **Container ships*:*** cargo packed in containers.
- **General cargo ships:** any type of dry non-bulk cargo. These ships are adaptable vessels that can be equipped with one or more cranes to facilitate loading and unloading.
- **Other ships:** includes several types of vessel, e.g. roll-on/roll-off ferries (Ro-Ros) such as ferries and dedicated car carriers, and service vessels – such as tugs and offshore supply vessels.

Ships can also be categorised according to two main types of operations, which have implications for how easily they can be refurbished, replaced or converted to run on alternative fuels. The first type is liners, which travel on fixed schedules and routes. Worldwide there are approximately 6 000 liners in operation, primarily in the form of container ships and RoRo ferries (World Shipping Council, 2020). Liners are likely to be well placed to make the transition to new fuels, as it is easier to predict their fuel needs when new bunkering facilities are installed at ports along their regular shipping routes. The other type – tramp-trade ships – do not have a fixed schedule and are chartered on the spot market, going from port to port dropping off and picking up cargo according to shippers' needs.

Specific fuel consumption (energy use per kilometre travelled) depends on several variables, but the most important ones are speed and deadweight tonnage. Container ships generally have the highest fuel consumption as they travel at high speeds (specific fuel consumption increases with the square of the speed), carry large volumes of goods and cover the longest distances. This is due to the fact that they normally operate as liners, which means that they have a busy schedule with only short stops to load and unload containers. This explains why container ships are the largest contributors to energy consumption and CO_2 emissions in the shipping sector, even though bulk carriers account for a larger share of total transport activity in maritime shipping (Figure 5.9).

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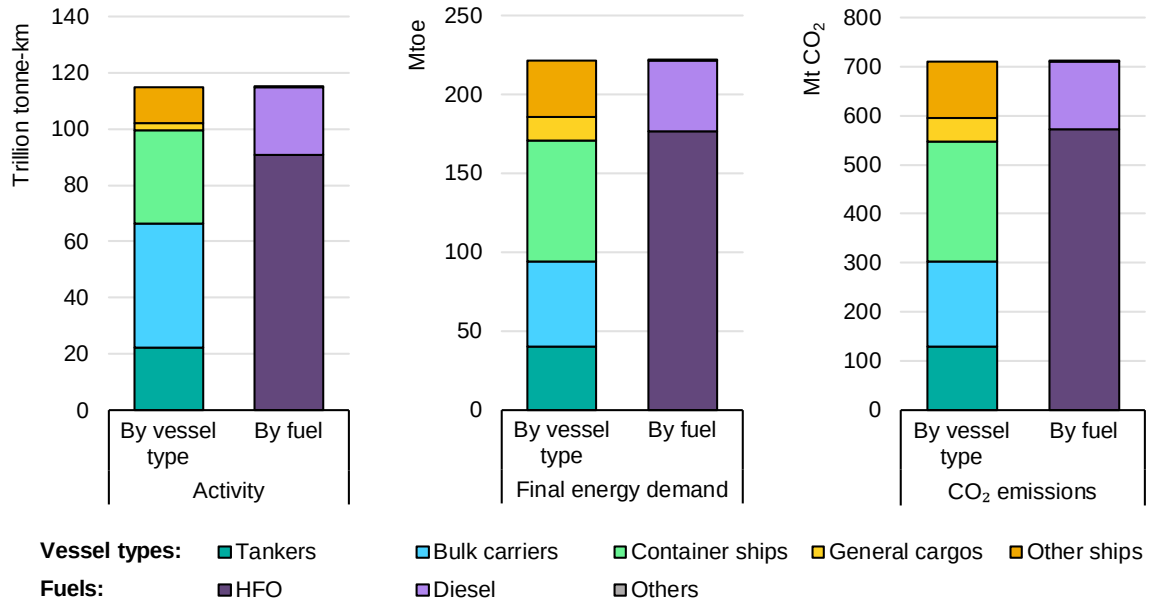
Figure 5.9 Global freight activity, energy consumption and CO_2 emissions in international maritime shipping by vessel type and fuel, 2019



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Notes: HFO = heavy fuel oil. Other fuels include LNG, biofuels and electricity.

Bulk carriers and container ships dominate in international shipping, together accounting for about 60% of total energy use in the sub-sector – almost entirely in the form of oil – and CO_2 emissions.

Some national and international policies and regulations aiming to reduce pollution and GHG emissions in shipping are in effect (Table 5.3). These include the International Maritime Organization (IMO) regulations to limit air pollution through a cap on sulphur levels in fuel and a target to reduce GHG emissions by at least 50% by 2050 compared with 2008 (IMO is the United Nations agency responsible for regulating international shipping). There is a risk that short-term measures to reduce sulphur and other pollutant emissions may lock-in investments in fossil fuels, hampering efforts to reduce CO_2 emissions in the longer term.

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Table 5.3 Main international regulatory policies covering air pollution and GHG emissions in maritime shipping

Name	Geographic coverage	Year introduced	Description	Regulatory actor
IMO Initial Strategy	Global	Adopted in 2018	Reduce absolute GHG emissions from shipping at least 50% by 2050 relative to 2008. Reduce CO_2 emissions per transport work at least by 40% by 2030, pursue efforts towards 70% by 2050.	IMO
Data collection system (DCS) for fuel oil consumption	Global	2019	All ships over 5 000 tonnes engaged in international voyage must collect consumption and other data for each type of fuel oil consumed. Flag states must collect and aggregate the data and submit to the IMO.	IMO
Submission of CO_2 emissions reports (MRV)	Ships calling at EU ports	2018	Companies must submit a CO_2 emissions report for all voyages in the European Union for all vessels under their responsibility.	European Commission
EU Emissions Trading System (ETS)	Ships calling at EU ports	2022 (expected)	Proposal to include shipping in the ETS as part of the Green Deal.	European Commission
Energy Efficiency Design Index (EEDI)	Global	Enforced in 2013	Requires minimum energy efficiency per tonne-km for new large vessels and mandates improvement steps depending on vessel type: 10% in 2015, 20% in 2020 and 30% in 2030 compared with average performance of vessels built in 2000-2010.	IMO
Ship Energy Efficiency Management Plan (SEEMP)	Global	Adopted in 2016	Monitors ship efficiency performance, mandates collection and submission of relevant data and establishes mechanisms to improve efficiency of existing ship operations.	IMO
Global Sulphur Cap	Global	January 2020	Limits the sulphur content of maritime fuel used on board vessels trading outside of sulphur ECAs to a maximum of 0.5%. Ships without exhaust gas scrubbers are not permitted to carry fuel for use with a sulphur content exceeding 0.5%.	IMO
Emission Control Areas (ECAs)	Baltic Sea, North Sea, Caribbean Sea and North American sea	Enforced respectively in 2005, 2006, 2012 and 2014	To operate in these areas, ship engines must comply with stricter standards for SOx and NOx than in global waters. In particular, there is a limit of 0.1% sulphur for fuel used by ships operating in SOx ECAs and NOx TIER III standards apply to ships operating in NOx ECAs.	IMO

Notes: IMO = International Maritime Organization; MRV = monitoring, reporting and verification; EC = European Commission; SOx = sulphur oxides; NOx = nitrogen oxides.

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International trade is expected to recover from the disruption caused by the Covid-19 pandemic and to continue to expand in the years ahead. In the Stated Policies Scenario, shipping activity increases by an annual average of 2.5% and expands by 260% between 2019 and 2070. In the Sustainable Development Scenario, it increases by 2.4% a year on average and by 230% over the period to 2070. The growth in activity is slightly lower in the Sustainable Development Scenario because of a reduced need for oil tankers and coal carriers, which is partially offset by the rise of international trade in hydrogen and hydrogen carriers and biofuels. The increase in shipping activity in both scenarios underlines the need to reduce pollution and eliminate CO_2 emissions in the coming decades.

Box 5.3 Is the Covid-19 crisis impacting marine regulations?

The International Maritime Organization (IMO) continues to enforce the 2020 **global sulphur cap** (Table 5.3). Covid-19 safety precautions have made it more difficult to report compliance, but that reduced ability does not necessarily imply increased levels of non-compliance. The two main options available for complying with the cap are the installation of sulphur dioxide (SO_2) scrubbers and the use of very low sulphur fuel oil (VLSFO). Since the sulphur cap was announced in October 2016, ships have been preparing for it by installing scrubbers or adapting their vessels to use VLSFO and refineries have been increasing their production of VLSFO.

Overall, lower oil demand due to the Covid-19 pandemic and an oversupplied oil market have caused bunker fuel prices to drop. Prices for VLSFO spiked in January 2020 as the IMO cap kicked in, but prices plummeted in March with the outbreak of the pandemic. In April, VLSFO recorded prices of USD 150/tonne, effectively closing the price gap with high sulphur fuel oil (IEA, 2020b). This fall in the VLSFO price has affected the short-term competitiveness of the technology options for compliance with the sulphur cap. Before the pandemic, some ship owners viewed the use of SO_2 scrubbers as a least cost compliance option. Low VLSFO prices have now made the use of the fuel more economically attractive than installing a scrubber: many scrubber installation projects have been cancelled (Bockmann, 2020). It is unclear which technologies shippers will choose over time based on the extent of a VLSFO price rebound.

There are a number of options with varying degrees of technological readiness and economic competitiveness to help shippers meet the targets set out in the **IMO initial GHG strategy.** The IMO has given no indication that it intends to delay implementing these targets in light of the Covid crisis. New regulations are still expected to be implemented before 2023 (Lloyd's List, 2020).

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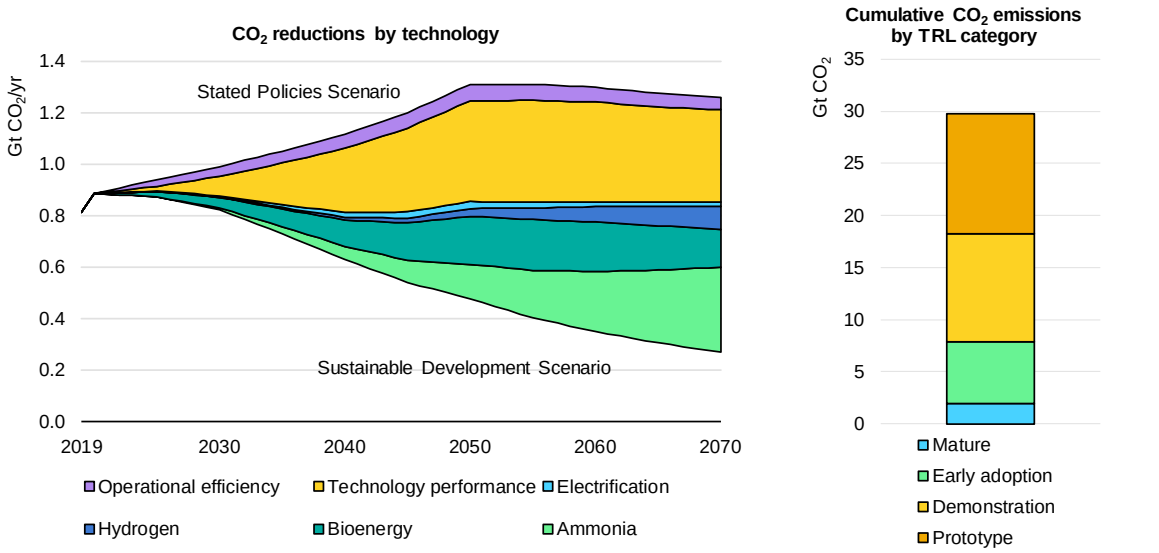
Technology pathways towards net-zero emissions

CO_2 emissions from maritime shipping are projected to rise again after the 2020 drop related to the Covid-19 pandemic. In the Sustainable Development Scenario, CO_2 emissions from shipping peak in the early 2020s at about the same level as 2019, i.e. 710 Mt, and thereafter decline to 120 Mt in 2070 (Figure 5.10). This trajectory is broadly in line with the IMO GHG emissions target for 2050. Maritime shipping does not reach zero emissions until after 2070 reflecting the difficulty and high cost of abating emissions in this sub-sector (see Chapter 3). CO_2 emissions from international shipping in 2070 are higher in the Stated Policies Scenario, in which they rise to almost 1 100 Mt in 2050, up almost 50% from 2019 levels, and then stabilise through to 2070 as efficiency measures and fuel switching counterbalance activity growth .

Figure 5.10 Global CO_2 emissions reductions in shipping by mitigation category (left) and technology readiness level (right) in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-70



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Note: TRL = technology readiness level. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature."

Biofuels and energy efficiency are the main contributors to international shipping emission reductions in the Sustainable Development Scenario in the short term, while hydrogen and ammonia contribute more in the long term.

CO_2 emissions reductions envisaged in the Sustainable Development Scenario are mainly achieved through a combination of technical and operational efficiency measures, lower levels of cargo transport as energy commodity trade falls, and a switch to low-carbon fuels and bioenergy. Efficiency measures make the biggest initial contribution to reducing emissions below the level in the Stated Policies

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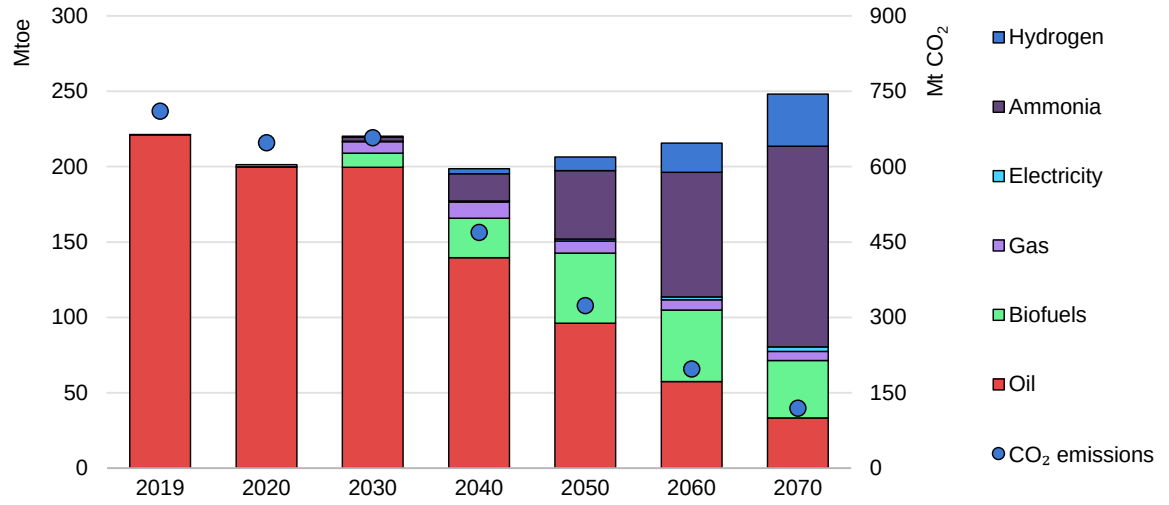
Scenario, and offset activity growth until about 2050, after which overall demand rises again. Efficiency measures include but are not limited to hybridisation (with electricity), kites, sails and Flettner rotors (spinning cylinders that convert wind power into thrust to help propel the ship), slow steaming (reducing vessel speed), contra-rotating propellers, improved hull coatings to reduce friction and waste heat recovery. Over time, however, the largest share of emissions reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario is achieved through a combination of fuel switching and new marine propulsion technologies (Figure 5.11). A more detailed look at the short, medium and long term brings out the changing contributions of different technologies and their overlaps over time in the Sustainable Development Scenario.

Figure 5.11 Global energy consumption and CO_2 emissions in international shipping in the Sustainable Development Scenario, 2019-70



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Notes: Efficiency improvements more than offset activity growth in the 2030s and 2040s, but by 2050 activity demand growth overwhelms efficiency improvements, leading to increases in final energy demand. The category biofuels includes biomethane and is considered to be carbon neutral.

Emissions from international shipping fall by more than four-fifths between 2019 and 2070 in the Sustainable Development Scenario, mainly due to switching to biofuels and hydrogen-based fuels.

In the short term, to meet mandatory regulations such as the IMO sulphur cap, shipping operations switch from high sulphur fuel oil to other oil-based fuels such as VLSFO, distillate fuels (marine diesel oil or marine gasoil) and LNG. Some large shipping operations install SO_2 scrubbers, but this locks in the use of carbon-intensive bunker fuel for the remaining lifetime of the ship, which levels only blending with biofuels as a partial mitigation option. Other shipping operations opt to use LNG in the early 2020s (mainly driven by its low cost, subsidies for developing infrastructure and IMO sulphur cap compliance), which improves air quality, but does

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not do much to reduce emissions: the tank-to-wheel GHG emissions reductions of LNG compared with diesel/HFO is up to 25% when burned in a high pressure injection fuel engine, and the level of emissions reductions can be minimal (or even negative) if gas leakages occur (ICCT, 2020a). In the 2020s, there is also some initial fuel switching from oil-based fuels to biofuels as well as some blending of biofuels with bunker fuels.

In the medium term, blending with biofuels increases. Biofuel use jumps from negligible levels today to more than 25 Mtoe in 2040 and to almost 50 Mtoe in 2060, by which time it accounts for more than one-fifth of total energy use in shipping. From about 2025, biofuel oil (BFO) is blended with VLSFO in increasing amounts; by 2070, blending accounts for 7% total energy use in shipping, displacing conventional residual fuel.[17] However, the supply of biofuels for all transport sectors is constrained by the availability of sustainable biomass a substantial amount – nearly 220 Mtoe – is required to decarbonise aviation in the long term (as discussed in this chapter).

In the longer term, biomass-to-liquids (BTL) – an alternative technological pathway to making diesel substitutes – makes an increasing contribution in shipping energy use as BTL moves to large-scale production from about 2050, while ammonia and hydrogen come increasingly to the fore. As ships using fossil fuels blended with some biofuel reach the end of their life from 2050 onwards, they are replaced by new vessels equipped with propulsion technologies compatible with ammonia and hydrogen, two technologies that become steadily more competitive after their first use on short and medium-distance trips from 2025, gradually replacing vessels using oil and, later, LNG, as they retire. Together they are used on over 60% of new vessels sold after 2060. Ammonia use for shipping reaches roughly 130 Mtoe in 2070, almost twice as much as was used worldwide for fertiliser production in 2019. The role of hydrogen as a fuel for large vessels is more limited, due to the high costs of hydrogen storage and its lower energy density[18]. Nonetheless, hydrogen use reaches 12 Mt in 2070, equivalent to 16% of 2019 global maritime bunker demand and 16% of today's global hydrogen use. By this time, oil and gas are responsible for only one-sixth of total shipping fuel consumption.

Ports have an important role to play in facilitating a switch in shipping to alternative fuels such as hydrogen and ammonia for refuelling operations. The 20 largest ports in the world account for more than half of global cargo (UNCTAD, 2018) and they could act as industrial hubs producing hydrogen and ammonia to be delivered to

[17] Combustion of bioenergy is considered carbon neutral in line with IPCC guidelines (IPCC, 2006) (see Chapter 2, Box 1).

[18] It is likely to be in vessels equipped with ICEs capable of burning hydrogen, as fuel cells are not expected to reach the required power outputs for covering transoceanic routes.

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both the chemical and refining industries, as well as for refuelling ships. The majority of these hubs are located in China, with others in key locations in the United States and Europe.

Throughout the period to 2070, the use of electricity as a fuel for maritime shipping remains limited, accounting for approximately 3 Mtoe in 2070. Electricity is used mainly in hybrid vessels, which are projected to account for around 5% of all new vessel sales in 2030. Hybridisation reduces energy consumption by 0.5 Mtoe and CO_2 emissions by 30 $MtCO_2$ in 2070 relative to the Stated Policies Scenario. Cold ironing – the provision of electrical power to a ship at berth which allows its main and auxiliary engines to be turned off – also helps to lower CO_2 emissions and pollution. There are some purely electric vessels, but their numbers are limited as they are only economically viable for short-distance trips.

Readiness and competitiveness of emerging technologies

Several of the technologies that are needed to move the maritime shipping sub-sector towards carbon neutrality – especially those enabling a switch to alternative fuels – are not yet commercially available (Table 5.4). Achieving the Sustainable Development Scenario trajectory therefore will require more intensive RD&D efforts.[19]

Cold ironing, the use of shore power when berthed, is the only main technology commercially available today (with a technology readiness level [TRL] of 9).[20] It was first adopted in Alaska in 2001 (other than military uses), then championed by the Port of Los Angeles from 2004 as a measure to limit air pollution (Port of Los Angeles, 2020). Cold ironing is increasingly being installed across the world (IEA, 2020a). Few other technologies have a TRL above 7, and none could completely decarbonise long-distance shipping. Pure electric battery powertrains, with a TRL of 8, are being increasingly adopted in the Nordic countries, not least as a result of regulatory measures limiting ferry traffic to zero-emission vessels, but electric battery powertrains cannot power larger vessels travelling long distances. Wind-assisted propulsion systems, such as kites and Flettner rotors have a TRL above 7, have gained official certification (DNV-GL, 2019), but are not widely available in the market place. No technology to replace the main engine of ocean-going vessels is yet commercially available.

[19] In recognition of this, the shipping industry has proposed to the IMO to levy USD 2 per tonne of fuel purchased for consumption to support a global R&D fund aiming at accelerating the development of zero-carbon technologies for ocean going ships.

[20] Cold ironing is when a berthed ship turns off its main engines and powers its auxiliary equipment with electrical power from shore facilities.

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Table 5.4 Status of main emerging technologies in shipping

Technology	TRL	CO_2 reduction mechanism	Year Available (Importance for net-zero emissions)	Deployment status
Ocean-going vessels				
Ammonia fuelled ICE	4-5	Fuel switching	2022/ 2030 (High)	Leading shipbuilders have recently joined forces to develop an ammonia ICE deep-sea tanker to be commercialised by 2030. Various shipbuilders have announced the development of large vessels running on ammonia ICE vehicles. Both MAN-Energy and Wartsila have each (separately) announced the development of an ammonia fuelled engine expected to enter in operation in 2023.
Hydrogen fuelled ICE	4-5	Fuel switching	2025/ 2030 (High)	Hyundai Heavy Industries has announced a plan to develop a large-scale hydrogen ICE by 2022. Japan's roadmap for zero emissions from maritime shipping aims to commercialise hydrogen fuelled ICE large-scale vessels by 2030.
Short and medium-distance vessels				
Ammonia fuel cell	4-5	Fuel switching	2030 (High)	The European Union ShipFC project aims to develop a 2 MW ammonia powered fuel cell ship to be operational in 2023.
Hydrogen fuel cell	7	Fuel switching	2020 (High)	Several large prototypes of hydrogen fuel cell ships have been tested. The Horizon2020 FLAGSHIP project is demonstrating technical feasibility on two small ships.
Hydrogen fuelled ICE	8	Fuel switching	2020 (High)	Hydroville, a ship that simultaneously burns hydrogen and diesel, has been operating since 2017. BeHydro has announced plans to develop hydrogen ICEs from 0.8 MW to 2.8 MW from 2020.
Pure battery electric powertrain	8	Fuel switching	2020 (High)	Nordic countries are pioneering the development of pure battery electric ships, which can cover distances of a few hundred kilometres before recharging. Several electric ships are in operation. By 2022 there are to be 80 purely electric ferries in Norway.
Shore power when at berth				
Cold ironing	9	Fuel switching	2020 (Medium)	Onshore infrastructure for cold ironing is available in more than 80 ports worldwide (mainly in Europe). An increasing number of vessels are being equipped with provisions for cold ironing.
Wind-assisted propulsion				
Kite	7-8	Energy efficiency	2020 (Medium)	A few companies are commercialising and installing kites on new and existing ships.
Flettner rotor / sail	8	Energy efficiency	2020 (High)	Some companies are commercialising these technologies and some vessels equipped with this technology are operating.

Notes: ICE = internal combustion engine. A broader list of technologies compatible with a low-carbon transition for the maritime shipping sub-sector is presented in the technology mapping portion of *The Covid-19 Crisis and Clean Energy Progress* (IEA, 2020b).

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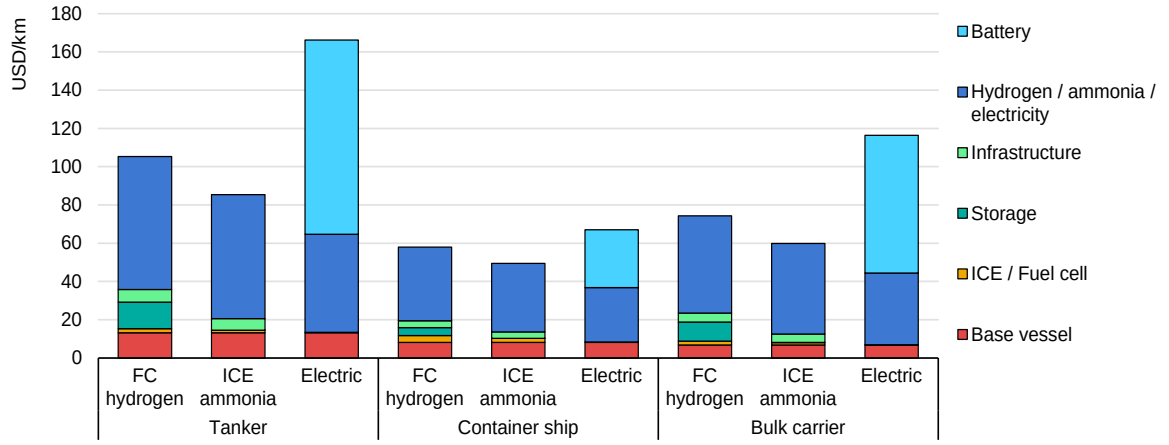
At present it looks likely that any low-carbon or carbon-neutral fuel suitable for shipping will be more expensive than the fossil fuels currently used. Moreover, with the exception of some biofuels and synthetic fuels (synthetic hydrocarbons that are made by storing electrical energy from renewable sources in the chemical bonds of liquid fuels), low-carbon fuels are expected to have a lower volumetric energy density than fossil fuels. The adoption of low-carbon and carbon-neutral fuels is therefore likely to depend on the adoption of appropriate regulations or market incentives. The prospects for the main alternative fuel technologies vary.

Pure electric ships powered by batteries are limited by their low energy density, which requires frequent recharging, making them impractical for long voyages. They could be competitive with other non-fossil fuel options for distances up to 200 km (such as ferry routes) on the assumption that costs fall, but less than 1% of the transport activity of vessels operating on international routes fall into that category (ITF, forthcoming). Major advances in battery technology would be needed for electric ships to become economically viable for longer distances (Figure 5.12).

Figure 5.12 Total cost of ownership of hydrogen, ammonia and electric vessels by ship type, 2030



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Notes: FC = fuel cell; ICE = internal combustion engine. Battery capacity and hydrogen/ammonia tankers are designed to cover a distance of 10 000 km. Annual travel: 96 000 km for an oil tanker, 98 000 km for a bulk carrier and 180 000 km for a container ship (in line with average speeds and days at sea registered by IMO, 2014). Fuel costs in 2030 (including production and distribution): USD 0.17/kWh for hydrogen (produced via electrolysis), USD 0.13/kWh for ammonia (produced via electrolysis) and USD 0.2/kWh for electricity.

The high cost of storing hydrogen makes it less economical than ammonia. The economics and technical performance of electric vessels need to improve to become a competitive technology for long-distance shipping.

Biofuels are the most promising fuel option for shipping in the short to medium term because they can be blended at gradually higher shares as a drop-in fuel into heavy

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fuel oil or diesel, which avoids the need for new vessels and fuel systems. Biofuels could play a smaller role depending on the pace of progress of hydrogen and ammonia technologies, and on the speed of the scale up of second- and third-generation biofuels production capacity. However the majority of vessels sold today run almost exclusively run on fossil fuels, and they will still be operating in 2050 unless regulations encouraging or mandating early retirements are put in place.

Several pathways are available for biofuels to be blended with the maritime fossil fuels, each with advantages and disadvantages. Biofuel oil (BFO) is the cheapest option, although it is currently only being pursued by a few companies. Its potential to scale up is not limited by any technology barrier, but rather by sustainable feedstock availability and fatty acid methyl esters (FAME) production rates (BFO is a residue of FAME production). For diesel vessels the biofuel pathways for markedly reducing CO_2 emissions are essentially FAME in the medium term and biomass-to-liquids (BTL) in the longer term, both of which are drop-in biofuels for marine technology[21] and so can be blended in any share. However, the fuel specification of FAME is higher than required for many marine engines and therefore incurs an unnecessary high cost premium. FAME is currently produced commercially on a large scale (TRL 9), while BTL requires further development (TRL 5-6) to be deployed at commercial scale. However, BTL is less limited by sustainable feedstock constraints than FAME, as BTL can use a wide variety of feedstocks, including residual waste from agriculture and forestry. Furthermore, BTL may offer opportunities to efficiently integrate carbon capture, utilisation and storage (CCUS) technology with fuel production at costs that can be commercially attractive if there is an adequate carbon price.

Hydrogen-fuelled ships are at an early stage of technological development. Some projects demonstrating the viability of hydrogen fuel cells and ICEs in small ships are underway but large-scale deployment is not expected before 2030. Hydrogen used as a fuel does not produce CO_2 emissions: its only product is water when used in a fuel cell and NOx emissions when used in an internal combustion engine. When produced via steam methane reforming with CCUS, hydrogen can be low-carbon, and when produced via electrolysis with electricity from renewable or nuclear sources hydrogen can be zero-carbon (see Chapter 2). But hydrogen does have some disadvantage for use in shipping. It needs to be liquefied to increase its volumetric density for use as a long-distance fuel – a very energy- and capital-intensive process – making it expensive to produce. It needs storage equipment when in liquid form, which is capital intensive, consumes significant energy and takes up more space than alternative low- and zero-carbon fuels. Plus hydrogen is flammable, which is an

[21] Unlike FAME biodiesel, BTL diesel has identical characteristics to fossil diesel and is considered a drop-in fuel for all transport sectors. However, FAME biodiesel can be used up to 100% blend in marine diesel engines and fuel systems (IEA Bioenergy, 2017).

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important safety consideration. For these reasons, hydrogen in maritime shipping is most likely to be used as a fuel for short- and medium-distance ships, mostly in the form of compressed hydrogen thus avoiding the need for a complex and onerous storage system on-board. While hydrogen may also be used on long-distance vessels, it is likely to be confined mainly to those routes where frequent bunkering is possible, thus limiting the size (and cost) of on-board hydrogen storage.[22]

The "chicken-and-egg" dilemma of developing hydrogen vessels and hydrogen refuelling infrastructure in tandem is another barrier. Ports will need to play a crucial role in this area. Ports located close to refineries or other industrial plants that already use hydrogen could use excess supplies of hydrogen to fuel vessels and scale up production capacity to provide fuel to an increasing number of vessels (IEA, 2019a). The Port of Rotterdam, the sixth biggest in the world by annual cargo throughput, has declared its ambition to become a hydrogen hub.[23] Other ports around the world located close to industrial facilities or power plants that use (or could use) hydrogen could also become hubs, opening the possibility of establishing a hydrogen bunkering network.

Ammonia – a compound of nitrogen and hydrogen – is attracting interest as a potential carbon-free fuel for shipping and other sectors because of its high liquefaction temperature and energy density compared to hydrogen when both are in liquid form (see Chapter 2). Ammonia also benefits from a well-established infrastructure system, plus it is easier to store and transport than hydrogen (The Royal Society, 2020).[24] Moreover, since ammonia is the most traded chemical, there is already significant industry expertise when it comes to handling it on-board as a cargo as opposed to hydrogen. The main barrier to its use as a shipping fuel is that it is acutely toxic and leaks can cause severe water pollution. Its cost is also a problem. Ammonia can be used in a fuel cell (in the same way as hydrogen) as well as in a conventional ICE, but further technology advances are needed for ammonia fuel cells to see lower costs and become a viable technology on a large scale. The main technological challenge to be addressed for ammonia use in ICEs is related to its low flame speed (AMF TCP, 2020).

Energy efficiency alone is not sufficient to achieve zero emissions in shipping, but it can reduce the cost of doing so. Although low-carbon shipping fuels are more expensive than fossil fuels, energy efficiency measures reduce energy needs for any

[22] A study found out that 99% of the trips by container ships along the corridor between the United States and China could be fuelled by liquid hydrogen with minor addition of the capacity of on-board tank (ICCT, 2020a).

[23] www.portofrotterdam.com/en/news-and-press-releases/energy-transition-results-in-extensive-plans-for-hydrogen.

[24] However, the ammonia infrastructure is currently used only for carrying ammonia across countries and not for bunkering it to ships. Therefore, while there is much know how on ammonia handling in harbours and ships, the storage and bunkering capacity for ammonia needs to be largely expanded for it to play the role envisioned in the Sustainable Development Scenario.

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given service, thus helping ship operators to limit additional fuel costs. There are a number of technologies under development to improve the energy efficiency of ships. The main policy at present to foster improvements in energy efficiency in the maritime sector is the Energy Efficiency Design Index (EEDI) (see Table 5.3), although there is indication that observed energy efficiency improvements may have resulted from the need of ship operators to cut operational costs in the face of high fuel prices rather than by the need to comply with the EEDI regulation (CE Delft, 2016). Some organisations are therefore pressing the IMO, which is responsible for the EEDI, to introduce tougher standards to encourage the uptake of new technologies that would improve energy efficiency in vessels even further (ICCT, 2019).

Energy efficiency measures for shipping can be divided in two categories:

- *Technical measures*, which reduce the power requirement of the propulsion system by improving fuel efficiency. Leading technical measures to improve energy efficiency include wind assist (Flettner rotors, sails and kites), hull lubrication systems and waste heat recovery. Flettner rotors and sails both use aerodynamics to provide thrust to the vessel (Norsepower, 2020; DNV-GL, 2020b). Automatically controlled kites can be attached on the bow of the vessel when the wind conditions are favourable, thus pulling the vessel along (CNBC, 2015). These three technologies use different principles to exploit the free energy provided by the wind to gain propulsion, thus reducing fuel consumption. The actual potential fuel saving largely depends on the type of vessels and on the route covered, but in general it ranges between 5-20% (DNV-GL, 2019). Waste heat recovery consists of reusing the heat dissipated by the engine, and can save approximately 5-10% of fuel. Hull coating and air lubrication systems are technologies that improve the vessel's aerodynamics to limit drag and thus the power requirement, implying fuel savings ranging between 3-12%. These technical measures are generally more applicable on new vessels, due to the high cost or technical impossibility of retrofitting existing ones. A further tightening of the EEDI targets (which is currently being discussed by the IMO) could promote more RD&D on these technologies.
- *Operational measures,* which reduce fuel consumption via improved operation and maintenance of the vessel. Operational measures can be implemented both by existing and new vessels and do not require significant investment in additional equipment. One example is slow steaming, which consists of reducing the vessel's speed and as a consequence its specific fuel consumption.

Currently, all low-carbon fuel options to decarbonise the shipping sector are more expensive than conventional fossil fuels; ship owners and operators are unlikely to adopt them without policy measures that mandate or encourage such action. The fuel supply market for international maritime shipping is not a captive market – ships do not need to bunker every time they call at a port – so policies that increase the

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price of fossil fuels implemented by a single country or region would probably result in "fuel leakage" (ships would bunker in other countries to avoid the higher fuel price resulting from a single country's action). This points to the need for collective measures implemented worldwide. There is a good case for policy action targeting vessels, particularly since the IMO regulates vessels and not their fuel suppliers.

One policy well worth considering is "operational fuel standards" (also called goal-based mechanisms), which would mandate objectives for ships to reduce their operational carbon intensity. Such standards could be implemented at regional and/or global level, using as a baseline the emissions levels registered in the European Union Monitoring Reporting and Verification (MRV) and the IMO Data Collection System (see Table 5.3). Set at progressively more stringent levels, the operational carbon-intensity objectives would reduce the CO_2 intensity of the vessel over time and, if stringent enough, eventually encourage the adoption of zero-carbon fuels. This mechanism would also provide the flexibility to market actors to choose the most convenient and suitable compliance strategy, within a stable and long-term regulatory framework that reduces the risk linked to developing new technologies and building the associated refuelling infrastructure.

Aviation

Overview and outlook in the wake of Covid-19

Commercial passenger aviation is the energy demand sub-sector hardest hit by impacts related to the Covid-19 crisis. Passenger volumes hit bottom when they dropped by nearly 95% in April 2020, and the number of scheduled flights in the first week of May was nearly 70% lower than in the same week in 2019, but with as few as 37% of seats occupied. More than a third of the world's aircraft remained grounded in late July 2020. Industry estimates indicate that passenger volumes as a whole (measured in revenue passenger-kilometres [rpk][25]) will decline by 50% in 2020, and that international passenger volumes will decline by 60% (IATA, 2020a).

Demand rebounded rapidly after previous crises, including the 2008 financial crisis. However, the nature and extent of the current crisis is fundamentally different, and demand is unlikely to return quickly to anywhere near its pre-Covid levels. In the meantime, airports have been forced to adopt screening and social distancing procedures that dramatically reduce throughput, and airlines have scrambled to reconfigure standard procedures, cabins and seating to minimise risks of spreading the virus. Current industry estimates project that passenger volumes will recover to

[25] Revenue passenger-kilometres (rpk) refers to the number of revenue-generating passengers (i.e. excluding crew) carried, multiplied by the distance flown. It is the common metric of passenger activity for commercial passenger aviation.

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2019 levels sometime between late 2022 and 2025 (IATA, 2020b; ICF, 2020; Oliver Wyman, 2020), but that there will be permanent changes to the structure of demand – to the relative shares of essential, leisure and business flights, and of domestic and international flights. The question is not whether such changes can be expected, but how big they will be. Demand is set to decline in long-distance leisure and especially business flights (IEA, 2020c), and this has potentially wide implications because corporate travel has a disproportionate impact on airline profitability, even though business travellers account for only a small fraction of commercial aviation demand. Shifts have also occurred between commercial passenger operations and freight: fewer flights meant reduced airplane belly cargo capacity, and that reduced capacity resulted in rate increases for freight; those rate increases have in turn led airlines to repurpose passenger aircraft for dedicated cargo freight.

The impacts of the Covid crisis are beginning to pose an existential threat to many players in an industry where only about 30 out of more than 120 major airlines out of more than 120 in total earn profits in a given year (IATA, 2020c), and where margins typically range from 6-8%. Airlines will sustain losses in 2020 that, at a minimum, exceed their combined revenues from 2018-19. In 2019, more than 30 airlines declared bankruptcy, and by July 2020 another 23 had joined their ranks.[26] Consolidation will inevitability follow, and may result in operational efficiencies and greater flexibility in deploying newer, more efficient aircraft on routes that suit them. Older, inefficient aircraft, especially wide-body planes that serve long-distance flights where demand contracted most, are already being stored or scrapped. For those that are still operating, plans for accelerated retirement are being made, as in the case of British Airways retirement of 31 Boeing 747s, Air France's early phase out of their remaining A340s, and many other airlines' retirements of Boeing 747 and Airbus 380 planes. Years of reduced, deferred or cancelled orders lie ahead for aircraft and jet engine manufacturers, delaying the entry to service of the most recent and most efficient models. The efficiency implications of airline bankruptcies and aircraft retirements are discussed briefly in the following section and will be examined in depth in a forthcoming IEA publication (IEA, forthcoming).

Despite these existential challenges to individual airlines, aviation may well regain its place as the fastest growing mode of passenger transport in activity terms by the 2030s at the latest, driven by rises in population, prosperity and international trade. What was once a marginal source of CO_2 emissions has become increasingly critical to efforts to fight climate change and constitutes a potential hurdle to net-zero emissions. Aviation as a whole accounted for nearly 3% of energy sector direct CO_2 emissions from fossil fuel combustion in 2019. The current framework for reducing

[26] The concurrent fall in fuel prices has offered airlines some degree of relief; while jet fuel averaged USD 77/barrel in 2019, the projected average price in 2020 is just under USD 37/barrel. Consequently, fuel is expected to drop to only about 15% of overall costs, as opposed to nearly 24% in 2019 (IATA, 2020d).

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emissions as administrated by the International Civil Aviation Organization (ICAO), including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), is generally regarded as lacking sufficient stringency and ambition to lead to effective reductions in CO_2 emissions. CORSIA was also recently weakened by resetting its benchmark year to 2019 (Box 5.4).

Box 5.4 Making CORSIA work for the climate challenge

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a carbon market-based system that was adopted in 2016 by the International Civil Aviation Organization Assembly as part of a broader package of measures to help achieve ICAO's aspirational goal of carbon-neutral growth for civil aviation from 2021 onwards. CORSIA is designed to complement the other climate mitigation measures of the package relating to technological innovations and operational improvements within the aviation sector. The scheme provides credits to airlines that use sustainable aviation fuels or purchase offsets of CO_2 emissions that cannot be reduced within the aviation sector itself. The ICAO Council will conduct a periodic review of the CORSIA every three years from 2022.

CORSIA consists of three phases: pilot phase (2021-23), first phase (2024-26) and second phase (2027-35). The pilot and first phases are voluntary, while the second phase will be mandatory for all ICAO member states and is expected to cover one half of all aviation emissions (ICCT, 2020b). Airlines operating on routes between participating states will be subject to offsetting requirements under CORSIA based on growth over baseline emissions for the aviation sub-sector. Offset credits are generated through emissions reductions arising from the implementation of carbon mitigation projects in other sectors. There are currently six eligible programmes through which to purchase carbon offset credits (ICAO, 2020). Some of these programmes, however, have been criticised for not guaranteeing the environmental integrity of the generated credits. To address this risk, CORSIA's Technical Advisory Board has adopted various eligibility criteria that could limit the risk of carbon offset credits not representing real emission reductions.

Originally, the baseline from which to calculate the carbon-neutral growth of the sector was set to be the average of total CO_2 emissions for 2019 and 2020. Due to the Covid-19 pandemic, however, flight activity is expected to be 50% lower in 2020 than in 2019. Including 2020 CO_2 emissions level in the baseline calculation for CORSIA would therefore decrease the previously anticipated baseline emissions level by at least 25-30%. Driven by concern that this reduced baseline would place an undue economic burden on airplane operators by effectively requiring the purchase of more carbon offsets than originally envisioned under the scheme, the ICAO Council,

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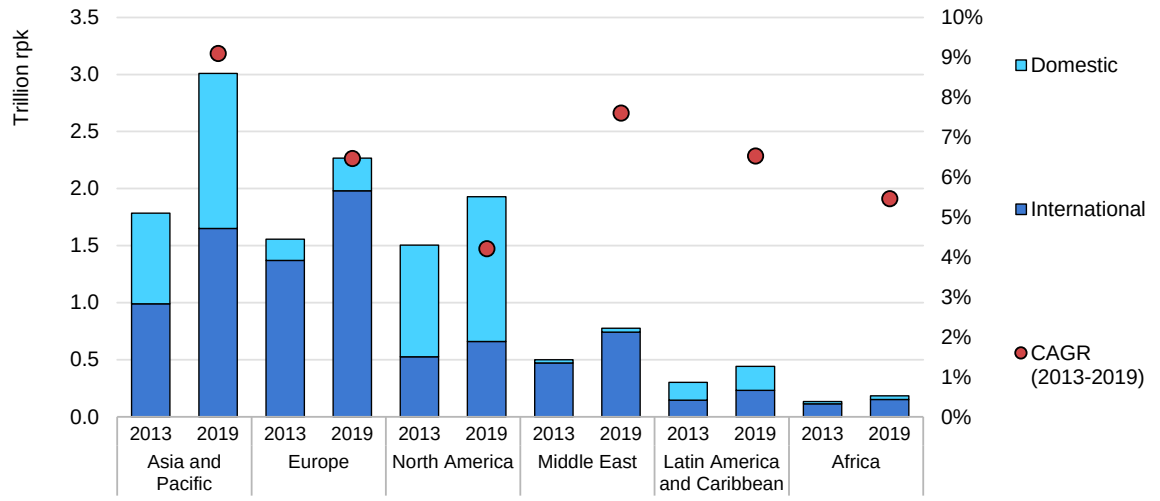
following a request from the International Air Transport Association (IATA), agreed that 2019 emissions alone should be used as the baseline for the pilot period between 2021 and 2023. If flight activity rebound takes as long as most industry projections expect, this decision will nullify any offset obligations during CORSIA's pilot phase, putting at risk CORSIA's credibility.

Prior to the outbreak of the Covid pandemic, worldwide passenger aviation activity was at record high: it exceeded 8.6 trillion revenue per passenger- kilometre in 2019 –75% higher than in 2010 and more than 350% on 2000. Both international and domestic activity has been growing strongly. Asia-Pacific, which saw growth of over 9% per year over the six years to 2019, is now the leading regional market, accounting for over one-third of total travel, followed by Europe (26%) and North America (22%) (Figure 5.13).

Figure 5.13 Growth of revenue passenger-kilometres by region, 2013-19



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Notes: rpk = revenue per passenger kilometre, CAGR = compound average growth rate. 2019 estimates are based on regional annual growth rates, which are applied equally to domestic and international aviation segments, and verified to match domestic and international growth from 2018-19 as reported by IATA.

Sources: International Civil Aviation Organization (ICAO) annual reports (2013-2018) and International Air Transport Association press release on 2019 industry growth (IATA, 2020d).

Asia-Pacific is the largest passenger aviation regional market, followed by Europe and North America.

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Jet kerosene[27] refined from crude oil accounted for practically all of the fuel consumed by aircraft worldwide in 2019. Total consumption of jet kerosene amounted to 6.8 mb/d (340 Mtoe), accounting for 7% of global oil demand (aviation gasoline accounted for most of the rest); biojet kerosene accounted for 50 million litres (44 thousand tonnes of oil equivalent [ktoe], or about 0.01% of fuel used). Passenger traffic growth increased by an average of 6.9% annually from 2000 to 2019, led by growing demand in international flights. Thanks to technical and operational efficiency improvements, fuel demand and CO_2 emissions grew at a slower average annual rate of 2.2% a year (IATA, 2020d; ICAO, 2007; 2013-2018; IEA, 2020d). Commercial passenger aviation (including cargo carried on passenger flights) accounted for about 86% of jet kerosene fuel use in 2019; the remaining 14% was consumed by non-scheduled flights (both commercial and private) (4.5%), dedicated cargo freight (about 8%) and military (about 1%).

Demand for air travel is strongly related with income levels across the world, with flying becoming affordable above a certain income threshold (a single return flight per year on average becomes affordable in countries where per capita income in purchasing power parity terms exceeds USD 60 000) (Box 5.5). Demand for air travel tends to rise fastest in developing countries where an affluent middle class is emerging: it rises less rapidly in the richest countries where there are saturation effects. Despite tremendous growth in recent years, people in emerging economies fly much less than those in advanced economies. Deregulation of passenger aviation has helped to drive the growth of route networks and enabled the strong growth of low-cost carriers, which, for example, now claim market shares of up to 62% of available seat capacity on short-haul routes in Southeast Asia (Boeing, 2019). The short-haul market segment (less than 1 500 km) accounts for about one-fifth of all passenger boardings worldwide.

[27] Fossil jet kerosene, the term adopted here, is consistent with the terminology used in the IEA energy balances. The industry standard term is conventional aviation fuel.

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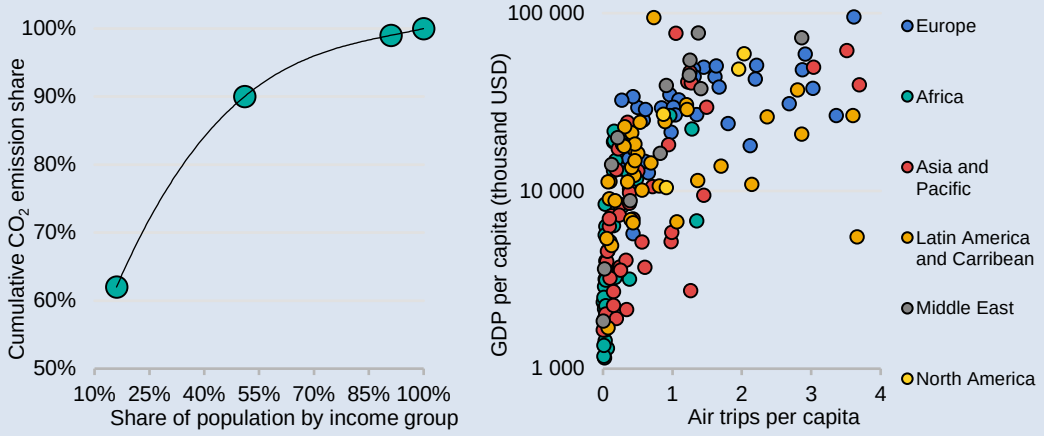
Box 5.5 Who flies and how much?

The United States has by far the world's largest aviation market, with over 1.2 trillion revenue passenger-kilometres (rpk) flown on domestic flights in 2019, followed by China with 820 billion domestic rpk in 2019 (both countries also command high shares of international flights, as do the United Arab Emirates and United Kingdom). While air travel is growing fastest in the emerging economies, the frequency with which people there fly is much lower than in the advanced economies. In 2018, US citizens made on average just over two trips – almost five-times more than the Chinese and 17-times more than people in India (Airbus, 2019).

The distribution of flights is also unbalanced within countries: a small group of travellers are responsible for most travel and, therefore, for the bulk of jet fuel consumption and emissions. More than half of respondents to recent travel surveys in the United Kingdom and United States had not flown in the previous year (Airlines for America, 2018; Civil Aviation Authority, 2019), while the top 15% of air travellers made an average of five trips in the United Kingdom and nine trips in the United States. This imbalance is even higher in emerging economies where income disparities are often bigger.

The distribution of flights across countries is also unbalanced. Worldwide, 16% of the global population living in the highest-income countries accounted for 62% of CO_2 emissions from aviation, while the half living in low and lower-middle income countries accounted for only 9% in 2018.

CO_2 emissions by income quartile (left) and air trips by GDP per capita and region, 2018 (right)



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Notes: In the left-hand figure, the four data points are given, the curve is interpolated. In the right-hand figure, each point represents a country. All figures are in GDP PPP.

Sources: Becken and Pant (2019) (left-hand figure). Airbus (2019) (right-hand figure).

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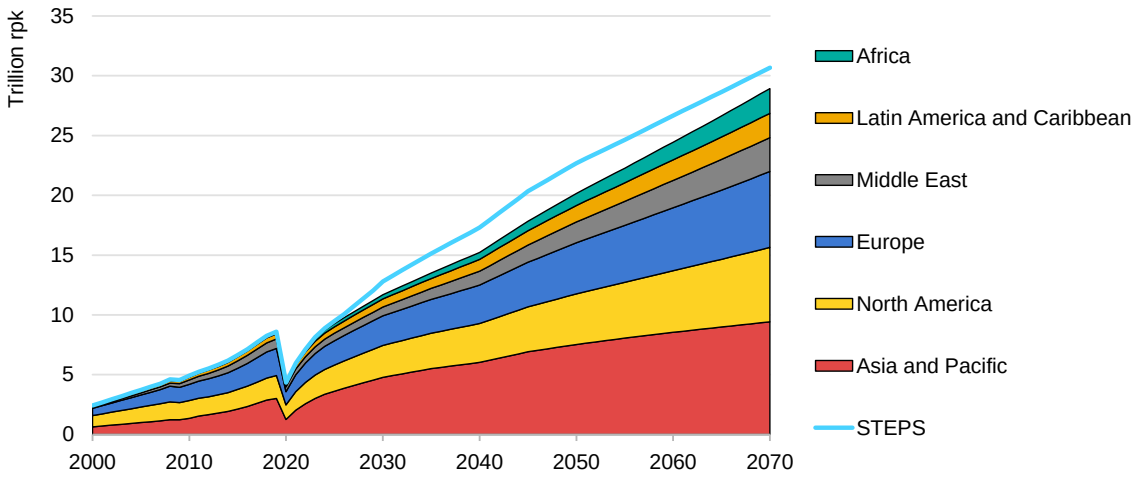
In the Sustainable Development Scenario, air travel takes more than three years to return to 2019 activity levels in the wake of Covid-19, and then continues to expand as household incomes rise, notably in developing countries, especially in Asia-Pacific and Africa. Nonetheless, a comprehensive set of stringent government policies, including measures that increase the overall cost of air travel and hence dampen activity demand, leads to aviation activity (measured by rpk) being about 12% lower by 2040 in the Sustainable Development Scenario than in the Stated Policies Scenario, a gap which remains at above 10% to 2070 (Figure 5.14).[28] Asia-Pacific experiences the most growth of any region in both scenarios (about one-third), with notable activity increases in China, India and Association of Southeast Asian Nations (ASEAN) member countries. Europe and North America each account for about one-fifth of the activity growth. The fastest increase in activity is in Africa (with annual average growth of around 6%).

Figure 5.14 Passenger aviation activity by region in the Sustainable Development Scenario, 2019-70



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Notes: rpk = revenue passenger-kilometre; STEPS = Stated Policies Scenario. Not including unscheduled or private flights. The projections were developed using the Aviation Integrated Model developed by University College London Energy Institute (AIM, 2020).

Despite strong policy measures, including taxes that reduce overall demand, air passenger traffic increases by about 350% through to 2070 in the Sustainable Development Scenario.

[28] At 3.4%, the projected average annual growth in the Stated Policies Scenario for the period 2019-40, is lower the activity growth over 20 years projected prior to the Covid-19 crisis by Airbus (4.3%), Boeing (4.6%) and the ICAO (4.3%) (Airbus, 2019; Boeing, 2019; ICAO, 2018). The 3.4% growth, however, is in line with the pre-Covid-19 projections of the International Transport Forum (ITF, 2019).

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Air cargo volumes have also been increasing, though not as rapidly as commercial passenger aviation numbers.[29] The volumes of cargo carried on both dedicated and associated (or "belly freight") flights increased by 3.8% per year on average over 2013-19. Belly freight is projected to expand by 2.0% per year on average over the projection period in the Sustainable Development Scenario. The practice of turning passenger aircraft into dedicated freight aircraft at the end of their passenger aviation service means that the energy efficiency improvements embodied in new aircraft models take time to work through to freight aviation.

Direct CO_2 emissions from jet kerosene combustion for aviation, which in 2019 accounted for 2.8% of all energy sector CO_2 emissions, are hard to abate because aviation requires a fuel with a high energy density (Figure 5.17). Even with major advances in technology, electric batteries based on current designs are unlikely to ever provide sufficient density to make electric planes viable for mid- and long-range flights, which account for the majority of energy use. The use of biofuels continues to be constrained by competition from other uses and the limited availability of sustainable biomass. Other low-carbon fuels, such as synthetic fuels and hydrogen, while technically feasible, are currently much more expensive than conventional kerosene (Figure 5.18). Long aircraft lifetimes and slow innovation cycles (typically about 15 years between successive new generation aircraft designs) also constrain how quickly net-zero aviation emissions can be achieved: the bulk of the fleet of passenger aircraft in operation today is made up of models that were introduced before 2000, principally the Airbus A320 and Boeing 737 (DVB Bank, 2017).

Technology pathways towards net-zero emissions

In the Sustainable Development Scenario, CO_2 emissions from aviation are reined in through a suite of rigorous and concerted government policies to support investment in the production of alternative, sustainable aviation fuel pathways and fuel efficiency technologies for airframes and engines (Figure 5.15).[30] Operational efficiency gains and shifts to less energy-intensive modes of travel also reduce fuel use. In the medium term, technical and operational efficiency gains play a supporting role alongside the faster deployment of sustainable aviation fuels. In the longer term, synthetic fuels (kerosene derived from hydrogen and CO_2) make an important contribution to reducing upstream and operational CO_2 emissions,[31] particularly after 2050.

[29] Dedicated cargo freight is not explicitly modelled for *Energy Technology Perspectives*. Within passenger aviation, the metric of revenue tonne-kilometres (rtk) is the sum of revenue passenger kilometres, assuming that each passenger plus luggage weighs on average 90-95 kilogrammes, and belly freight cargo expressed in metric tonnes multiplied by the distance flown. These projections are taken into account in our modelling. In the Sustainable Development Scenario, rtk on passenger aircraft (and not including dedicated cargo freight) grows by 1.4% per year on average over the period 2020-70.

[30] Sustainable aviation fuels are fuels that do not use crude oil as feedstock (e.g. biojet fuel and synthetic jet kerosene).

[31] In the case of aviation, the climate impacts of CO_2 are amplified by relatively short-lived non-CO_2 climate forcing mechanisms (such as contrails and contrail induced cirrus cloud formation, NOx emissions and others), the magnitudes of which are still very uncertain, but in the short term may double the climate impacts of flying.

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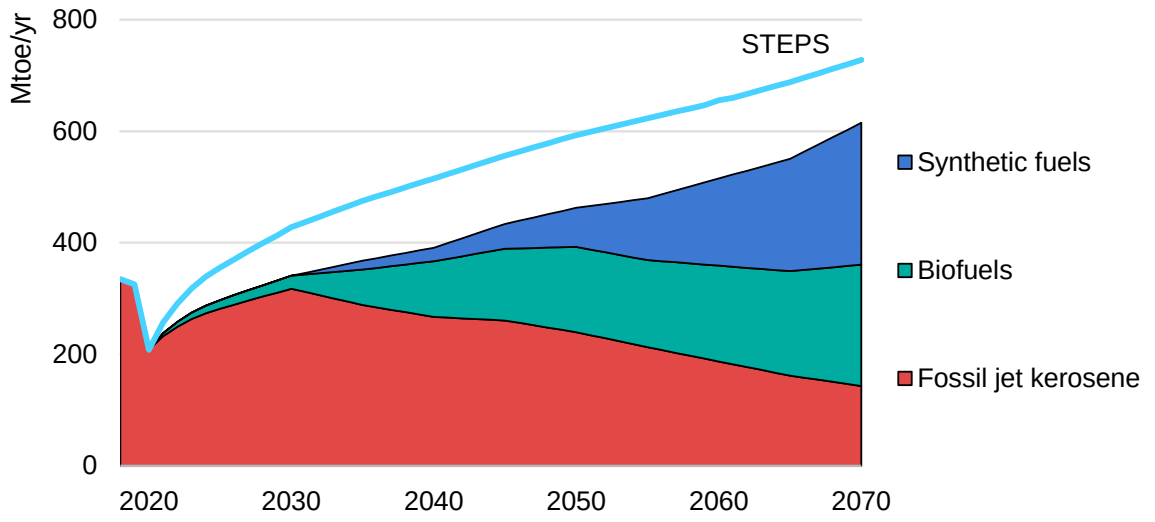
Figure 5.15 Global aviation fuel consumption in the Sustainable Development Scenario and total fuel use in the Stated Policies Scenario, 2019-70



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Notes: STEPS = Stated Policies Scenario. Projections developed using the Aviation Integrated Model developed by University College London Energy Institute (AIM, 2020).

Rigorous policies to promote the development and adoption of sustainable aviation fuels play the leading role in reducing the climate impacts of aviation in the Sustainable Development Scenario.

Sustainable aviation fuels play a pivotal role in reducing emissions from aviation in the Sustainable Development Scenario, especially during the second half of the projection period (Figure 5.16). However, they do not entirely displace jet kerosene which continues to supply one-quarter of the market in 2070.

- Biofuels for jets (biojet fuels), blended into conventional petroleum-based jet fuel, currently account for only 0.01% of total aviation fuel consumption, but that share rises to about one-quarter by 2040 and about 35% by 2070. Around 4.4 mboe/d of biofuels are used in aviation in 2070, more than double the total biofuels produced in 2019 for road transport purposes (about 2 mboe/d).
- Synthetic jet kerosene is produced from CO_2 captured from concentrated industrial sources, using biomass feedstocks, or via direct air capture (DAC) and low-carbon hydrogen (see Chapter 3). It complements biojet fuel, the supply of which is constrained by the limited availability of sustainable biomass and the demand for biomass in other energy sectors. Synthetic jet fuel's building blocks are not limited in the same way as biomass, and synthetic methods can produce a hydrocarbon fuel with characteristics identical to conventional jet kerosene, allowing the fuel to be blended or entirely replace jet kerosene. Commercial-scale synthetic jet kerosene production starts in the 2030s in the Sustainable Development Scenario, and the share of the jet fuel market taken by synthetic

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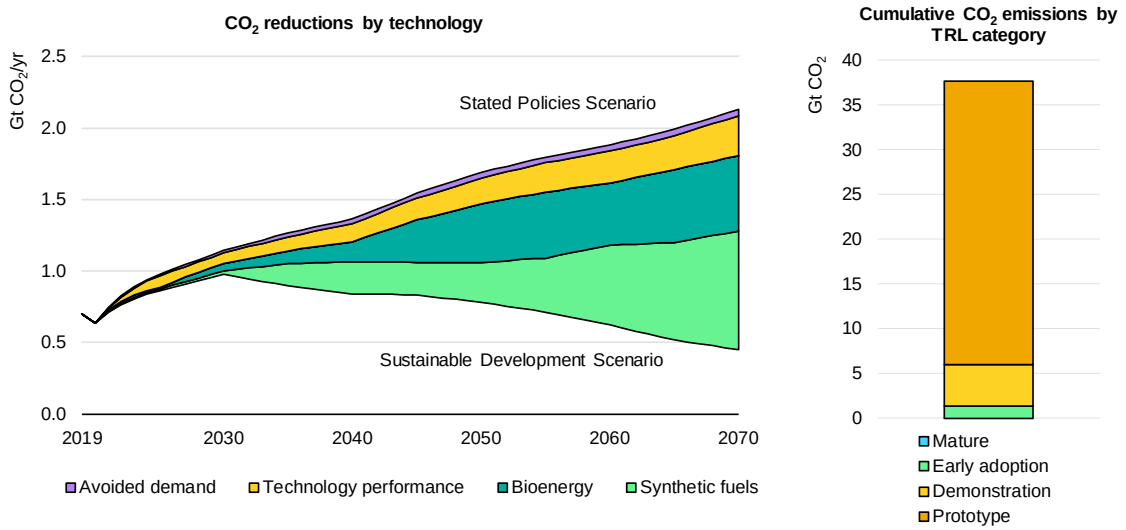
production reaches more than 40% by 2070. In 2070, around 5.1 mboe/d of synthetic fuels are used in aviation, equivalent to about three-quarters of jet kerosene consumption in 2019.

Figure 5.16 Global CO_2 emissions in aviation by abatement measure (left) and technology readiness level (right) in the Sustainable Development Scenario relative to the Stated Policies Scenario



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Notes: The projections were developed using the Aviation Integrated Model developed by University College London Energy Institute (AIM, 2020). TRL = technology readiness level. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

Rigorous polices that promote sustainable aviation fuels, efficiency and shifts to alternative transport modes reduce emissions substantially in the Sustainable Development Scenario.

Energy efficiency is a key technological driver of emissions reductions throughout the Sustainable Development Scenario. Despite the improvements driven by the imperative to cut fuel costs that have been made in the last few decades, there remains considerable potential for further gains. The maximum potential for cost-effective operational and technical fuel burn reductions for new aircraft by 2034 is estimated at 40% (ICCT, 2016). Most of this potential is exploited in the Sustainable Development Scenario.

In contrast to the case of cars and trucks, where vehicle efficiency standards propel vehicle and powertrain efficiency technologies into the market (and simultaneously save drivers and consumers money through reduced expenditure on fuel), efficiency targets in the airline industry lag behind recent non-regulated rates of improvement. Both the aspirational 2% annual average improvement rates in fuel efficiency targeted by ICAO on international flights (ICAO, 2013), and IATA's 1.5% annual improvement targets for 2009-20 for international and domestic flights combined (IATA, 2018) fall short of the actual improvement rates demonstrated by the industry overall

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(domestic plus international) achieved in the 2009-19 period (2.9% on an rpk basis and 2.4% on an rtk basis). As outlined in the overview section, aircraft retirements and airline consolidation in the wake of Covid-19 are likely to give a substantial boost to overall fleet efficiency, particularly in wide-body aircraft. Putting to one side the impact of lower passenger occupancy rates, the retirement of one-quarter of the current aircraft fleet constructed before 2001 would result in an overall reduction in the fuel burn per available seat-kilometre of around 8%.

Projected gains in energy intensity of new aircraft average 2.2% per year (on an energy per rpk basis) in the 2019-30 period. At a time of unprecedented growth in air travel, where new aircraft that will operate for decades are being delivered to key growth markets such as Asia-Pacific, these efficiency gains help to restrain growth in demand for aviation fuel, although they do not stop it. Efficiency improvements in the Sustainable Development Scenario will need to be driven mainly by taxes on fuels or pollutant emissions that encourage airlines to opt for more efficient aircraft, or by clean fuel standards that effectively lead to rapid uptake of sustainable aviation fuels (discussed in detail in the next section). The long operational lives of aircraft means that the improvements in new aircraft efficiency take nearly a decade to show up in the Sustainable Development Scenario. The efficiency gains come from a combination of technical and operational innovations.

Transport policies that encourage investment in more energy efficient modes, such as high-speed rail, also reduce aviation demand in the Sustainable Development Scenario. The range of flights for which high-speed rail can serve as a direct substitute for air travel is essentially the same as the maximum range that electric aircraft may one day be capable of achieving, and then only with breakthroughs in battery technologies (IEA, 2019b), but electric aircraft may have a role on routes where travel volumes are too low to justify building expensive rail infrastructure. Other technologies that can play a role in limiting demand, such as video conferencing and virtual reality teleconferencing as substitutes for business travel, are likely to become more commonly used given their widespread adoption during recent periods of lockdown and reduced travel with the Covid-19 crisis. The forthcoming *World Energy Outlook* (IEA, forthcoming) will discuss the potential impacts of such substitutes for business travel on energy demand.

Rapid and effective policy action is needed to put aviation onto the fuel and emissions trajectory set out in the Sustainable Development Scenario. Fiscal measures and others that stimulate the market adoption of sustainable aviation fuels (such as offtake agreements and/or low-carbon fuel mandates [including volumetric]) are assumed to play an increasingly important role, together with regulatory policies that mandate minimum fuel efficiency standards on aircraft and engines. However, such policies need to recognise and account for trade-offs between fuel efficiency, noise, safety and local pollution (Box 5.6).

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Box 5.6 Trade-offs in making aircraft more fuel efficient

The scope to make full use of the opportunities to boost the fuel efficiency of aircraft is constrained by a number of commercial and practical trade-offs. These include:

- **Optimal range and speed:** The right-sizing of aircraft based on their load factor and optimum operational range can enable airlines to minimise fuel use per rpk. But systematically matching an aircraft and a route is not necessarily straightforward. Airlines may favour bulk purchases of a limited number of aircraft models to obtain a better price and for the ease and cost savings that come from more uniform maintenance and pilot training needs across their operations. This leads to many aircraft being used on routes far shorter than their optimal range over their entire lifetime.
- **Stopovers:** Take-off is the flight stage that burns the most fuel (per distance travelled), followed by landing; cruising is far less fuel intensive. Minimising travel with connecting flights may therefore lead to better trip fuel efficiency. However, flying longer distances means a need to carry more fuel, boosting fuel consumption – the so-called "burning fuel to carry fuel" drawback.[32] At distances of more than approximately 6 000 km, planes can save fuel by stopping mid-way and refuelling if doing so does not cause them to deviate from the direct flight path from the origin to destination airport.
- **Noise:** Reducing aircraft noise, particularly in densely populated areas around airports, is a priority for policy-makers and the general public. Although high bypass ratio turbofans are both more fuel efficient and quieter than turbojets, other measures that reduce noise actually incur fuel use penalties and increase costs and emissions. Examples include adopting longer flight routes to avoid populated areas and the use of steeper, and hence more fuel intensive, take-off and landing manoeuvres. Efforts to reduce NOx emission face similar trade-offs, as these can increase fuel burn.

Source: Filippone (2012).

[32] For example, an A330 consumes 150 kg of fuel to carry each additional tonne of fuel on a typical route, i.e. a 15% penalty (Airbus, 2012).

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Readiness and competitiveness of emerging technologies

Among the technologies that can reduce CO_2 emissions in aviation, those that are generally most ready to be deployed concern operational measures and technical improvements that result in aircraft fuel efficiency (Table 5.5). Operational measures that could be (and are) implemented with little barrier include single engine or electric taxing, improved congestion management and optimised departures and approaches at airports. Technical efficiency opportunities concern designing new airframes and jet engines in ways that can lead to reduced fuel burn. New aircraft models are typically improved versions of previous generations of similar models, and recent Airbus and Boeing aircraft offer fuel efficiency improvements of up to 25% over previous versions of similar models. Efficiency gains can be achieved by improvements to engines, airframes and powertrains. Improved engines have contributed substantially recent efficiency gains, primarily through increasing air bypass ratio – the ratio between the mass flow rate of the bypass stream and the mass flow rate entering the core (the higher the ratio, the lower the fuel consumption for the same thrust). More disruptive designs, such as the open rotor or ultra-high-bypass-ratio (UHBR) engine, have the potential to further increase the ratio and to produce fuel burn reductions of up to 30%. However, their large engine diameter poses problems for existing aircraft designs. Futuristic concepts such as the notion of a blended-wing-body, being tested by Boeing and Airbus with small-scaled prototypes, would radically change what aircraft look like, and could open the way to use of UHBR or similar engines. Such designs could enable fuel savings of up to 20%. Risk-sharing mechanisms and public investments in R&D, perhaps financed through CO_2 taxes or fees on flights, are likely to be needed for manufacturers to be willing to take on the high risks and huge development costs involved in bringing such disruptive airframe designs to market.

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Table 5.5 Status of the main emerging technologies in the aviation sector

Technology	TRL	CO_2 reduction mechanism	Year available (Importance for net-zero emissions)	Deployment status
Engines				
UHBR engines	5	Fuel efficiency	2030-35 (High)	Ground tests of Rolls Royce's UltraFan with a 25% fuel saving potential will start in 2021. The manufacturer collaborates with Airbus under the EU Clean Sky 2 programme and this UHBR engine will be available towards 2030.
Open rotor engines	5	Fuel efficiency	2035 (High)	Demonstration of the GE36 open rotor engine dates back to the 1980s. In 2017 SAFRAN ground-tested a demonstration model with 30% potential fuel savings that will be market ready in 2030.
Airframes				
Blended wing-body aircraft	3	Fuel efficiency	N/A (Medium)	Boeing together with NASA conducted test fights of a small-scale prototype until 2013 and Airbus in 2019. This concept is validated yet neither manufacturer has confirmed plans for a large prototype.
Alternative powertrains				
Hybrid electric aircraft	4-5	Fuel switch	N/A (Medium)	Airbus together with Rolls Royce is developing a prototype for a hybrid electric aircraft under the E-Fan X programme. The aim is to launch a test flight by 2021 with an aircraft with one electric motor and three regular jet engines. Wright Electric aims to launch a 186-seat aircraft for short-haul flights in 2030. Small aircraft (Cassio and the Ecopulse) have performed flight tests.
All-electric aircraft	3	Fuel switch	N/A (Medium)	A nine-seater seaplane, retrofitted with a battery and electric engine, had its inaugural flight in 2019 in Canada, trailblazing the development of small battery electric aircraft for very short distances (the aircraft has a range of about 160 km). Batteries with higher energy density will be needed for longer distances.
Fuel cell electric aircraft	3	Fuel switch	N/A (Medium)	DLR tested a fuel cell powered four-seater motor glider (HY4) in 2016. Boeing tested a fuel cell electric prototype in 2008. There are no announced programmes for larger aircraft.

Notes: UHBR = ultra-high bypass ratio. A broader list of technologies compatible with a low-carbon transition for the aviation sub-sector is presented in the technology mapping portion of *The Covid-19 Crisis and Clean Energy Progress* (IEA, 2020b).

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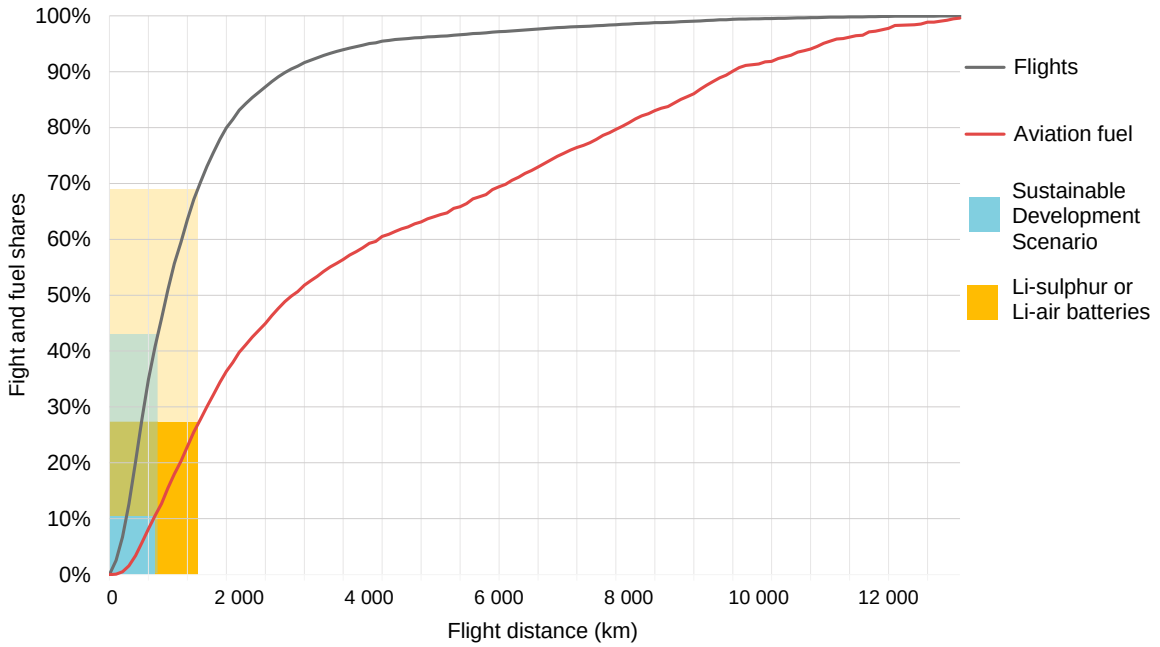
The uncertainty surrounding electric powertrains is even greater. RD&D programmes for fuel cell electric and hybrid electric aircraft are at an early stage with the first prototypes planned for the 2030s. The first battery electric flight took place in 2019, but the gravimetric energy density of currently available batteries would have to increase at least threefold to support short flights on regional jets. The projected progress in battery technology in the Sustainable Development Scenario by 2070 (i.e. near doubling of cell level energy density) meets technology requirements of battery electric aircraft with a range that is sufficient for about 40% of all flights (Figure 5.17). However, electric aircraft look set to remain unviable for the mid-haul and long-haul flight segments that use most fuel, and the potential to substitute fuel use on those flight segments is limited to about 10%.

Breaking that range limit would depend on further developments in advanced battery chemistries. Both potentially enabling chemistries (Lithium-sulphur and Lithium-air), are at very early stages of technology development (see chapter 6 for more details). Hybrid electric and fuel cell electric aircraft use batteries only to moderate power output, so battery weight is less of a constraint, but fuel cell electric aircraft face challenges stemming from the low volumetric energy density of hydrogen.

Figure 5.17 Share of flights and fuel use in overall commercial passenger aviation, 2017



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Note: The boxes show the share of aviation fuel use (solid) and flights (transparent) that could theoretically be offset by battery electric aircraft entering the fleet in 2070 in the Sustainable Development Scenario, or by lithium-sulphur batteries.

Source: IEA analysis based on OAG (2018); Schäfer et al. (2019).

Batteries at demonstration or prototype stage enable electric aircraft with flight ranges covering 10% of fuel use in 2070 in the Sustainable Development Scenario. Less mature alternative batteries could raise this threshold up to 30% at most.

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Available aircraft and engine technologies, including designs that are today only at the early prototype level, could reduce energy needs and, therefore, emissions from oil-based aviation fuels, but switching to clean fuels would be needed to achieve full decarbonisation during the second half of this century.[33] Currently, five biojet fuel production pathways[34] have been approved as compliant with the American Society of Testing and Materials (ASTM) standard D7566, the fuel standard required for international flights. Only one – hydrogenated ester fatty acid (HEFA) jet – is so far commercially available (TRL 9-10). All of the approved pathways except sugar-based synthetic isoparaffins (SIP) are technically drop-in fuels, though current regulations cap them at 10-50% blend rate with fossil-based jet kerosene.[35] There are a number of measures already in place that support the deployment of sustainable aviation fuels by providing certainty about future demand, including offtake agreements between airlines, airports and biojet fuel producers. Oslo Airport led the way in 2016, with United Airlines at Los Angeles Airport close behind (IATA 2019). Both use HEFA jet, with Neste producing the fuel for Oslo Airport and World Energy for Los Angeles Airport.

Commercially available HEFA will probably play a leading role in the early market development of aviation biofuels. When waste cooking oil and animal fat feedstocks are used, HEFA can offer deep decarbonisation (in the region of 80-90% versus fossil jet kerosene). However, ultimately a broader set of sustainable aviation fuels will be needed to deliver the volumes required by the Sustainable Development Scenario. This is because large-scale HEFA production from crop feedstocks raises questions regarding its potential impact on land use and food production, and because there are upper limits on the availability of the lowest carbon feedstocks, although practices such as sequential cropping and improvements in agricultural yields would increase the sustainable feedstock base. In addition, HEFA jet faces competition for the same feedstocks from hydrotreated vegetable oil (HVO) in road transport. A facility that produces HEFA jet can also produce HVO, which not only requires fewer chemical transformations (and is hence cheaper to produce), but can also be sold at a higher price at present because it is underpinned by more widespread policy support measures.

[33] The correct attribution of GHG emissions to sustainable aviation fuels is critical to accurately estimate their potential to displace fossil fuel use. For instance, the EU Renewable Energy Directive, Annex V, Section B lists default values for emissions savings from 40% to 95% for biofuels depending on the feedstock and pathway.

[34] These are hydrogenated ester fatty acid (HEFA) jet fuel, Fischer-Tropsch (FT) jet fuel, alcohol-to-jet fuel using an ethanol or isobutanol feedstock, hydroprocessed fermented sugar-synthetic isoparaffins and catalytic hydrothermolysis jet fuel. The FT route must use gasified biomass (biomass-to-liquid) to qualify as a sustainable aviation fuel.

[35] Sugars are fermented and converted into a long-chain hydrocarbon called farnesene, and then treated with hydrogen to produce farnesane. The molecular composition of this fuel is not exactly the same as the hydrocarbons found in fossil jet fuel, limiting the extent to which they can be blended.

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Biomass-to-liquid (BTL) jet, the next closest technology to commercialisation (TRL 5-6), holds great potential given its ability to handle a wide variety of feedstocks that do not face the same growth limitations as HEFA feedstocks. BTL can use woody biomass, energy crops cultivated on marginal land, municipal solid waste and residues from agriculture and forestry as feedstock. However, technical issues remain with unwanted tar formation during gasification, casting doubt about exactly when it could become commercially viable. While BTL is mainly in the demonstration plant phase, two commercial-scale plants which aim to produce aviation biojet fuel are under construction in the United States (BP 2018; Velocys 2020). Other ASTM-approved technology pathways allow ethanol, ether from crop or cellulosic feedstocks, to be converted into biojet fuels, therefore further amplifying the sustainable potential of biojet fuels to meet the demand projected in the Sustainable Development Scenario. In the longer term, clean synthetic jet kerosene would also be needed to meet jet fuel demand in order to achieve net-zero emissions in aviation (see Chapters 3 and 6 for more discussion on synthetic fuels).

The main barrier to large-scale deployment of biojet and synthetic fuels is that they cost much more at present than fossil jet. Some feedstock costs alone are usually higher than the market price of fossil jet, before even considering capital and operational expenditures. For instance, at the end of 2019 soybean oil was priced at USD 0.70 per litre (/L) while fossil jet kerosene was priced at USD 0.53/L (Bloomberg 2020). Crude oil prices would need to be in the USD 90-310/barrel range to allow biofuels to compete on equal terms with fossil jet kerosene today. The cost competitiveness gap with synthetic jet kerosene is even bigger. As with biojet fuel, the cost of both electrolysers and DAC systems need to be reduced considerably to make them commercially viable options, even with much higher carbon prices (see Chapter 3).

Bridging the gaps between the cost of producing biofuels and synthetic fuels on one hand and the price of fossil jet on the other cannot be done without policy intervention – at least initially and potentially for decades. With a high carbon price – USD 150/tonne in 2050 in the Sustainable Development Scenario – it currently looks as though HEFA jet and BTL-based biojet (with CCUS) fuel could eventually compete with fossil jet kerosene, though future production costs and oil prices are extremely uncertain (Figure 5.18). In the United States, the Low Carbon Fuel Standard (LCFS) in California coupled with the national Renewable Fuel Standard (RFS) has already made HEFA jet commercially viable, while the UK Renewable Transport Fuel Obligation also offers considerable financial support which could close the gap between HEFA and fossil jet fuel: much more would be needed to enable BTL-based biojet fuel and synthetic jet kerosene to also close the gap.

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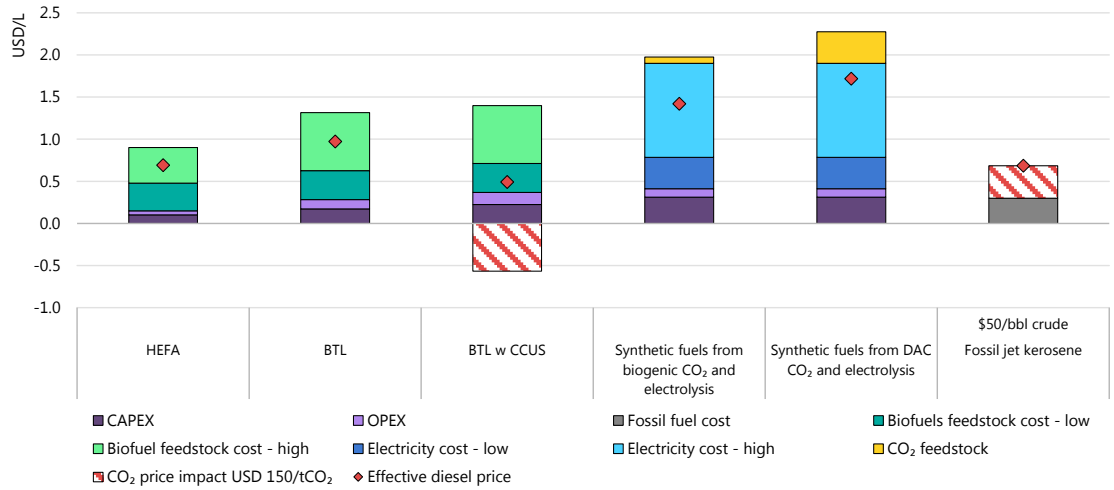
Figure 5.18 Levelised production costs of sustainable aviation fuels in 2050



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Notes: HEFA = hydrogenated ester fatty acid; BTL = biomass-to-liquid; CCUS = carbon capture and utilisation; DAC = direct air capture; CAPEX = capital expenditure; OPEX = operational expenditure. Effective diesel price refers to the levelised production cost with carbon prices included where shown. Levelised costs assume a discount rate of 8%. Crude oil price of USD 50 USD/bbl are assumed. Biomass feedstock costs range USD 5-15 per gigajoule. Synthetic fuel production here uses biogenic CO_2 at a cost of USD 30/tCO_2 and CO_2 from DAC at a cost of USD 150/tCO_2, and hydrogen from electrolysis powered by a dedicated renewable energy system. Electricity prices for hydrogen production and synthetic fuel production range USD 20-60 per megawatt-hour (MWh) across regions while an average electricity price of USD 40/MWh is assumed for biofuels and is included in the biofuel OPEX. For more details on synthetic fuel production costs, see Chapter 2.

With a carbon price of USD 150/tonne, sustainable aviation fuels begin to compete with oil-based jet kerosene, though policy support will need to account for the volatility and uncertainty of future feedstock costs and oil prices.

Despite the Covid-19 crisis, there are some signs that momentum may be starting to pick up for sustainable aviation fuels. In the United States, production of sustainable aviation fuels rebounded in the second-quarter of 2020 to nearly double the output from the second-quarter 2019. While most of the economic recovery packages in many countries did not include any requirements for sustainability, the bailouts for Air France-KLM call on these airlines to target 2% sustainable aviation fuels blending shares in their operations by 2025. The bailout of Austrian Airlines requires that airline to meet 2% sustainable aviation fuels blending shares on short- and medium-haul flights by 2030. Amazon has secured the purchase of 6 million gallons (22.7 million litres) of sustainable aviation fuels over the next year. If additional airline bailouts were to be made contingent on a commitment to sustainable aviation fuel blending targets, it would further boost production of those fuels. Public and shareholder pressure could also accelerate the adoption of sustainable aviation fuels.

A much stronger policy and regulatory push, together with support for technology development to bring alternatives to HEFA biojet fuel production pathways closer to commercialisation, is needed to reach the projected levels of sustainable aviation fuel production in the Sustainable Development Scenario. In addition to putting in

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place regulatory or fiscal mechanisms to promote their adoption, making national bailouts contingent on airlines meeting efficiency improvements in their new aircraft purchasing in excess of the current ICAO standards will be needed to limit the demand growth for jet kerosene once aviation activity picks up. National policy support for alternative fuels in domestic aviation could spur development of sustainable aviation fuel technologies and supply chains. Support could take the form of financial de-risking measures for project investment, low-carbon fuel mandates, dedicated volumetric, blend-in or carbon-intensity reduction mandates (such as the US Renewable Fuel Standards or the EU's Renewable Energy Directive and Fuel Quality Directive), market-based carbon policies on transport fuels (such as California's Low Carbon Fuel Standard) (IEA 2019c). If CORSIA ensures that both offsets and sustainable aviation fuels with robust lifecycle emission reductions are used for compliance, which could also make a real difference.

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References

Agility (2020), Ocean Freight Update: General Updates, www.agility.com/insights/COVID19/ocean-freight/.

Airbus (2019), Global Market Forecast 2019-2038, www.airbus.com/aircraft/market/global-market-forecast.html.

Airbus (2012), Saving fuel: It's a team sport (presentation), https://web.archive.org/web/20140326080413/http://www.iata.org/whatwedo/workgroups/Documents/MCC-2012-ATL/Day1/1150-1230-airbus-saving-fuel-team-sport.pdf.

Airlines for America (2018), Air travelers in America findings of a survey conducted by Ipsos, www.airlines.org/wp-content/uploads/2018/02/A4A-AirTravelSurvey-20Feb2018-FINAL.pdf.

AMF TCP (Advanced Motor Fuels Technology Collaboration Programme) (2020), Ammonia application in IC Engines - A literature review, https://iea-amf.org/content/publications/specialreports/special%20report%20on%20ammonia

Aviation Integrated Model (AIM) (2020), An open-source model developed by the University College London Energy Institute, www.ucl.ac.uk/energy-models/models/aim.

Becken, S. and P. Pant (2019), Airline initiatives to reduce climate impact: ways to accelerate action (white paper), https://amadeus.com/en/insights/white-paper/airline-initiatives-to-reduce-climate-impact.

Bloomberg (2020), Bloomberg Terminal Professional Service (accessed 28 February 2020).

Bockmann, M.W. (2020), Shrinking fuel oil spread cuts scrubber earnings premiums, https://lloydslist.maritimeintelligence.informa.com/LL1131354/Shrinking-fuel-oil-spread-cuts-scrubber-earnings-premiums.

Boeing (2019), Commercial Market Outlook 2019-2028, www.boeing.com/resources/boeingdotcom/commercial/market/commercial-market-outlook/assets/downloads/cmo-sept-2019-report-final.pdf.

BP (2018), Biojet set to take off as construction begins on waste-to-fuel plant, www.bp.com/en/global/corporate/news-and-insights/bp-magazine/construction-begins-on-waste-to-fuel-plant.html.

CCSA (Committee for the Coordination of Statistical Activities) (2020), How COVID-19 is changing the world: a statistical perspective, 2020, https://unstats.un.org/unsd/ccsa/documents/covid19-report-ccsa.pdf

CE Delft (2016), Historical Trends in Ship Design Efficiency, www.transportenvironment.org/sites/te/files/publications/2016_CE_Delft_Historical_Trends_in_Ship_Design_Efficiency.pdf.

Civil Aviation Authority (2019), UK Aviation Consumer Survey, publicapps.caa.co.uk/docs/33/CAP1831%20ComRes_CAA_UKACR_Wave%207_full%20report_v2.pdf.

IEA. All rights reserved.

CNBC (2015), How kites can save the planet – or the shipping industry, www.cnbc.com/2015/09/14/how-kites-can-save-the-planet--or-the-shipping-industry.html.

DNV-GL (2020a), Veracity, www.veracity.com/.

DNV-GL (2020b), Wind ships ahead, www.dnvgl.com/expert-story/maritime-impact/Wind-ships-ahead.html?utm_campaign=MA_20Q1_ART_Ind_190_Hard%20sail%20conce_Bul_Fer_Gas_MPV_Off_Tan_Yacht&utm_medium=email&utm_source=Eloqua.

DNV-GL (2019), ECO FLETTNER rotor sail stands the test, www.dnvgl.com/expert-story/maritime-impact/ECO-FLETTNER-rotor-sail-stands-the-test.html.

Dünnebeil, F. et al. (2015), Future measures for fuel savings and GHG reduction of heavy-duty vehicles, Federal Environment Agency (Germany), https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_32_2015_summary_future_measures_for_fuel_savings.pdf.

DVB Bank SE (2017), An Overview of Commercial Aircraft 2018-2019, www.dvbbank.com/~/media/Files/D/dvbbank-corp/aviation/dvb-overview-of-commercial-aircraft-2018-2019.pdf.

Filippone, A. (2012), Advanced aircraft flight performance (Cambridge Aerospace Series), Cambridge University Press, https://doi.org/10.1017/CBO9781139161893.

Holland, S. et al. (2015), Some inconvenient truths about climate change policy: The distributional impacts of transportation policies, Review of Economics and Statistics, Vol. 97 (5), pp. 1052-1069, https://doi.org/10.1162/REST_a_00452.

IATA (International Air Transport Association) (2020a), COVID-19 Outlook for air travel in the next 5 years (presentation), www.iata.org/en/iata-repository/publications/economic-reports/covid-19-outlook-for-air-travel-in-the-next-5-years/.

IATA (2020b), Recovery delayed as international travel remains locked down (press release), 28 July 2020, www.iata.org/en/pressroom/pr/2020-07-28-02/.

IATA (2020c), COVID-19 Outlook for the airline industry 2020-2021 (presentation), www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance-june-2020-presentation/.

IATA (2020d), Slower but steady growth in 2019 (press release), 6 February 2020, www.iata.org/en/pressroom/pr/2020-02-06-01/.

IATA (2019), Sustainable Aviation Fuels (fact sheet), www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-fact-sheet-2019.pdf.

IATA (2018), Climate Change & CORSIA (fact sheet), https://www.iata.org/contentassets/c4f9f0450212472b96dac114a06cc4fa/fact-sheet-climate-change.pdf.

ICAO (International Civil Aviation Organization) (2020), Technical Advisory Body recommendations on CORSIA eligible emissions units, www.icao.int/environmental-protection/CORSIA/Documents/TAB/Excerpt_TAB_Report_Jan_2020_final.pdf.

IEA. All rights reserved.

ICAO (2018), Forecasts of Scheduled Passenger and Freight Traffic, www.icao.int/sustainability/Pages/eap-fp-forecast-scheduled-passenger-traffic.aspx.

ICAO (2007; 2013-2018), Annual reports of the council. 2018 version available at: www.icao.int/annual-report-2018/Documents/Annual.Report.2018_Air%20Transport%20Statistics.pdf.

ICAO (2013), ICAO Environmental Report 2013: Aviation and climate change, https://cfapp.icao.int/Environmental-Report-2013/files/assets/common/downloads/ICAO_2013_Environmental_Report.pdf.

ICCT (International Council for Clean Transportation) (2020a), The climate implications of using LNG as a marine fuel (working paper), https://theicct.org/publications/climate-impacts-LNG-marine-fuel-2020.

ICCT (2020b), COVID-19's big impact on ICAO's CORSIA baseline, https://theicct.org/blog/staff/covid-19-impact-icao-corsia-baseline.

ICCT (2019), Turning the ship, slowly: Progress at IMO on new ship efficiency and black carbon, Staff blog, 21 May 2019, https://theicct.org/blog/staff/mepc74.

ICCT (2018), European heavy-duty vehicles: Cost-effectiveness of fuel-efficiency technologies for long-haul tractor-trailers in the 2025-2030 timeframe (white paper), https://theicct.org/sites/default/files/publications/ICCT_EU-HDV-tech-2025-30_20180116.pdf.

ICCT (2016), Cost assessment of near and mid-term technologies to improve new aircraft fuel efficiency, https://theicct.org/sites/default/files/publications/ICCT%20aircraft%20fuel%20efficiency%20cost%20assessment_final_09272016.pdf.

ICCT (2011), Indirect land-use change in Europe – considering the policy options (working paper), www.theicct.org/sites/default/files/publications/ICCT_iLUC-EU-options_Nov2011-1.pdf.

ICF (2020), COVID-19 air passenger recovery phases and forecast, www.icf.com/insights/transportation/covid-19-air-passenger-recovery-forecast.

IEA (International Energy Agency) (forthcoming), World Energy Outlook 2020, IEA, Paris.

IEA (forthcoming), Energy Efficiency Market Report 2020, IEA, Paris.

IEA (forthcoming), World Energy Outlook 2020, IEA, Paris.

IEA (2020a), Global EV Outlook 2020, IEA, Paris, www.iea.org/reports/global-ev-outlook-2020.

IEA (2020b), The Covid-19 Crisis and Clean Energy Progress, IEA, Paris, www.iea.org/reports/the-covid-19-crisis-and-clean-energy-progress/transport#abstract.

IEA (2020c), Energy Technology Perspectives Clean Energy Technology Guide, IEA, Paris, www.iea.org/articles/etp-clean-energy-technology-guide.

IEA (2020d), World Energy Balances, 2020, IEA, Paris, www.iea.org/reports/world-energy-balances-overview.

IEA. All rights reserved.

IEA (2019a), The Future of Hydrogen, IEA, Paris, www.iea.org/reports/the-future-of-hydrogen.

IEA (2019b), The Future of Rail, IEA, Paris, www.iea.org/reports/the-future-of-rail.

IEA (2019c), Are aviation biofuels ready for take-off?, IEA, Paris, www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off.

IEA (2017), The Future of Trucks, IEA, Paris, www.iea.org/reports/the-future-of-trucks.

IEA (2016), Energy and Air Pollution, IEA, Paris, www.iea.org/reports/energy-and-air-pollution.

IEA Bioenergy (2017), Biofuels for the marine shipping sector, https://www.ieabioenergy.com/publications/biofuels-for-the-marine-shipping-sector/

IFC (International Finance Corporation) (2020), The Impact of COVID-19 on Logistics, IFC, World Bank Group, www.ifc.org/wps/wcm/connect/2d6ec419-41df-46c9-8b7b-96384cd36ab3/IFC-Covid19-Logistics-final_web.pdf?MOD=AJPERES&CVID=naqOED5.

IMO (Internatyional maritime Organisation) (2014). Third IMO Greenhouse gas study 2014. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

IPCC (International Panel on Climate Change) (2006), IPCC Guidelines for National Greenhouse Gas Inventories, www.ipcc-nggip.iges.or.jp/public/2006gl/.

ITF (International Transport Forum) (forthcoming), ITF Transport Outlook 2021, OECD, Paris.

ITF (2019), ITF Transport Outlook 2019, OECD, Paris, https://doi.org/10.1787/transp_outlook-en-2019-en.

Krause, J., and A. Donati (2018), Heavy duty vehicle CO_2 emission reduction cost curves and cost assessment–enhancement of the DIONE model, EUR 29284 EN, ISBN 978-92-79-88812-0, http://dx.doi.org/10.2760/555936, JRC112013.

Lloyd's List (2020), Shipping's steady course toward decarbonisation, https://lloydslist.maritimeintelligence.informa.com/LL1132991/Shippings-steady-course-toward-decarbonisation.

Norris, J. and G. Escher (2017), Heavy Duty Vehicles Technology Potential and Cost Study. Final Report for the International Council on Clean Transportation (ICCT), Ricardo Energy & Environment, https://theicct.org/publications/heavy-duty-vehicles-technology-potential-and-cost-study.

Norsepower (2020), Technology, www.norsepower.com/technology.

OAG (Official Airline Guide) (2018), Origin-Destination of Commercial Flights (database), retrieved from: www.oag.com/analytics/traffic-analyser.

Oliver Wyman (2020), Update: Impact of COVID-19 on Commercial MRO www.oliverwyman.com/content/dam/oliver-wyman/v2/media/July_Update_Impact_of_COVID19_on_Commercial_MRO_2020.pdf.

Port of Los Angeles (2020), Alternative Maritime Power, www.portoflosangeles.org/environment/air-quality/alternative-maritime-power-(amp).

Schäfer, A.W., et al. (2019), Technological, economic and environmental prospects of all-electric aircraft, Nat Energy 4, 160–166, https://doi.org/10.1038/s41560-018-0294-x.

IEA. All rights reserved.

Shanghai International Shipping Institute (2020), Industrial Updates, http://en.sisi-smu.org/index.php?c=article&a=type&tid=43.

The Royal Society (2020), Ammonia: Zero-carbon fertiliser, fuel and energy store (policy briefing), https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf.

UNCTAD (United Nations Conference on Trade and Development) (2018), Review of maritime transport, https://unctad.org/en/PublicationsLibrary/rmt2018_en.pdf.

US EPA/NHTSA (United States Environmental Protection Agency and National Highway Traffic Safety Administration) (2016), "Greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles - phase 2", Federal Register, Vol. 81/206, www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

Velocys (2020), Velocys completes Red Rock Biofuels reactor order (press release), 3 August 2020, www.velocys.com/2020/08/03/velocys-completes-red-rock-biofuels-reactor-order/.

Verbeek, M. et al. (2018), Assessments with respect to the EU HDV CO_2 legislation, TNO 2018 P10214, https://publications.tno.nl/publication/34626415/j8AF3b/TNO-2018-R10214.pdf.

World Shipping Council (2020), How Liner Shipping Works (web page), www.worldshipping.org/about-the-industry/how-liner-shipping-works.

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Chapter 6. Clean energy innovation

- Innovation is an uncertain and competitive process in which technologies eventually pass through four stages: prototype, demonstration, early adoption and maturity. Size, modularity and synergies with other technologies are all attributes that determine the speed with which technologies pass through these stages. Governments have a particularly central and wide-ranging role to play in this process that goes far beyond the provision of funds for R&D.
- Achieving net-zero emission targets depends on strong and targeted R&D and innovation efforts in critical technologies. In the Sustainable Development Scenario, almost 35% of the cumulative CO_2 emissions reductions by 2070 compared with the Stated Policies Scenario come from technologies that are currently at the prototype or demonstration phase which will not become available at scale without further R&D. About 40% of the cumulative emissions reductions rely on technologies that have not yet been commercially deployed in mass-market applications.
- The Faster Innovation Case examines what would be needed in terms of even faster progress in clean energy technology innovation to deliver net-zero emissions globally by 2050 rather than 2070. CO_2 savings from technologies currently at the prototype or demonstration stage would be around 75% higher in 2050 than in the Sustainable Development Scenario, and about 45% of all emissions savings in 2050 would come from technologies that have not yet been commercially deployed, even on a very limited basis.
- A transition to net-zero emissions as in the Faster Innovation Case would further amplify the required pace and scale of technological change. The power sector would need to decarbonise sooner while generating additional electricity of nearly 20 000 TWh in 2050 relative to the Sustainable Development Scenario (a 35% increase) to support higher electricity demand, including higher need for hydrogen and synthetic fuels. Average annual renewable capacity additions to 2050 would be 770 GW, almost 50% above the Sustainable Development Scenario. Additional demand for alternative fuels would be almost 20% higher: hydrogen demand would rise by more than 50%, requiring nearly 50 GW of additional electrolyser capacity each year.
- Most of the additional decarbonisation effort in the Faster Innovation Case comes from electrification (accounting for 35% of additional emission cuts in 2050), CCUS (more than 25%) and bioenergy (more than 20%). In addition, the use of low-carbon hydrogen accounts for 30% of the additional emissions reduction from heavy industry.

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Introduction

As discussed in the preceding chapters, a rapid shift to net-zero emissions of greenhouse gases (GHG) is needed if we are to meet the energy-related United Nations Sustainable Development Goals. This requires the use of a wide range of clean energy technologies. Some are well established; others are at an early stage of development, or exist only as prototypes. Other technologies may emerge in due course from current research work. These clean energy technologies may also offer additional benefits including cleaner air and enhanced energy security as a result of, for example, improved electricity systems flexibility.

Success will not be easy or straightforward. It depends upon technological innovation, and this takes time: it has taken decades for solar photovoltaics (PV) and batteries to reach their current stage of development, for example. And not every technology that is developed will be successful; the evolution of existing and new technologies is inherently uncertain. But these points merely serve to underline the importance of finding ways to innovate that are successful in bringing about rapid change.

This chapter analyses the role of innovation in the Sustainable Development Scenario and highlights the need for an efficient innovation cycle to help countries reach net-zero emissions in the most cost-effective manner. It also analyses a Faster Innovation Case that explores just how much more clean energy technology innovation would be needed to bring forward the time at which the Sustainable Development Scenario reaches net-zero emissions from 2070 to 2050.

This chapter draws on the recent *Energy Technology Perspectives Special Report on Clean Energy Innovation*[1] with the aim of informing policy makers about the critical role that innovation plays in creating a cleaner and more resilient energy sector with net-zero emissions, and of setting out why the economic stimulus packages to address the impacts of the Covid-19 pandemic should include measures to accelerate clean energy innovation, including through support to research and development (R&D), demonstration projects and market diffusion. At the time of writing in mid-2020, it is too early to tell with certainty how lockdowns, damage to economic activity, or changed attitudes towards risk and values will impact clean energy innovation. However, some data are available for the first-half of 2020 which sheds light on early trends.

[1] *Energy Technology Perspectives Special Report on Clean Energy Innovation*, (www.iea.org/reports/clean-energy-innovation).

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Clean energy innovation and the vital role of governments

This report treats technology innovation as the process of generating ideas for new products or production processes and guiding their development all the way from the lab to mainstream diffusion into the market (IEA, 2020a). Each stage of the process involves funding risks, technical risks and market risks that are influenced by various social and political factors. As a result, only a minority of products ever make it all the way to mass market deployment.

The innovation journey of any given technology is evolutionary. Both radical and incremental advances can characterise the process of innovation. There are three main ways in which a technology evolves with experience to become better adapted to its environment, notably through improved cost and performance: learning-by-researching, learning-by-doing and achieving economies of scale. As the technology improves, it is more likely to be supported by research and development (R&D) funders and chosen by new users. This creates a virtuous cycle and so-called "increasing returns to adoption". However, in the early stages, when costs are usually higher than those of competitors, such feedback loops may be weak and it requires concerted and risk-taking investment to access the first market opportunities.

Choices about technology are made in an environment that is constantly changing as companies, consumers, policies, competing technologies, infrastructure and social norms change. Technologies can become more attractive to users for a variety of reasons. These include changes in related technologies, consumer behaviour and policy, and sometimes they include a change in the information available to users. Each of these variables can change in ways that cause a technology to be overlooked in favour of alternatives, or lead to a technology that was previously rejected finding new market opportunities. Governments and private sector actors raise their chances of successful innovation by simultaneously addressing the improvement of technology, for example through research, and of the selection environment, for example though regulation, advertising or the development of new business models.

Successful innovation systems involve a wide range of actors with aligned interests and a wide variety of functions, each of which can be enhanced by public policy (Gallagher et al., 2012). These functions can be grouped under four headings. An innovation system will struggle to translate research into technological change unless it is performing successfully under each.

- **Resource push:** There must be a sustained flow of R&D funding, backed by a skilled workforce and research infrastructure. These resources can come from private, public or even charitable sources.

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- **Knowledge management:** It must be possible for knowledge arising to be exchanged easily between researchers, academia, companies, policy makers and international partners.
- **Market pull:** The expected market value of the new product or service must be large enough to make the R&D risks worthwhile, which is often a function of market rules and incentives established by legislation. If the market incentives are high, then much of the risk of developing a new idea can be borne by the private sector.
- **Socio-political support:** There needs to be broad socio-political support for the new product or service, despite potential opposition from those whose interests might be threatened.

Successful new ideas pass through four stages… eventually

Innovation processes are rarely linear, and no technology passes all the way from idea to market without being modified. Their trajectories are influenced by feedback loops and spillover between technologies at different stages of maturity and in different applications, and often involve setbacks and redesign. It is nevertheless worth considering the four distinct stages through which all successful technologies eventually pass because each stage has different characteristics and requirements (Figure 6.1). These stages are relevant to all the different level of technology definition – type, design, component – but are most applicable to technology designs.

- **Prototype:** Following its initial definition, a new concept is developed into a design and then a prototype for a new device, a new configuration of existing devices or a new component to improve a product on the market. The probability of success at this stage is low, but the costs per project are also generally low.
- **Demonstration:** The first examples of the new technology are introduced into a given market at the size of a single full-scale commercial unit. Demonstration involves more time, cost and risk than the prototype stage. This phase is often referred to as the "valley of death", especially for large-scale, tangible technologies.
- **Early adoption:** At this stage, there is still a high cost and performance gap compared with existing technologies, but the technology is used by customers who want to try it out or need it for a particular purpose. This period represents a continuation of the valley of death and in many cases revenue from early niche markets does not cover costs. In cases where governments see a broader social, environmental or economic benefit from its wider diffusion, they may help, for example through discretionary procurement or financial support. Operating in a commercial environment means however that more of the costs and risks can be

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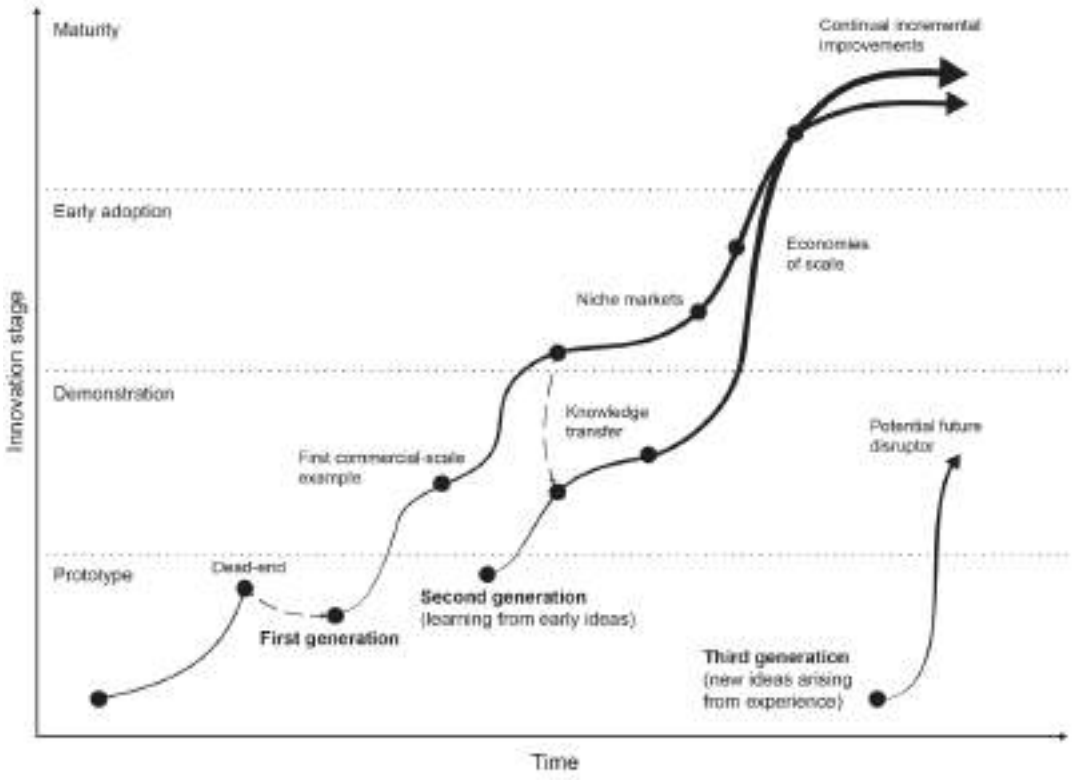
borne by the private sector, with competition driving down costs and encouraging refinements. As the number of niches grows, the technology arrives at a material share of 1% or more of the market it is seeking to address.

- **Maturity:** As deployment progresses beyond materiality to maturity, the product moves into the mainstream for new purchases and may even start to compete with the stock of existing assets. Incremental learning-by-doing continues during this stage, as feedback from engineers and users stimulates new ideas for more radical enhancements to be prototyped. A dominant design has become accepted and the risks are generally familiar enough for private investors to bear.

Throughout the early adoption and maturity stages, innovation continues to improve the technology. In some cases, significant discontinuous improvements occur long after market deployment has started, as for example with lithium-ion (Li-ion) batteries for electric vehicles. In other cases, technologies reach a point where only very incremental changes are expected from continuous learning processes, as for example with large hydropower plants.

Figure 6.1 Four stages of technology innovation, feedbacks and spillovers that improve successive generations of designs



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Successful technologies eventually pass through four stages of innovation, with R&D contributing improvements and spurring ideas for novel prototypes at each stage.

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The role of governments and other actors in innovation systems

At each stage of the energy innovation journey, a variety of public and private sector actors, including not-for-profit research institutions and funders, play essential roles.[2] For all actors, competition is a major driver of energy innovation. Firms of all sizes have incentives to refresh their offerings to customers to increase market share and to avoid losing out to competitors with cheaper or better performing products. Countries also often compete to secure investment and market share for companies and workers.

The role of governments is particularly crucial. It encompasses educating people, funding R&D, providing network infrastructure, protecting intellectual property, supporting exporters, buying new products, helping small and medium-size enterprises, shaping public values, and setting the overall regulatory framework for markets and finance (Hekkert et al., 2007; Bergek et al., 2008; Grubler et al., 2012; Roberts and Geels, 2018; Kim and Wilson, 2019). The essential justification for public intervention in innovation is that new ideas and technologies are undersupplied by the market – a so-called public goods market failure that arises because companies prioritise those activities and expenditure from which profits are most certain. In particular, radical new concepts, or "disruptive" technologies, often arising from basic scientific research, are rarely supplied by incumbent companies, which tend to focus on incremental improvements to their existing technology portfolio (OECD, 2015). Disruptive technologies can be of particular importance in relation to social or environmental outcomes that are desired by governments but have low market value.

Evidence suggests that the productivity of corporate research is increasingly dependent on ideas arising from publicly funded R&D (Fleming et al., 2019). Public funding for energy R&D may well stimulate more private sector spending, not less (Nemet and Kammen, 2007). A mechanistic description of how governments fill gaps left by the private sector underplays their ability to make things happen. They have in the past used their powers to set incentives for, and work with, the private sector to deliver desirable outcomes: examples include space exploration, vaccines and nuclear power. It is increasingly recognised that many of the biggest clean energy technology challenges could benefit from a "mission-oriented" approach (Díaz Anadón, 2012; Mazzucato, 2018). Support for industrial clusters, strategic use of public procurement and investment in enabling infrastructure could all play a part in such an approach, increasing the probability of innovation success.

[2] For more details, see the *Energy Technology Perspectives Special Report on Clean Energy Innovation*, (www.iea.org/reports/clean-energy-innovation).

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History underlines the importance of R&D at the start of the innovation journey, and the key role of governments around the world in helping major new technologies achieve success.

Covid-19: A threat or an opportunity for clean energy technology innovation?

The Covid-19 pandemic has delivered a brutal shock to countries around the world. By mid-May 2020, around one-third of the global population was under full or partial lockdown. Assuming that containment measures are gradually phased out during the second-half of the year, the global economy is expected to contract by around 6% in 2020; this would be the largest economic dip since the global depression of the 1930s (IEA, 2020b).

Technology innovation is a driver of structural change. New technologies outcompete older ways of doing things and bring new services to society, attracting investment at each stage. Evidence suggests that clean energy technology innovation brings particular economic benefits, as well as being essential for the creation of a more sustainable energy system (Aghion et al., 2016). While the macro relationship between jobs and R&D expenditure is complicated, other studies suggest that R&D that supports new high-tech products is correlated with increased employment (Calvino and Virgillito, 2017).

Worldwide, some 300 million full-time jobs could be lost as a result of Covid-19, and nearly 450 million companies are facing the risk of serious disruption. Clean energy innovation is labour intensive: we conservatively estimate that over 750 000 people are currently employed in energy R&D around the world, representing 1.5% of the approximately 40 billion workers in the global energy system, with half of these jobs being in China, France, Germany, Japan and United States. If these workers are lost to the sector, it will be hard to build up the expertise associated with them again: it takes many years to acquire the specialist skills and experiences necessary to identify technology needs, formulate improved concepts and build the teams to test them.

There are several ways in which clean energy innovation jobs and outputs are threatened by the Covid-19 pandemic. These include pressures on public and private budgets, a riskier environment for clean energy venture capital and disrupted global supply chains (see next section). Public R&D is expected to hold up better than private R&D, and there is a reasonable chance that the governments of major economies will seek to boost innovation funding in response to the crisis. Companies face lower revenues and a lack of cash flow for capital investment to meet near-term growth targets, but there is little sign of those who have made commitments to reduce their emissions intensity and test new energy technologies seeking to back away from those commitments. For a rapid assessment of the likely impacts of Covid-19 on their ability to support innovation towards longer term goals, we surveyed

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industrial contacts in May 2020. Responses indicated no change in long-term commitments and an expectation that R&D budgets would be resilient, but overall sentiment about the impact on the full range of innovation activities was gloomy.[3]

The second-half of 2020 presents a unique opportunity to double down on clean energy innovation. While near-term responses to the crisis have understandably focused on mitigating health, employment and liquidity risks, attention is now turning to the speed of the recovery, creation of new jobs and the future shape of the economy. New players with new ideas aiming to displace high-carbon producers and to scale-up quickly may find a supportive environment if they are able to enter the market at the right moment. Economic stimulus plans now being proposed in countries around the world offer a once-in-a-generation opportunity to boost clean energy technology innovation. Many of the sectors that are critical to achieving net-zero emissions have investment cycles of many decades, so there is no time to lose.

Global status of clean energy innovation in 2020

A clean energy transition to net-zero emissions requires a radical change in both the direction and scale of energy innovation. However, not all of the many characteristics of a national innovation system that is designed to support net-zero emissions can be tracked closely using data available today, and there are further indicators of healthy innovation systems that are even less quantifiable (IEA, 2020a). Despite this, a picture of the performance of clean energy innovation systems can be constructed using information that is available across the four pillars described in the previous section. At the more general level of the whole economy, this type of approach is followed for the Global Innovation Index, which aggregates 80 indicators (Cornell University, INSEAD and WIPO, 2018).

The IEA has developed methodologies for tracking a number of key indicators of "resource push" factors and intermediate outputs for clean energy innovation on an annual basis. While it is important to remember that this set of indicators presents only a partial view based on data available at the global level, it nevertheless offers an important insight into the level of innovation effort around the world. There is scope for it to be expanded in the future.[4]

[3] For more details on the results of this survey, see *Energy Technology Perspectives Special Report on Clean Energy Innovation*, (www.iea.org/reports/clean-energy-innovation).

[4] Better quality data on demonstration projects, technology-level corporate R&D, component-level import-export trends, public sentiment and bilateral energy innovation collaborations would be valuable additions: so would much-needed improvements to data quality for public energy R&D spending.

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There are benefits for policy makers and investors in such tracking activities. In the early 1990s, few analysts attempted to assess the efforts dedicated to developing solar PV and Li-ion batteries and their technical progress: better data might have helped governments allocate resources more effectively and accelerated the development of these technologies. At a national or regional level, more granular analysis is sometimes already possible (Wilson and Kim, 2019).

Government R&D funding

Worldwide government energy-related R&D spending in 2019 increased by 3% to USD 30 billion, around 80% of which was directed to low-carbon energy technologies. While the growth rate in 2019 was below that of the previous two years, it remained above the annual average since 2014. In China, the low-carbon component of energy R&D rose by 10% in 2019, with big increases in R&D for energy efficiency and hydrogen in particular. In both Europe and the United States, spending on public energy R&D rose by 7%, an increase that is above the recent annual trend.

Raising public energy R&D spending and aligning it more closely with decarbonisation needs was behind the pledge made in 2015 by 24 leading countries and the European Commission to double their public investment in clean energy R&D over five years under the Mission Innovation initiative.[5] Governments of major economies have been increasing energy research investments since then, with some countries including India making clear links between their R&D activity and their membership of Mission Innovation.

The IEA has maintained a consistent dataset of national public budgets allocated to energy R&D since the 1970s.[6] When adjusted for inflation, these data show that spending on low-carbon energy R&D in IEA member countries almost doubled between 2000 and 2012, but has been broadly stable since (Figure 6.2). However, it remains just below the levels observed in the early 1980s, when nuclear energy research dominated the national budget in several countries. In absolute terms, R&D spending on fossil fuels has remained roughly constant, though its share of total energy R&D has fallen with growth in total spending (except for 2009).

[5] Definitions of clean energy and the precise types of spending to be doubled vary between countries.

[6] Based on national data submissions, the dataset covers IEA member countries plus the European Union and is open to any country wishing to participate. Its scope includes spending allocated to demonstration projects as well. In general, countries report energy-specific research programme spending regardless of the sponsoring government department, but differ in reporting budgets versus actual spending, and the extent to which they include basic research on energy-related topics or demonstration project funds (IEA, 2020d). While basic energy research is sometimes managed by funding institutions with oversight for energy technology, for example in the United States, in many other countries this research is not isolated and reported as such. Given the outsized importance of publicly funded R&D in the basic sciences, which leads directly to the breakthroughs that underpin new energy technologies and start-ups, it is likely that reported data underestimate total spending. Tax exemptions, loans and general support to innovative energy technology companies are not included (IEA, 2011).

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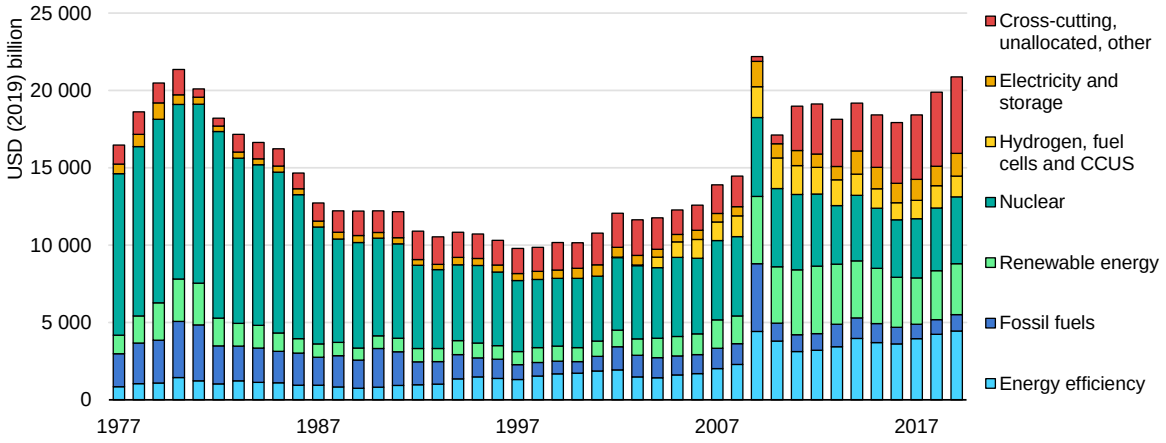
Figure 6.2 Public energy technology R&D and demonstration spending by IEA member governments by technology, 1977-2019



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Notes: CCUS = carbon capture, utilisation and storage. Peak in 2009 was due to post 2007-08 financial crisis stimulus funding, especially in the United States.

Source: IEA (2020d).

IEA member government R&D spending, which goes mostly to low-carbon technologies, has been broadly flat since 2012 after having doubled over the previous decade or so.

The technology portfolio in public energy R&D is more balanced today than in previous decades, with far more money going to energy efficiency and renewables.[7] Despite this, the portfolio remains strongly oriented towards supply-side technologies rather than the types of end-use innovations needed for sectors that currently have no commercially available and scalable options for achieving deep emissions reductions. Furthermore, although energy R&D budgets are growing in the aggregate, including for developing low-carbon technologies, they are not growing as a share, and they account for a shrinking share of total government R&D spending in most cases.

Private sector R&D funding

Companies active in energy technology sectors have increased their total annual energy R&D spending by around 40% over the last decade (IEA, 2020c); their total energy R&D spending reached around USD 9 billion in 2019. In 2019, growth was 3%, lower than the 5% annual growth observed in the two periods 2010-13 and 2015-18, which were preceded by the global financial crisis and divided by the economic impact of the oil price collapse of 2014. That oil price collapse caused a 10% decline in the R&D spending of oil and gas companies over two years, and it took four years for spending to recover.

[7] Precise comparisons are difficult due to the rising levels of spending that are not allocated to a particular technology application or are allocated to cross-cutting projects, which include research that cannot be allocated to a specific category, such as systems analysis or joint research on the integration of energy sources into networks or end-uses.

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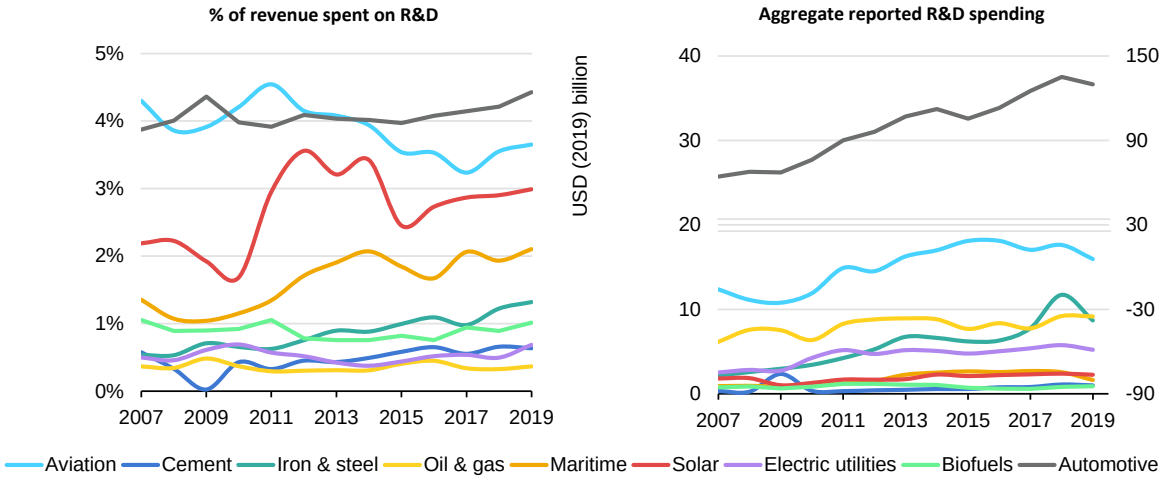
It is worth noting that companies active in renewable energy technologies have increased their R&D spending faster than other energy technology sector companies. They increased their expenditure on R&D by 74% between 2010 and 2019, adding over USD 2.5 billion to efforts to improve renewable energy technologies.

The automotive sector spends more on R&D than any other that relies heavily on energy (Figure 6.3).[8] Companies have continued to increase their spending in recent years, with government policies and competitive pressures leading them to focus more on energy efficiency and electric vehicles: growth in energy-related R&D seems, however, to have flattened between 2018 and 2019. New companies, especially those making battery and fuel cell electric vehicles, meanwhile are starting to enter the market and trying to dislodge the major manufacturers.

Figure 6.3 Global corporate R&D spending as a share of revenue in selected sectors, 2007-19



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Notes: Includes companies reporting 50% or more of their revenue in these sectors, per Bloomberg Industrial Classification System (BICS), and for which both reported R&D and revenue data are available in a given year. Total R&D expenditure (not only energy-related R&D) is scaled by the company's revenue share in the reported sector. Automotive is shown on the right-hand axis in the chart of aggregate reported R&D spending. Like other classifications such as International Standard Industrial Classification (ISIC) and the classification of economic activities issued by the European Commission. Acronym NACE comes from French (Nomenclature statistique des activités économiques dans la Communauté européenne), BICS provides a structure for analysing data related to different economic activities. It is used here because of the high degree of disaggregation of firm-level data for energy-related sectors.

Source: Bloomberg LLP (2020).

Some sectors for which new technologies will be critical to net-zero emissions typically reinvest a small share of their revenue in R&D, while auto companies markedly outspend other sectors.

[8] Information and communication technologies (ICT) are increasingly important to clean energy transitions, and are also enabling productivity gains in fossil technologies, but this sector is not included here as its outputs are not energy-specific.

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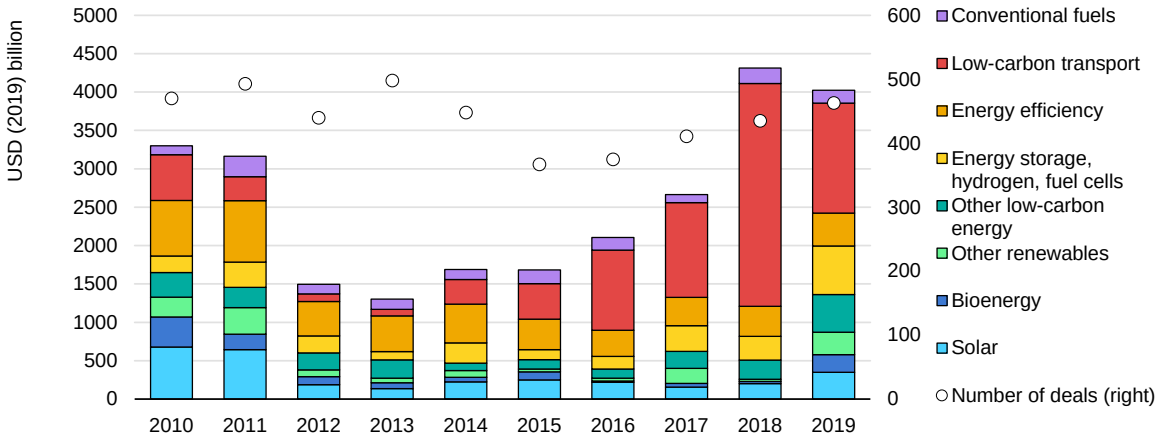
Other sectors that are heavy users of energy – notably cement, biofuels, electric utilities, and iron and steel – invest much less in R&D as a proportion of their revenue. Solar PV manufacturers, maritime and aviation sectors invest rather more than these, but still much less than the automotive sector. This may reflect a view that new technology-driven products are of less importance to their competitiveness than is the case for automakers. Electric utilities and heavy industrial companies are generally consumers of technology, typically engaging in technology development via partnerships with suppliers. Nonetheless, it is striking that companies in sectors for which new technologies will be critical to achieving net-zero emissions typically invest relatively little in R&D. These sectors will need to test, modify and, in some cases, develop new processes and products for deep decarbonisation.

Venture capital

Total equity investment in energy technology start-ups by all investor types stood at USD 16.5 billion in 2019. Of this, early-stage venture capital (VC) (seed, series A and series B), which supports innovative firms through their highest risk stages, is estimated to account for USD 4 billion (Figure 6.4). These sums are lower than those spent on energy-related R&D by governments and companies, but this private risk capital plays an important role in helping the most market-ready technologies to create markets and scale-up. The total value of reported deals in 2019 was 7% lower than in 2018, but the figure in both years was well above the average for the decade.

Figure 6.4 Global early-stage venture capital deals for energy technology start-ups



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Notes: Transport includes alternative powertrains and their infrastructure, but does not include shared mobility, logistics or autonomous vehicle technology. Bioenergy does not include biochemicals. Other low-carbon energy includes CCUS and smart grids. Conventional fuels include fossil fuel extraction and use, and vehicle fuel economy. Includes seed, series A and series B financing deals. Outlier deals of over USD 1 billion that distort the year-on-year trend are excluded; they totalled USD 1.6 billion in 2016, zero in 2017, USD 2.1 billion in 2018 and zero in 2019.

Sources: IEA calculations based on Cleantech Group (2020).

Venture capital investment remained robust in 2019, with investments spread more evenly between sectors than in recent years. Storage and hydrogen saw the most growth.

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Venture capital fulfils a valuable role by providing finance and imposing the discipline of private capital in cases where its providers see a potential near-term market opportunity and a longer term chance to capture significant market share. VC investors provide risk capital to entrepreneurs in the expectation that the winners in a portfolio of technology and business ideas will scale-up rapidly and profitably enough to pay back their investments in the whole portfolio at around 20% per year over five years. In the energy sector, venture capital has typically been most effective in supporting start-ups with digital technologies or service offerings that can be quickly prototyped and are not capital intensive (Gaddy, Sivaram and O'Sullivan, 2016; IEA, 2017). Hardware areas like electricity storage, electric vehicles and hydrogen production, however, have recently attracted more VC investment (IEA, 2020c).

To boost activity, some governments are exploring direct investment in clean energy start-ups, for example by taking so-called "anchor" equity stakes in riskier start-ups. Breakthrough Energy Ventures Europe, a USD 100 million fund established in 2019, is an example (Breakthrough Energy, 2020). Some governments provide targeted grant support to clean energy start-ups instead. Companies, too, are starting to include venture capital in their energy innovation strategies. Faced with regulatory and technological uncertainty, especially in areas dominated by unfamiliar or digital products, they are increasingly turning to corporate venture capital[9] and "open innovation" rather than allocating corporate R&D budgets to developing them in-house (Bennett, 2019).

Patenting

Following a decade of strong growth in the number of patents filed for low-carbon energy technologies, there has been a marked decline since 2011 (Figure 6.5). Patents provide an insight into the research activities that are generating new knowledge with perceived commercial value: they capture some of the intermediate outputs of R&D, a proportion of which will be translated into commercial products. They do not provide a direct measure of all R&D outputs, not least because they over-represent technologies and jurisdictions where patenting is more common: moreover in some fast-moving fields, the patenting process can take longer than the opportunity to recoup R&D costs from marketing the technology ahead of the competition, while

[9] Corporate VC is a subset of venture capital involving equity investments in start-ups that are developing a new technology or services by companies whose primary business is not venture capital nor other equity investments. In addition to playing the traditional role of a venture capital investor, corporate VC investors often provide support to the start-ups via access to their customer base, R&D laboratories and other corporate resources. Corporate VC in the energy sector has been around since the mid-20th century, when Exxon Enterprises invested in a variety of technologies, including solar, as part of a diversification strategy.

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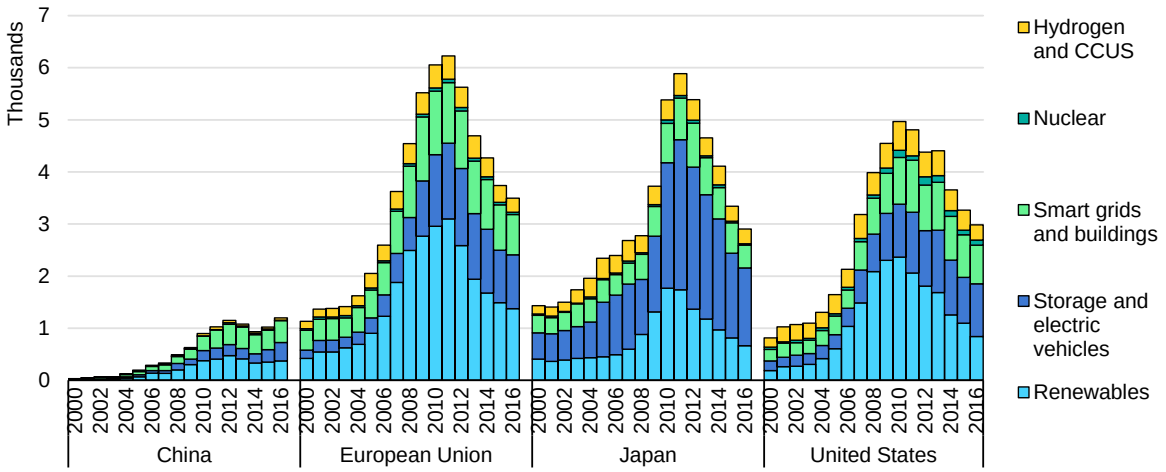
many digital services based on software and apps are not patentable. Nonetheless, overall trends in patenting provide useful information about the extent and focus of clean energy innovation.

Figure 6.5 Issuance of patents for low-carbon energy technologies in selected countries/regions



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Notes: CCUS = carbon capture, utilisation and storage.

Patent count refers to the number of granted international patent families that include at least two geographical offices. Counts are allocated to countries based on the country of the inventor.

Source: OECD (2020).

Following a decade of strong growth in patents for low-carbon energy technologies, there has been an almost uninterrupted slowdown since 2011.

The decline in renewable energy patenting activity since around 2011 may in large part reflect the maturity of some technologies. The dominance of existing solar PV, ethanol and wind technologies may deter researchers from seeking to improve them and enter the market in Europe, Japan and the United States. Patenting activity for renewable energy remains higher than at any time before around 2007 and patenting for batteries, particularly Li-ion, is a growth area (EPO and IEA, 2020). However, it is still a concern that the decline in patenting since 2011 has so far not been offset by patents in advanced biofuels, novel PV, geothermal, ocean or other renewables.

The adoption of some low-carbon technologies relies on the development of other non-energy technologies in the same value chain. However, patent trends indicate that the level of attention to different technology applications in the same value chain is not consistent.

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Potential impact of Covid-19 on clean energy innovation

Before the pandemic hit, 2020 was expected to be a critical year for several major energy innovation policy initiatives, with keen interest in the details of the European Union's Horizon Europe and Innovation Fund, for example, and in the energy R&D elements of China's 14th Five-Year Plan. These policies, and many others in preparation around the world, are still of great interest, but the immediate focus has shifted to managing revenue losses and economic recovery in most countries. At the same time, many companies are facing severe pressures, and all are having to adjust to a changed and uncertain economic outlook.

While the immediate task of protecting health and livelihoods understandably occupied all parties in the first months of the Covid-19 pandemic, measures that directly or indirectly address clean energy innovation have nevertheless already featured in the policy responses of several governments. Details are still emerging, and other governments are considering their positions; even so, these policy signals help to give at least an initial idea about how the environment for clean energy technology might evolve between mid-2020 and 2025.

The overall picture that emerges from the policy announcements and the data presented in this section is that of a seriously weakened innovation system, with demonstration, market entry and learning-by-doing suffering most in the first instance. Sectors that currently have few commercially available and scalable low-carbon options could face even longer delays in making progress on clean energy innovation. Although emerging economies have yet to publish economic stimulus plans, many of them are likely to be facing particularly significant pressure on their R&D budgets. The evidence so far suggests a systemic challenge: although the risks to basic R&D and prototyping may be lower in the near term, their impact will be diminished if the system as a whole has less capacity to make good use of them.

Government R&D funding

While it is too early to determine the impact of the Covid-19 pandemic on public energy R&D, the outlook is an uncomfortable one. In many cases, the relevant budgets may be fixed for the next couple of years, and the budgetary pressures may be strongest in the period 2022-25. This seems to be what happened in the years following the 2007-08 financial crisis. In Europe, for example, R&D budgets significantly decreased in 2011-13, with the decreases beginning three years after the financial crisis, and being particularly significant in those countries with the deepest recessions (Izsak et al., 2013). It is worth noting, however, that several major countries turned to R&D policy as a way to reduce reliance on the financial sector after 2008-09 and introduced new types of innovation instruments, such as guarantees, loans and support for venture capital. This is consistent with policies in these countries to

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pursue counter-cyclical R&D policy, but it is not an option that is available to all governments (OECD, 2009; Pellens et al., 2018).

Emerging economies like Brazil and India, which have recently been raising their ambitions to develop indigenous clean energy technologies, may suffer setbacks unless they can tap into additional budget resources. As emerging economies represent most of the projected growth in energy demand in the coming decades, what they decide has important implications for the clean energy transition as a whole. A prolonged downturn in any country would also carry the risk of the loss of highly skilled and highly mobile staff.

Private sector R&D funding

Corporate R&D is highly likely to be cut or to grow much more slowly in most energy-related sectors as a result of lower revenues in 2020 and beyond. This impact is already evident in company reports for the first-half 2020, with companies representing a large share of global revenue in the automotive, aviation and chemicals areas spending less on R&D than in previous years. Reductions were seen in all sub-sectors, with some declines of around 8%. This matches the perceptions of respondents to our survey in May 2020, which anticipate pressure on corporate R&D budgets for key net-zero emissions technology areas for the rest of 2020 and into 2021.

The financial crisis of 2007-08 and the oil price collapse of 2014 provide some insight into the likely response of companies to the impacts of the Covid-19 pandemic. In 2009-10, the total R&D spending in major energy sectors held up well relative to revenues, with the exception of the automotive sector (Figure 6.6). However, in absolute terms, the electricity supply and renewables sectors were the only energy areas not to experience slower growth in R&D or cuts to R&D budgets in this period. As in 2009, the outcome related to the Covid-19 crisis will be heavily influenced by government policies: for example, tax incentives and R&D-specific loans being proposed for inclusion in some stimulus packages should be helpful. It is also worth noting that there is some evidence that recessions can create opportunities for companies to reorient to disruptive technologies (Archibugi et al., 2013).

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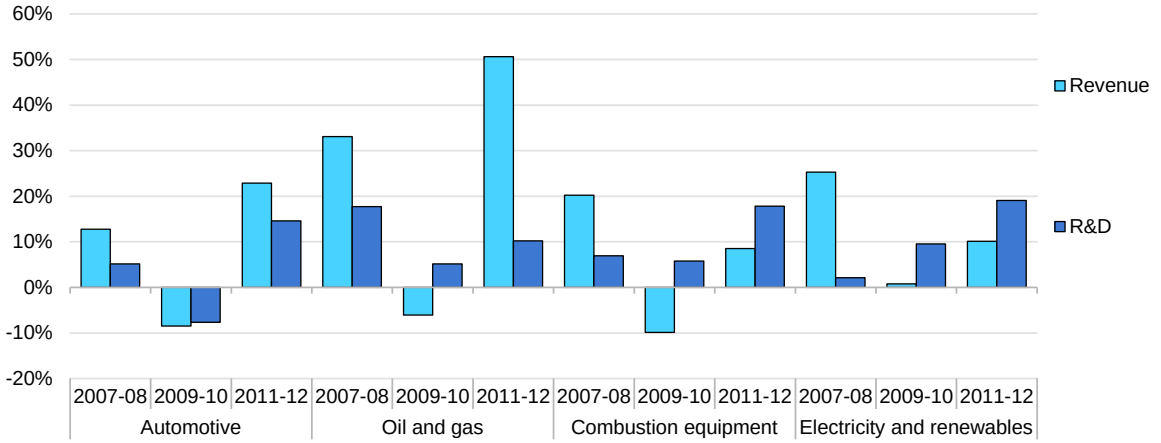
Figure 6.6 Growth rates for revenue and R&D for selected sectors, 2007-12



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Note: Shows average annual growth rates per pairs of years for the top 20 R&D spenders per sector that reported data in each year.

Source: IEA calculations based on Bloomberg LLP (2020).

Total R&D spending of key energy sectors grew more slowly in 2009-10 than before the 2007-08 financial crisis, with a decline in the automotive sector; electricity and renewables were an exception.

Venture capital

Early-stage venture capital energy deals decreased by about 20% in the first-half of 2020 relative to 2019 levels. Global declines are expected in the second-half of 2020 as a result of financial risks, travel, and other restrictions and policy uncertainty. If growth equity is included, a global decline in the first-half of 2020 is also visible in the data (Figure 6.7).

It is widely recognised that many start-ups and innovative will struggle to stay afloat and will face cash flow and debt challenges, leading to lay-offs and losses of energy technology experts. Other start-ups may have to sell shares in their companies at a low price. Young companies developing capital-intensive technologies, such as those needed in many sectors that currently have limited commercially available and scalable low-carbon options, may be less attractive to VC investors if market conditions reduce investor willingness to wait for financial returns. This could put a brake on financing for innovative entrepreneurs at a time when several major governments are seeking to rely more heavily on VC financing to bring clean energy technologies to market.

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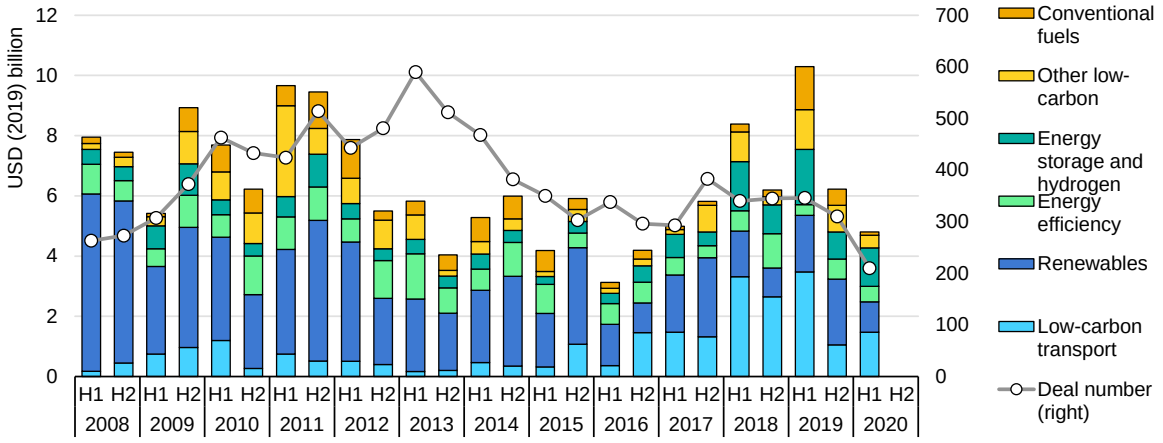
Figure 6.7 Value and number of global energy-related venture capital deals (early and late stage) by semester and year



Notes: H1 = first-half of the year; H2 = second-half. Transport includes alternative powertrains and their infrastructure, but does not include shared mobility, logistics or autonomous vehicle technology. Renewables includes bioenergy but not biochemicals. Other low-carbon includes CCUS and smart grids. Conventional fuels includes fossil fuel extraction and use as well as vehicle fuel economy.

Includes seed, series A, series B, grants, growth equity, buyout and late-stage private equity, coin/token offering and private investment in public equity financing deals. Deals reported in the last week of June 2020 are not counted. Outlier deals of over USD 1 billion that distort the year-on-year trend are excluded; they totalled USD 2 billion in 2008, USD 1.9 billion in 2009, USD 1 billion in 2010, USD 3.5 billion in 2011, USD 4.8 billion in 2012, USD 7.9 billion in 2013, USD 6.4 billion in 2014, USD 1.3 billion in 2015, USD 1.6 billion in 2016, USD 3.9 billion in 2017, USD 9.4 billion in 2018, USD 1.3 billion in 2019 and USD 1.2 billion in 2020.

Sources: IEA calculations based on Cleantech Group (2020).

The first-half 2020 saw half as much energy-related venture capital activity (early and late stage) as in the same period in 2018-19; high-value later stage fundraising rounds were affected most.

Innovation needs in the Sustainable Development Scenario

Technological change – the development and diffusion of technology to meet growing demand or displace existing energy assets – drives the clean energy transition in the Sustainable Development Scenario. Most of the capital stock that makes up today's energy system, from supply to end-use, will need to be adapted or transformed to reach the goal of net-zero emissions. To reach net-zero emissions globally in five decades, major reductions in cost and improvements in performance will be needed in a wide range of technologies already in use or in the early stages of development.

Developing a new technology and successfully bringing it to market is typically a long process. Technologies go through a journey in which they evolve from a concept to a prototype, are demonstrated at scale and, if successful, are adopted and commercialised more widely. Given that we cannot predict the emergence of

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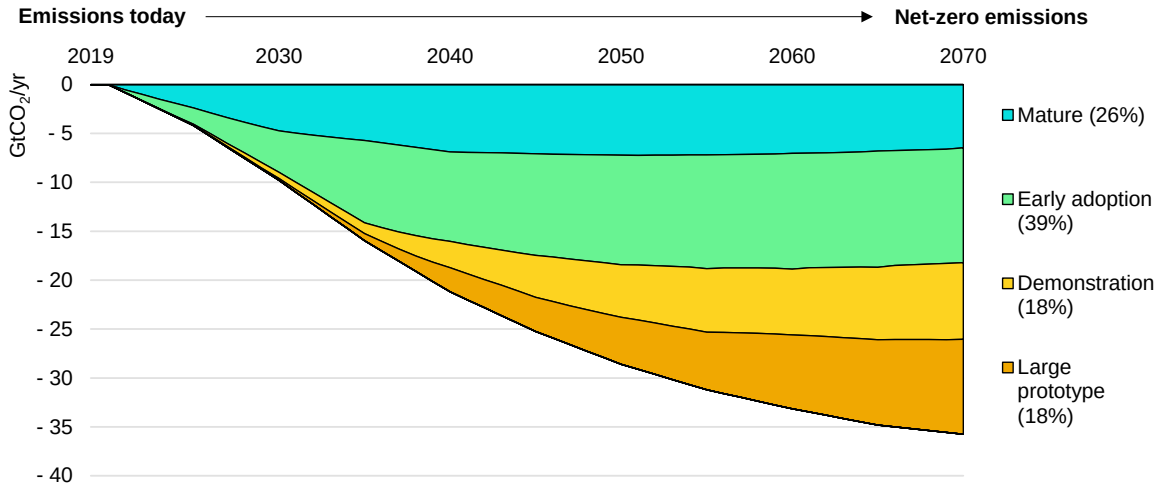
technologies that are not known today or which ideas might prove successful, the portfolio of energy technologies in the Sustainable Development Scenario includes those for which at least a large prototype is already proven today and the pathway to commercial scaling-up is understood, which means that that basic information on potential technology performance and costs is available. There are, nonetheless, a variety of factors that could delay or disrupt the clean energy transition in practice, including unexpected future events and the hard-to-predict responses of companies, investors and governments to such events.

Almost 35% of the cumulative carbon dioxide (CO_2) emissions reductions achieved by 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario come from technologies that currently are at large prototype or demonstration phase, and around 40% from technologies that have not yet been commercially deployed on a large scale (Figure 6.8). The contribution of technologies at large prototype or demonstration stage to emissions reductions is even higher in heavy industry and long-distance transport, where commercially available and scalable options for achieving deep emissions reductions are currently limited.

Figure 6.8 Global energy sector CO_2 emissions reductions by current technology maturity category in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-70



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Notes: $GtCO_2$ = gigatonnes of carbon dioxide. Percentages refer to cumulative emissions reductions by 2070 between the Sustainable Development Scenario and the Stated Policies Scenario enabled by technologies at a given level of maturity. See Box 2.6 in Chapter 2 for the definition of the maturity categories: large prototype, demonstration, early adoption and mature.

Technologies that are only at the large prototype or demonstration stage today contribute almost half of the emissions reductions in 2070 in the Sustainable Development Scenario.

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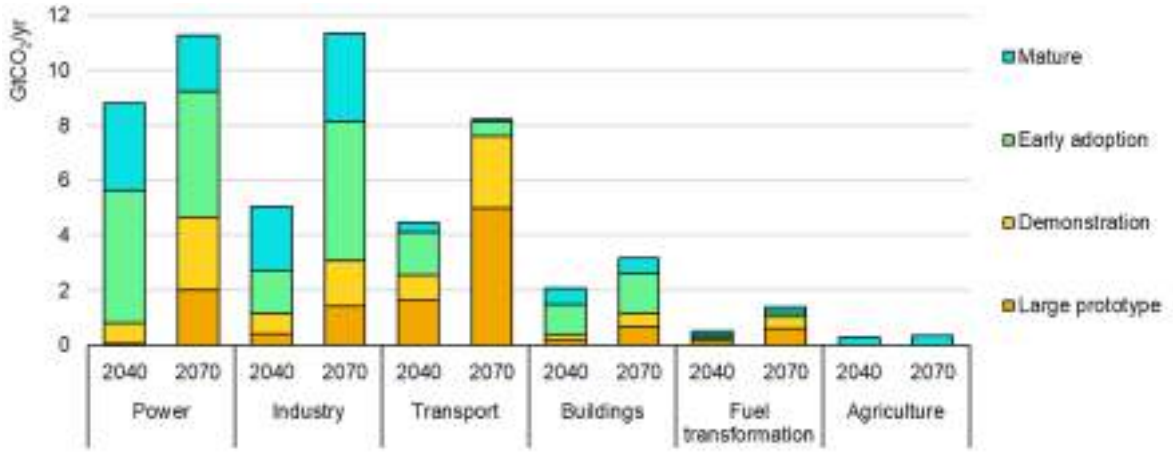
The share of emissions reductions in the Sustainable Development Scenario attributable to each technology maturity category varies between sectors (Figure 6.9). In the transport sector, the bulk of the emissions reductions in 2070 in the Sustainable Development Scenario result from technologies that have not reached markets today. This is because significant electrification of heavy-duty vehicle fleets depends on advances in high-energy density batteries which go beyond Li-ion chemistries and which are at an early stage of development today, and because reducing emissions in long-distance transport depends on deployment of alternative fuels. In industry, the contribution to emissions savings from technologies at large prototype, demonstration or early adoption stage today triples between 2040 and 2070 in the Sustainable Development Scenario as today's long-lived industrial assets come to the end of their lives during that period. These changes in demand sectors trigger innovations in energy supply, for instance in the provision of alternative clean fuels at scale. Negative emissions technologies that are at demonstration or prototype stage today also make significant contributions in the long term to the achievement of net-zero emissions.

Figure 6.9 Global CO_2 emissions reductions by current technology maturity category and sector in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2040 and 2070



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Notes: $GtCO_2$ = gigatonnes of carbon dioxide. See Box 2.6 in Chapter 2 for the definition of the TRL categories large prototype, demonstration, early adoption and mature.

Emissions reductions enabled by technologies that are at large prototype or demonstration stage today increase more than threefold between 2040 and 2070 in the Sustainable Development Scenario.

The critical role of innovation in the Sustainable Development Scenario highlights the need for an efficient innovation cycle to reach net-zero emissions in the most cost-effective manner. The speed at which energy-producing and energy-consuming equipment would have to be replaced and new technologies introduced in the

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Sustainable Development Scenario is as fast as has ever been seen in the history of energy. For those technologies at an early stage of development today, diffusion time would need to be reduced by several decades compared with historical averages. This clearly indicates that clean energy innovation needs to be shielded from any potential disruption from the Covid-19 crisis to increase the chances of achieving net-zero emissions.

Box 6.1 Potential negative impacts of Covid-19 on clean energy innovation – Reduced Innovation Case

Clean energy innovation has the potential to play a major part in reshaping the future energy sector. However, the Covid-19 crisis could jeopardise progress if governments respond to it by reducing R&D spending and financial support to demonstration projects, and by being deflected from action to achieve long-term climate goals.

In the Reduced Innovation Case, we explore the impact that a slowdown in the pace of innovation could have on direct electrification, CCUS, and hydrogen and hydrogen-derived fuels, which together account for about 40% of the cumulative emissions reductions in the Sustainable Development Scenario until 2070 relative to the Stated Policies Scenario.

The Reduced Innovation Case assesses the implications of two key assumptions:

- For demonstration projects that are either underway or announced, we assume a five-year delay in their completion.
- For technologies at early adoption phase, we assume a slowdown in the pace of deployment of 50% through to 2025, 30% to 2030 and 15% to 2040.

It is uncertain what effect the Covid-19 crisis will have on adoption rates and development plans for electric technologies. Given the higher levels of risks associated with the development plans of technologies at small prototype or below, we focus our analysis of the impact of delayed progress on those technologies at the early adoption stage, and in particular on heat pumps and electric road vehicles.

A slower uptake of heat pump designs that are already commercial combined with a five-year delay in the demonstration of innovative designs would result in in the Reduced Innovation Case in around 3 gigatonnes of carbon dioxide ($GtCO_2$) of additional direct emissions from fossil fuel boilers in the buildings sector cumulatively by 2040 (roughly equivalent to all buildings-related direct emissions in 2019) compared to the Sustainable Development Scenario. The installed output thermal capacity of innovative heat pumps would be 60% lower in 2030 in the Reduced Innovation Case than in the Sustainable Development Scenario. The products mostly affected by delayed testing and demonstration would be those integrating storage solutions or next-generation components (e.g. advanced vapour-compression cycles)

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and non-vapour-compression systems (e.g. evaporative cooling). These jointly account for around 60% of the decrease in thermal capacity in 2030 relative to the Sustainable Development Scenario.

The Reduced Innovation Case could also result in a slowdown in the uptake of electric road vehicles; this in turn would lead to around 2.5 $GtCO_2$ of additional cumulative emissions by 2040 compared to the Sustainable Development Scenario. This slowdown would translate into a 20% decrease in cumulative battery production by 2040 compared to the Sustainable Development Scenario. The annual reduction in battery manufacturing capacity in 2040 would be equivalent to 34 gigafactories[10] and would imply a slowdown in learning-by-doing and other drivers of innovation, which in turn would translate into an increase of 8% in average battery costs by 2025 relative to the Sustainable Development Scenario.

In the Reduced Innovation Case, a delay in demonstration projects for pre-commercial **carbon capture, utilisation and storage** technologies together with a slowdown in the deployment of CCUS technologies at early adoption stage would bring about reductions in captured CO_2 emissions of 50% in 2030 and 35% in 2040 compared to the Sustainable Development Scenario. As a result, CCUS deployment by 2040 would be reduced by around 8 $GtCO_2$ cumulatively, which is equivalent to the entire direct emissions of the transport sector in 2019. CO_2 captured from cement production and power generation in particular would be affected over the next two decades, with these two sectors accounting between them for almost 80% of the reduction in CCUS deployment in that period in the Reduced Innovation Case relative to the Sustainable Development Scenario.

In the Reduced Innovation Case, a delay in demonstration projects for pre-commercial **hydrogen** technologies, together with a slowdown in the deployment of hydrogen technologies at the early stage of adoption, would result in a reduction of 10% in 2030 and 11% in 2040 in annual hydrogen demand relative to the Sustainable Development Scenario. This reduction would result in more than 1.5 Gt of additional CO_2 emissions cumulatively by 2040 compared to the Sustainable Development Scenario, or almost twice the annual emissions related to hydrogen production today. A drop of almost 7.5 million tonnes per year (Mt/yr) cumulative production capacity of electrolytic hydrogen by 2030 would result in an increase of almost 10% in the average capital expenditure of water electrolysers in 2030 relative to the Sustainable Development Scenario as a result of slower technology learning. This increase is barely noticeable in the levelised cost of producing electrolytic hydrogen, which would increase only marginally (up to USD 3.1 per kilogramme),[11] but it would put additional stress on upfront investment financing for projects that are already highly capital intensive.

[10] Battery gigafactory capacity considered at 35 gigawatt-hours per year.

[11] Hydrogen levelised cost is based on 69% conversion efficiency, USD 50/MWh electricity price, 5 000 full-load hours and a weighted average cost of capital of 8%.

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Just because the technological transformation in the Sustainable Development Scenario would be unprecedented does not make it impossible. Many of the technologies needed in the Sustainable Development Scenario rely on digitalisation, for example, making them unlike energy technologies of the past, and on rapid adoption by consumers, who are operating in a world in which information spreads faster than ever before. Other technologies require extensive new infrastructure (e.g. integrating carbon capture), but are backed by strong social and regulatory pressure for change.

Timescales in taking technologies from the laboratory to market

History shows that it can take between 20 and almost 70 years for new energy technologies to go from first prototype to materiality (that is, to reach 1% of a national market) (Gross, 2018; Bento, Wilson and Anadón, 2018). Even recent success stories in clean energy technology development – such as solar photovoltaic (PV) and Li-ion batteries to power electric vehicles – took around 30 years from their first prototype to commercialisation. Having achieved market introduction, it took a further 25 years for solar PV to achieve a 1% share of a national electricity supply market in Spain, closely followed by Germany, while it took just six years for Li-ion battery-powered electric vehicles to achieve the same national market first in Norway. Among leading energy technologies, light-emitting diode (LED) lighting for buildings achieved materiality in the shortest amount of time, being introduced in the United Kingdom just ten years after the initial prototype was developed. In each of these cases, government intervention accelerated innovation.

In general, the Sustainable Development Scenario assumes somewhat shorter development periods than those observed in the past, since policy support is assumed to be much stronger, and to lead to more efficient exchange of technical knowledge and stronger exploitation of synergies between sectors. Factors that have in the past led to discontinuous learning, including a lack of financial resources, fossil fuel price risks and political instability, are assumed not to affect innovation in the future.

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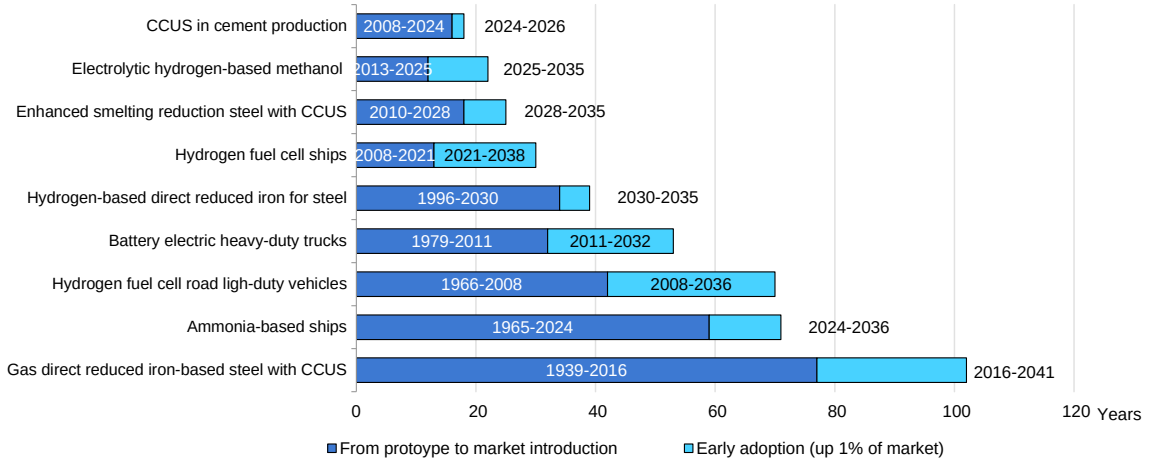
Figure 6.10 Time to materiality for selected technologies in the Sustainable Development Scenario



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Notes: Time period from market introduction to materiality relates to global deployment projections in the Sustainable Development Scenario. Pace of deployment of a given technology depends not only on observed historical patterns for analogous examples, but also on how competitive it is on cost and performance compared with alternative available low-carbon technologies delivering an equivalent service, as well as the effectiveness of policies to stimulate uptake.

Sources: Matsunaga, Tatsuya and Kuniaki (2009); Zemships (2008), Molino et al. (2018); European Cement Research Academy (2012); Brohi (2014); TATA Steel (2017); Kohl and Nielse (1997); Ballard (2019); Kraftwerk Forchung (2013), Nuber, Eichberger and Rollinger (2006).

Bringing new clean energy technologies to market on a large scale after the first prototype can take from 20 years to more than 80 years in the Sustainable Development Scenario.

For large, non-modular, site-tailored technologies at a pilot stage today, a six to eight year period from first large prototype to full-scale demonstration is assumed in the Sustainable Development Scenario, followed by a seven to ten year period to first commercial introduction under prevailing market conditions. In some cases, up to five full-scale major demonstration projects operating for five to ten years in commercial environments around the world may be required to generate investor and regulatory confidence, with knowledge transferred between them. On the other hand, small and/or modular technologies like engines, batteries and electrolysers are assumed to reach markets no later than 12-14 years from early prototype in the Sustainable Development Scenario.[12] As a result, various technology designs that become increasingly competitive take differing lengths of time to reach the early adoption stage in the Sustainable Development Scenario (Figure 6.10 above).

[12] This consideration applies only to the projected period, and excludes instances in which technologies may already have taken a longer period from first prototype to reach current status of development prior to 2020.

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Moving down the learning curve

When learning-by-researching, learning-by-doing, standardisation, collaboration across an industry and economies of scale collectively result in cost and price reductions that continue over a decade or more, empirical "learning curves" (or experience curves) can be constructed to inform future expectations for similar technologies. The typical approach is to correlate the percentage cost reduction with the time it takes to double the cumulative installed capacity, which is a proxy for the level of experience and scale acquired by the industry.

Solar PV and Li-ion batteries are good examples of learning curves. Each time the cumulative amount of capacity has doubled worldwide since the 1970s unit costs for PV have fallen by 24%. In recent years, the fall in PV unit costs associated with each doubling of capacity (the learning rate) has increased to more than 30%. The equivalent learning rate for Li-on has been around 20%. For both technologies, these learning rates have led to an exponential decline in prices. Future cost declines are expected as capacity expands further, although they are likely to require novel technology configurations.

It is clear that not all technologies will follow the same journey, and learning rates in the Sustainable Development Scenario are adjusted in line with those seen for analogous technology scales and manufacturing methods. The learning rates observed for solar PV and Li-ion batteries are applied as appropriate in the Sustainable Development Scenario to other small, simple, modular and adaptable designs. For example, electrolysers and fuel cells, which have been manufactured in only limited volumes to date, see rapid adoption in the next decade that drives down costs and spurs mainstream diffusion (Figure 6.11). In some cases, the learning rates applied are lower, reflecting a more mature stage of development for a given technology. For example, heat pumps, for which significant learning experience has already been gained, follow a slower cost reduction trajectory.

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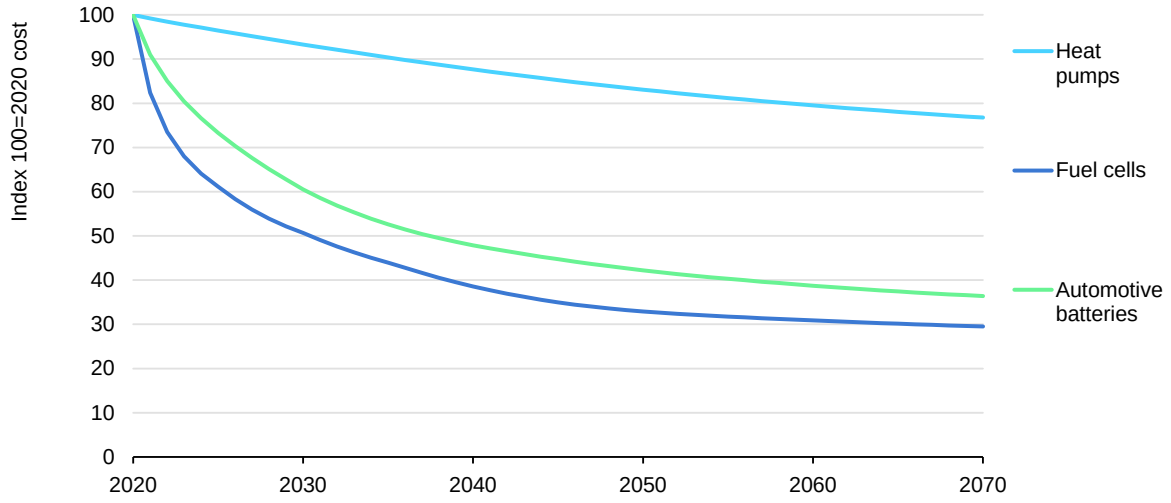
Figure 6.11 Unit cost reductions for selected technologies in the Sustainable Development Scenario, 2020-70



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Notes: Cost reductions are calculated as a function of cumulative installed capacity in 2018, projected capacity additions from the model and component-specific learning rates. Learning rates for heat pumps, automotive battery cells and fuel cells stacks are 10%. Learning rates for battery packaging and fuel cell balance of plant are 5%.

Technology costs decline in the Sustainable Development Scenario, though at different rates reflecting specific scale and technology attributes.

Technology attributes for faster innovation

Understanding the innovation dynamics of different technology designs is vitally important for governments and investors alike. Various types of technology have attributes that benefit from different means of innovation support and attributes that can favour (or disfavour) rapid innovation cycles (Bennett, 2019). Knowing how these attributes affect innovation can help governments determine whether they should take a leading role at any given stage of the innovation value chain or whether the private sector might reasonably be expected to take on much of the innovation risk.

There are a number of attributes that influence the rates of learning and technology adoption in the Sustainable Development Scenario (Table 6.1). They include small unit size and modularity – both of which favoured mass production, standardisation and continuous learning as for PV and Li-ion – as well as spillover. These attributes can give a better chance of success, but do not guarantee it: the history of energy is littered with examples of failed or stalled technological developments. In some cases, resources were allocated to solve a problem, such as perceived oil shortages, that did not persist and so the business case for the R&D strategy unravelled (Grubler and Wilson, 2013).

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Table 6.1 Energy technology attributes that can favour more rapid innovation cycles or faster learning

Attribute	Description	Past examples	Examples in the Sustainable Development Scenario
Small enough unit size to be mass produced	Small units can be prototyped and tested quickly before factories are built. As a result, global demand can support many factories and industrial competition can lead to faster turnover of products. New generations of these technologies hit the market every few years, with associated innovative improvements. In some cases, mismatched investment and consumption cycles can, however, lead to oversupply and intensive competition for market share.	• PV • Li-ion batteries	• Heat pumps • Fuel cells
Modularity	Modularity confers many of the same benefits as small unit size, but can also apply to larger units that cannot be mass produced but can be readily standardised and added sequentially to a facility. One of the main benefits is lower capital requirements for each stepwise addition, reducing the risks associated with scaling-up and enabling the pace of deployment to match that of other elements in the value chain.	• PV • Aluminium smelting	• Solid sorbent-based direct air capture • Electrolytic hydrogen routes for chemicals production • Small modular nuclear reactors • Standardised building retrofits
Offers services valued by consumers	Technologies need to be first taken up in niche markets where a small number of consumers are willing to pay a premium for their specific benefits. End-users, especially early adopters, will often pay a premium for a product that offers convenience, fun and reputational benefits. While many low-carbon technologies offer limited performance or economic advantages, low-carbon products could offer reputational and other benefits that consumers want, helping them to enter a virtuous cycle of adoption, learning, network effects and expansion to new applications.	• Passenger cars • Smart thermostats • LEDs • Micro-mobility • Smartphones (which replace up to 18 other devices)	• Autonomous, connected, electric and shared vehicles • Connected appliances • Building-integrated PV • Decentralised energy trading • Electrochromic fenestration
Spillovers (strong synergies with technology advances elsewhere)	Shared between researchers and engineers from different sectors, reducing the need for dedicated energy R&D. This is because the advances needed to make a technology commercial in one application are simultaneously beneficial in another unrelated application. Electric vehicles are an example of a technology that was promoted for decades without uptake until spillovers from consumer electronics batteries, hybrid vehicles, lightweighting and motors helped it to take off.	• Combined-cycle gas turbines (from jet turbines) • PV (from semiconductors) • Li-ion for EVs (from Li-ion for consumer products) • LEDs for lighting (from LEDs for electronics) • Offshore wind and geothermal (from oil and gas)	• CCUS (from oil and gas exploration, chemical catalysis and gas separation) • Batteries, fuel cells and electrolysers (from each other and other electrochemical technologies) • Biofuels (from agriculture) • Smart, connected energy

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Attribute	Description	Past examples	Examples in the Sustainable Development Scenario
Can be used as a drop-in replacement or bolt-on device.	A new technology can be adopted more quickly if it requires no changes to associated equipment or infrastructure. A "drop-in" replacement is a substitute that is fully compatible with the dominant existing means of providing an energy service. A "bolt-on" device is fully compatible with existing processes, but leaves them intact and adds an additional function, such as emissions capture. CO_2 capture has the potential to be a "bolt-on" device, but usually requires significant changes to associated infrastructure (e.g. CO_2 storage).	• Certain biofuels, e.g. hydrotreated vegetable oil • Biomethane • Catalytic converter • Desulphurisation	• Hydrogen-based synthetic fuels • Electric vehicles using existing road and electricity infrastructure • Biojet fuel
Replaces hardware or labour with digital solutions	Many recent energy sector innovations have replaced manual or analogue processes with digital ones. Innovation in digital technologies requires limited capital and allows continuous experimentation and cheap upgrading *in situ*. In addition, many digital products generate data that have commercial value, meaning that the risk of investment is shared between the energy-related and data-related value streams.	• Seismic geological exploration • Power grid management	• Autonomous, connected, electric and shared vehicles • Passive demand response • Digital twin O&M • 3D printing
Minimal dependence on improvements in other technologies in the value chain	For instance, the success of CO_2 capture depends in large part on simultaneous developments in CO_2 transport, utilisation and storage. Though it is less of a bottleneck than for CCUS, the same factor has affected variable renewable power generation, which often relies on improvements to the grid or storage solutions. These dependencies raise the risks of R&D in each coupled element of the value chain and can significantly slow the pace of innovation.	• Biomass power generation • Nuclear • LEDs • Coal gasification	• Renewables plus storage • Enhanced smelting reduction-based steel
Minimal need for adaptation to local conditions	Some technologies, such as batteries, may need to be adapted to local climatic conditions when they are deployed in a new region. Temperature extremes, temperature swings or frequent storms are examples of local conditions that can dramatically change performance. Variations in fuel supply, for example for biomass gasification, can also make it harder to standardise a technology for a global market. In some cases, end-use products need to be adapted to local consumer preferences, regulations and expectations. Technologies that do not encounter these problems can	• Internal combustion engines • Turbines	• Novel battery chemistries • Fuel cells

Note: EVs = electric vehicles; CCUS = carbon capture, utilisation and storage; O&M = operation and maintenance.

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Box 6.2 Spillovers as an important attribute for faster innovation

The history of energy technology development is rich with examples of spillovers that changed the course of investment and industrial competition. Knowledge accumulated in one technology area has been a powerful driver for innovation in other related technologies. This factor, often overlooked, is of vital importance to technology policy because the benefits of spillovers can be harnessed at relatively low cost and can avoid or reduce the need for additional R&D. In the Sustainable Development Scenario, spillovers play a significant role in the transition towards net-zero emissions.[13]

Spillovers can refer to knowledge transferring across technology areas (knowledge spillovers) or knowledge obtained by implementing a technology across different applications (application spillovers), though the boundaries between the two are sometimes blurred. Knowledge spillovers across different domains can occur if two technology designs share a common scientific base, similar manufacturing techniques, or common installation and operation skills. Application spillovers can occur when a technology design or technology component (such as an input material) that is optimised for one application becomes suitable for a different purpose. They are more likely to occur if the technology can be adapted to a large number of uses. The most potent cases of application spillovers have been termed "general-purpose technologies". Archetypal examples include steam engines, electric power and information technology (Bresnahan and Trajtenberg, 1995; Ruttan, 2008).

The knowledge transferred via spillovers can be transmitted through researchers, engineers, consultants and plant operators. Geographical proximity can enhance spillovers, as can professional societies and conferences. An important part is played by companies that provide services to different sectors, such as engineering, procurement, and construction contractors and technical consultancies (Hoppmann, 2018).

Many critical spillovers that have benefited specific energy technologies have come from outside the energy sector. The development of combined-cycle gas turbines, which now play an integral role in electricity generation systems, was initiated by the aerospace sector. The first gas turbine jet engine was developed in 1939 following government-funded military R&D in the United Kingdom. Another example is provided by the cost-competitive mass production of solar PV panels, which was enabled by knowledge spillovers from parallel developments in the production of silicon for

[13] For more a detailed analysis on the role of spillovers in the Sustainable Development Scenario, see the *Energy Technology Perspectives Special Report on Clean Energy Innovation*, (www.iea.org/reports/clean-energy-innovation).

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microprocessors. Adoption of semiconductor manufacturing processes by the PV sector and sharing of silicon production between the two sectors were vital factors in cutting PV costs. Likewise, the development of the carbon anode used in Li-ion batteries benefited from knowledge and techniques developed by the petrochemical sector: the first functioning carbon anode was developed by a petrochemical company.

Clean energy innovation needs faster progress

The impact of the Covid-19 pandemic has greatly affected economic activity, including in the energy sector. In response, governments are now increasingly looking at economic stimulus packages: these offer an important opportunity for action that helps to ensure continued security of energy supplies while supporting clean energy transitions, including the needed technology innovation.

In this section, we complement the Sustainable Development Scenario by analysing a Faster Innovation Case that explores just how much more clean energy technology innovation would be needed to bring forward the time at which the Sustainable Development Scenario reaches net-zero emissions from 2070 to 2050. This case serves to underline the importance of governments grasping the opportunity provided by stimulus packages to review their innovation portfolios and priorities, and align them with their long-term clean energy transition objectives.

The Faster Innovation Case – just how far could innovation take us?

The Sustainable Development Scenario reaches net-zero emissions from the energy sector within five decades on the back of ambitious technological change and optimised innovation systems comparable to the fastest and most successful clean energy technology innovation success stories in history. The Faster Innovation Case is a special case of the Sustainable Development Scenario that focuses on stretching underlying innovation drivers to bring forward net-zero emissions to 2050. This is a milestone year for clean energy transition efforts that has gained much prominence through the public debate that followed the release of the Intergovernmental Panel on Climate Change's *Special Report on Global Warming* of 1.5ºC (IPCC, 2018). The Faster Innovation Case is not designed to be an ideal pathway to net-zero emissions by 2050; the complexity of this question goes well beyond technology innovation

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alone, and is likely to require fundamental changes to current lifestyles.[14] Rather, it is designed to explore how much shorter development cycles would need to be than in the Sustainable Development Scenario, and how much more rapid technology diffusion rates would need to be in order to deliver net-zero emissions globally by 2050. There are three key changes that distinguish the Faster Innovation Case from the Sustainable Development Scenario:

- In the Sustainable Development Scenario, technologies that are still in the laboratory or early prototype stage today are not considered because of the high level of uncertainty about their performance and possible future commercialisation. To explore their potential contribution to reach net-zero emissions earlier, we include in the Faster Innovation Case those technologies at very low maturity stage today that are modular and small enough to be mass produced and that have the potential for high spillovers from and to other net-zero emissions technologies. We also include those technologies that have a lot of potential to unlock supply constraints and shift the supply curve towards lower cost resources.
- For technologies currently at prototype stage, we assume a further significant shortening of the period to market introduction, well below what has been achieved in recent success stories of clean energy technology development. We also assume that robust market deployment starts right after the completion of only one commercial-scale demonstration, which is not common practice.
- For new and emerging clean energy technologies, we boost adoption rates to a level that risks additional market bottlenecks and resource constraints along the supply chain if co-ordination fails in the face of rapid expansion.

There is little or no precedent for the required pace of innovation in the Faster Innovation Case and it does not leave any room for delays or unexpected operational problems during demonstration or at any other stage. These are, of course, bound to happen in practice. Nonetheless, while it can take several decades for a technology to move from the laboratory to mainstream diffusion, the projection horizon of this report is long enough to bring some surprises, some of which may be welcome ones. Mission-oriented approaches that support clean energy innovation in technology areas with attributes conducive to fast innovation cycles could speed up the pace of progress, particularly if they are coupled with a once-in-a-generation investment opportunity as a result of Covid-related recovery plans. Some technologies currently in the laboratory or at the level of small prototype that are outside the scope of the Sustainable Development Scenario might progress fast enough to be able to contribute to the transition to net-zero emissions in the timeframe. While the true

[14] See the *World Energy Outlook-2019* for a discussion of changes required for a 1.5 degree Celsius (°C) pathway (IEA, 2019).

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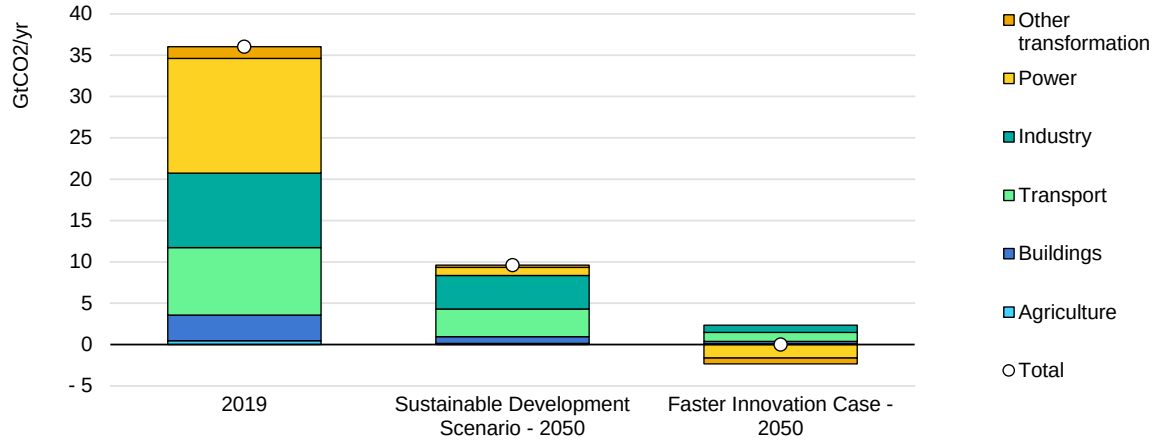
potential rate of scale-up for technologies at such early stages of maturity is highly uncertain, it is reasonable to consider what the impact might be if R&D is successful in bringing some of them to market within that period. This is the objective of the Faster Innovation Case.

In the Faster Innovation Case, enhanced clean energy technology innovation would need to lead to almost 10 $GtCO_2$ of additional net emissions savings compared to the Sustainable Development Scenario in 2050, which is the equivalent of almost 30% of today's energy sector emissions (Figure 6.12). The result is that emissions in end-use sectors would be significantly lower by 2050 in the Faster Innovation Case. By 2050, remaining transport-related emissions would be down to 1.1 Gt (mainly in heavy-duty trucking, aviation and shipping), in industry, they would be down to almost 0.9 Gt (mainly steel, cement and chemicals production); and in buildings, down to almost 0.3 $GtCO_2$. To put this into perspective, the additional emissions reductions reached in the Faster Innovation Case through innovative technologies in passenger transport, for instance, are equivalent to a drop of almost 60% in the level of passenger activity across different modes of transport in the Sustainable Development Scenario in 2050. Similarly, materials production from heavy industrial sectors would need to drop on average to around a quarter of the level reached in the Sustainable Development Scenario in 2050 to reach the level of emissions reductions in the Faster Innovation Case.

Figure 6.12 Global energy sector CO_2 emissions by sector, 2019 and 2050



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Notes: Emissions include those from fossil fuel combustion and those released in industrial processes from carbon contained in the raw materials used.

Despite the additional innovation push to reduce CO_2 emissions in the Faster Innovation Case, CO_2 emissions would persist in 2050, which would need to be offset by negative emissions.

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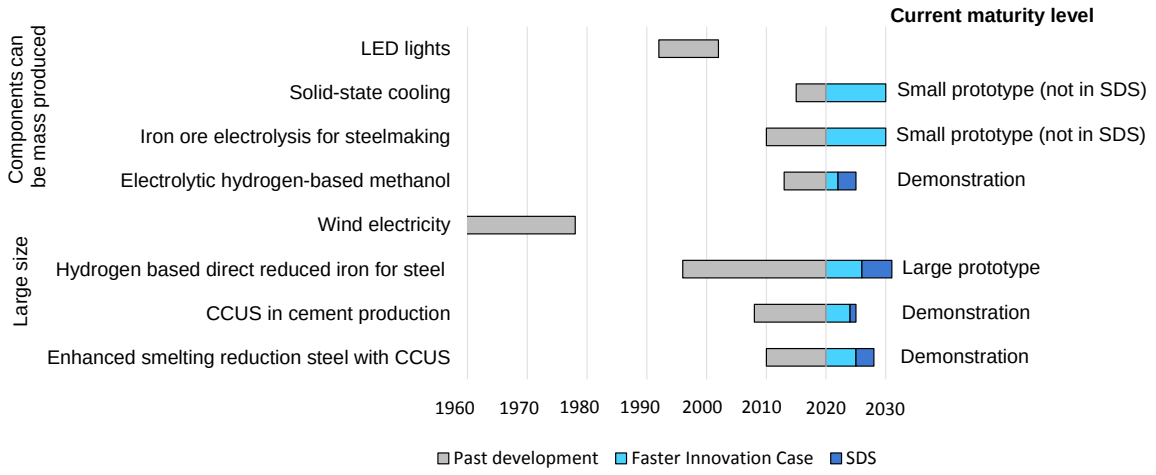
Innovation needs in the Faster Innovation Case

Achieving such a transformation of the energy landscape globally in just three decades would require innovation cycles much faster than those achieved in recent success stories of clean energy technology development. Key clean energy technologies at demonstration or large prototype stage today, such as hydrogen-based steel production, electrolytic hydrogen-based ammonia to fuel vessels or carbon capture in cement production, among others, are assumed to reach markets in six years from now at the latest. This is about twice as fast as in the Sustainable Development Scenario, which assumes that deployment starts after several demonstrations have been successfully completed, in line with normal innovation practice (Figure 6.13). Technologies at laboratory or small prototype stage are commercialised in the next ten years on average in the Faster Innovation Case, which is the minimum time required from the first prototype to market introduction observed across all technologies explored for this report: the only case for which there is historical evidence of such rapid progress is that of LEDs, which are small enough to be mass produced and to require a relatively low level of capital expenditure during the prototyping and demonstration phase.

Figure 6.13 Period from first prototype to market introduction for selected technologies, including the quickest examples in recent developments



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Notes: SDS = Sustainable Development Scenario; CCUS = carbon capture, utilisation and storage. The classification between large process technologies and those dependent on components able to be mass produced is based on the characteristics of the equipment or process steps within the technologies analysed that are not commercially available today.

Sources: Historic year from different technologies based on Gross (2018), European Cement Research Academy (2012); Brohi (2014); TATA Steel (2017) and Nuber, Eichberger and Rollinger (2006).

The time to market introduction for pre-commercial technologies would be reduced by almost 40% on average in the Faster Innovation Case compared to the Sustainable Development Scenario, on the basis that a single commercial demonstration would be enough to allow a move to vigorous market deployment.

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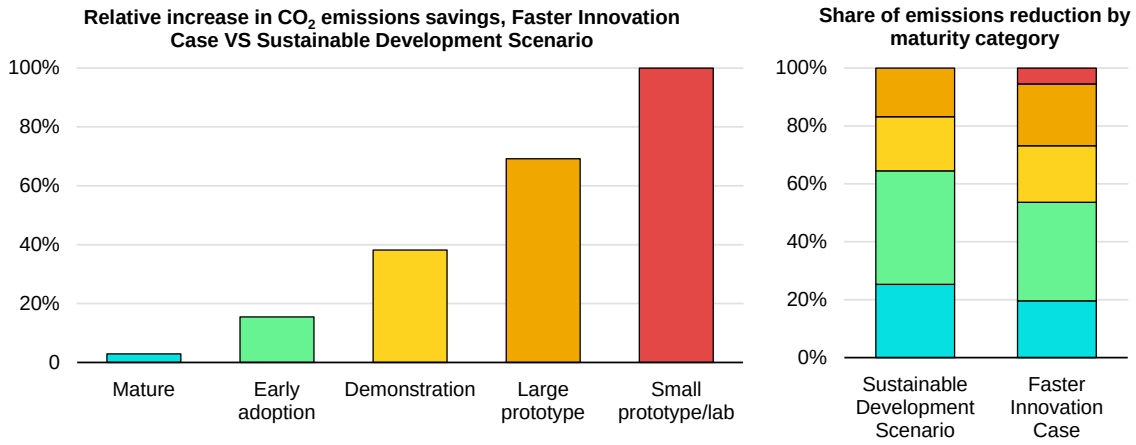
In the Faster Innovation Case, the pace of adoption of new technologies following their commercialisation increases by about twofold on average compared to the Sustainable Development Scenario, and up to almost threefold for technologies that can be mass produced and that have strong synergies with technology advances elsewhere. In 2050, the share of CO_2 emissions reductions achieved by deploying technologies that have not reached markets today would be more than 60% higher in the Faster Innovation Case than in the Sustainable Development Scenario (equivalent to 17 $GtCO_2$ or the combined energy-related emissions of China, United States and European Union in 2018) (Figure 6.14). Technologies now at prototype stage would enable the largest increase in emissions reductions, partly as a result of assumed actions to stimulate technologies in the laboratory and at small prototype stage that go beyond the scope of the Sustainable Development Scenario. Both the Sustainable Development Scenario and the Faster Innovation Case see a major role for technologies that are not commercially available today.

Figure 6.14 Contribution to global energy sector annual CO_2 emissions reductions in 2050 by current technology maturity category



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Notes: In the right graph, emissions reductions are relative to the Stated Policies Scenario. The Sustainable Development Scenario does not include technologies that are at small prototype stage or in the laboratory today.

Annual emissions reductions from technologies at the prototype stage today would be more than 70% higher in 2050 in the Faster Innovation Case than in the Sustainable Development Scenario.

Technology needs in the Faster Innovation Case

A transition to net-zero emissions by 2050 as depicted in the Faster Innovation Case would further amplify the scale of change required across all parts of the energy sector and across all technologies. The contribution of fossil fuels to total primary energy demand in the Faster Innovation Case would be reduced by almost 40% in 2050 compared with the Sustainable Development Scenario. Oil use would be most

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affected with a 40% decline in 2050, mostly driven by a radical transformation of the transport sector on the back of advanced battery chemistries and expanded hydrogen use. Bioenergy demand would increase by 15% by 2050, enabled by innovative technologies and strategies to unlock additional sustainable bioenergy resources. Demand for other renewables would be almost 50% higher than in the Faster Innovation Case in 2050 driven by increased use in power generation to support almost 25% growth in electricity demand.

A transition to net-zero emissions as in the Faster Innovation Case would indeed require very rapid transformation in the way energy is supplied. For instance, the power sector would need to decarbonise at an even faster pace while accommodating additional electricity generation of nearly 20 000 terawatt-hours (TWh) by 2050 relative to the Sustainable Development Scenario to contribute to deep emission cuts in end-use sectors (a 35% increase in electricity generation is roughly equivalent to the combined electricity generation of China and India in 2050 in the Sustainable Development Scenario). The surge in low-carbon electricity demand would support emissions reductions in end-uses (particularly transport and industry) in two ways: through direct electrification and supporting higher supplies of electrolytic hydrogen and electrolytic hydrogen-based fuels. This would require a further step change in low-carbon investments such as for renewables: annual renewables capacity installations would need to rise to 770 gigawatts (GW) per year by 2050, almost 50% higher than in the Sustainable Development Scenario and about four-times the record high in 2019 (Figure 6.15). Similarly, there would also be a higher call on alternative low-carbon fuels. Compared to the Sustainable Development Scenario, demand for alternative fuels such as hydrogen, ammonia, hydrocarbon synthetic fuels and biofuels would grow by around 20% in 2050 in the Faster Innovation Case to offset a decline in fossil fuel use by 40%. A more robust push in technology innovation would see the transport sector consume 40% of total final demand of alternative fuels in 2050 in the Faster Innovation Case, while industrial processes would absorb about a third.

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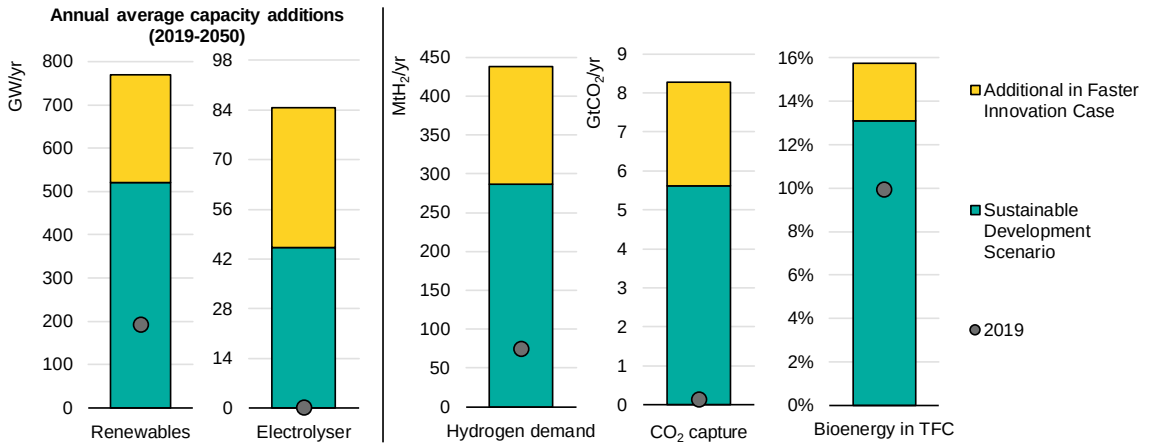
Figure 6.15 Selected decarbonisation indicators by scenario in 2050



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Notes: GW/yr = gigawatts per year; MtH_2/yr = million tonnes of hydrogen per year; TFC = total final energy consumption. Renewables exclude bioenergy-based power generation equipped with carbon capture. CO_2 capture includes captured emissions for storage and use.

Transitioning to net-zero emissions by 2050 in the Faster Innovation Case significantly amplifies the scale of change required across all technologies.

The main emissions abatement strategies in the Faster Innovation Case are not radically different from those in the Sustainable Development Scenario: new and emerging technologies would target the displacement of fossil fuels by electricity or alternative clean energy fuels such as hydrogen, hydrogen-derived fuels and bioenergy, or they would target the capture of CO_2 emissions for use and storage from fossil or bioenergy-based combustion. What varies is the step change in speed of innovation assumed in the Faster Innovation Case in all these technology areas.

Electrification, CCUS, bioenergy and hydrogen would account for almost 90% of the additional emissions reductions in the Faster Innovation Case in 2050 compared with the Sustainable Development Scenario (Figure 6.16). The boost in electrification and bioenergy would enable almost 60% of the additional emissions reductions, with a larger contribution from electrification. These contributions would stem partly from the widening of the technology portfolio in the Faster Innovation Case to include technologies that are today at small prototype stage or in laboratories and that have high potential for speeding up innovation cycles for advanced high-energy density batteries or conversion routes to exploit algae and aquatic biomass for the production of biofuels and biochemical, among others (Box 6.3). Additional emissions savings come from further shortening the period to market introduction of technologies that are at large prototype and demonstration stages today, as well as from accelerating market adoption rates of new and emerging technologies.

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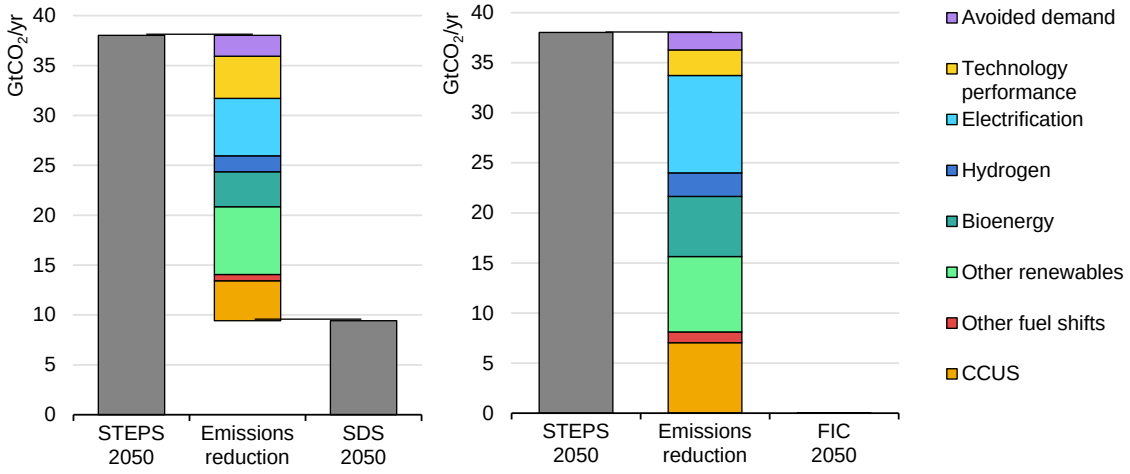
Stronger innovation efforts in CCUS would enable around 25% of the additional emissions reductions in the Faster Innovation Case in 2050 relative to the Sustainable Development Scenario. The bulk of the increase in captured emissions would come from carbon removal technologies either through bioenergy carbon capture and storage or direct air capture (DAC). The joint capture volume of these two technologies would increase by nearly 50% in 2050 reaching more than 2.5 $GtCO_2$ and this would help to offset residual emissions, which by 2050 would come mainly from long-distance travel and heavy industry.

Hydrogen-related technologies would enable the remaining additional emissions reductions in the Faster Innovation Case compared to the Sustainable Development Scenario in 2050. Demand for hydrogen, including for hydrogen-derived fuels, would grow by around 55% in the Faster Innovation Case in 2050 up to 150 Mt. For instance, compared to the Sustainable Development Scenario, the demand of hydrogen for low-carbon hydrogen-based processes in industry would increase a further 35% by 2050 in the Faster Innovation Case, and the demand for ammonia to power ships would increase almost 70% more.

Figure 6.16 Global energy sector annual CO_2 emissions reductions by type of abatement measure and total primary energy demand, 2050



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Notes: STEPS = Stated Policies Scenario; SDS= Sustainable Development Scenario; FIC = Faster Innovation Case. Hydrogen includes hydrogen and hydrogen-derived fuels such as ammonia and synthetic hydrocarbon fuels. Nuclear is included in other fuel shifts.

Electrification, CCUS, bioenergy and hydrogen account for around 90% of additional emissions reductions in the Faster Innovation Case in 2050 compared to the Sustainable Development Scenario.

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Box 6.3 Key opportunities among technologies at laboratory or small prototype stage

Policy makers seeking to support technologies currently at laboratory or small prototype stage that will have maximum impact as part of economic stimulus packages should consider, two kinds of technology that are likely to be particularly relevant. First are technologies that are modular and small enough to be mass produced and have potential for high spillovers from and to other net-zero emissions technologies. Second are technologies with significant potential to unlock supply constraints (e.g. those affecting bioenergy and rare or increasingly in demand materials) and that can shift the supply curve towards lower cost resources. Several such technologies are particularly important in the Faster Innovation Case: advanced battery chemistries and battery recycling techniques; innovative practices to boost biomass resources; direct electrification of primary steelmaking and advanced refrigerant-free cooling.

- **Advanced battery chemistries and recycling techniques.** Despite a near doubling of the gravimetric energy density at cell level of batteries in the Sustainable Development Scenario by 2070 compared with current levels, the use of batteries for transport remains largely confined to road vehicles, and short-distance shipping and aviation routes. An all-electric passenger commercial aircraft capable of operating over ranges of 750-1 100 kilometres, for instance, would require battery cells with densities of 800 watt-hours per kilogramme (Wh/kg), more than three-times the current performance of Li-ion batteries (Schafer et al., 2019). There are at least two alternative battery chemistries that theoretically could reach the necessary density: lithium-sulphur and lithium-air, which are at small prototype and concept stage today (Thackeray, Wolverton and Isaacs, 2012). Reaching the performance goal of 800 Wh/kg (cell level) by 2050 as assumed in the Faster Innovation Case (a level 60% higher than in the Sustainable Development Scenario) would boost the share of electricity in heavy-duty road freight from 15% in the Sustainable Development Scenario to almost 70% by that year, with battery electric trucks dominating the electric vehicle fleet. It would also enable a 50% increase in the coverage of aviation fuel use that electric aircraft built in 2050 would be capable of covering, as compared to the Sustainable Development Scenario.

  The demand-pull from the large-scale deployment of lithium-based batteries in the Sustainable Development Scenario increases lithium production in the Sustainable Development Scenario by thirty-fold by 2070 compared to current levels, with batteries taking 90% of total supply. In the Faster Innovation Case, the same level would be reached by 2040. Measures such as recycling that can prevent potential supply chain bottlenecks for lithium are important in this context. Battery recycling technologies today are mainly focused on high-value metals like cobalt and nickel:

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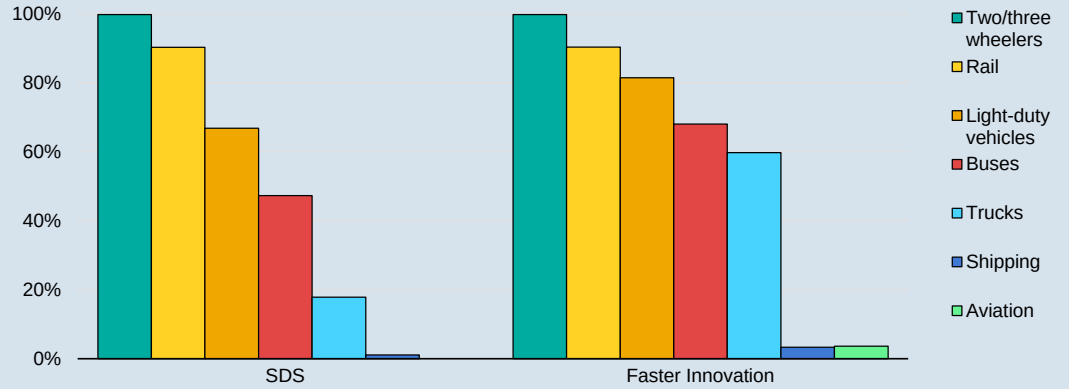
lithium is rarely recycled. This changes in the Sustainable Development Scenario: lithium recycling reaches 35% of all lithium demand in 2070, based on recycling technologies either available now or already at the demonstration phase. The Faster Innovation Case assumes that innovative battery recycling at earlier stages of development would be commercialised over the next decade, reducing demand for primary lithium and accelerating the electrification of the transport sector by lowering costs (IEA, 2020a).

Global share of vehicle activity electrified by mode in the Faster Innovation Case relative to the Sustainable Development Scenario, 2050



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- **Innovative techniques to expand sustainable biomass supply.** An increase and acceleration of bioenergy consumption in the Faster Innovation Case compared to the Sustainable Development Scenario is made sustainable by a set of innovative technologies and practices: using crops with higher yields, which allows the production of additional energy without a requirement for more land; developing new biomass resources such as algae and aquatic biomass for the production of biofuels and biochemicals; maximising the potential for agricultural land with the use of double cropping on a more widespread basis and developing advanced waste management systems on a much larger scale (IEA, 2020a).

  Enhancing the availability of sustainable biomass resources results in the share of bioenergy in final energy demand in the Faster Innovation Case being 25% higher than in the Sustainable Development Scenario by 2050. In industry, larger amounts of bioenergy would be directed towards medium- and high-temperature heating applications that do not require significant equipment retrofits, such as cement kilns. Biomass alternatives to energy-dense fossil liquids are particularly critical in shipping and aviation, where electrification is technically challenging and for which the total biofuel consumption combined would increase by about 18% in the Faster Innovation Case relative to the Sustainable Development Scenario in 2050.

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- **Direct electrification of primary steelmaking.** There are no economic and scalable technologies available today to make primary steel using non-fossil energy. One promising low-carbon technology – direct electrification of primary steelmaking (known as iron ore electrolysis) – is technically feasible, but the two most advanced processes (low-temperature alkaline electrolysis and high-temperature molten oxide electrolysis) have so far only been tested at small scale (IEA, 2020a). In the Faster Innovation Case, four factors would combine to make it possible to speed the deployment of iron ore electrolysis compared with other low-carbon processes for making primary steel in the Sustainable Development Scenario: relatively low risk in scale-up; spillovers from other electrolysis technologies; standardised and repetitive manufacturing; and compatibility with electricity grid needs. About 10% of global primary liquid steel production would be produced from iron ore electrolysis in the Faster Innovation Case in 2050, increasing electricity demand for steelmaking by 60% relative to the Sustainable Development Scenario.
- **Advanced refrigerant-free cooling.** Today many of the refrigerants used vapour-compression cycles, the standard technology for air conditioners, are powerful greenhouse gases. Hydrofluorocarbons are the most common refrigerant. Under the Kigali Amendment of the Montreal Protocol, more than 195 countries have committed to reducing the use of hydrofluorocarbon refrigerants by more than 80% in the next three decades. In the Faster Innovation Case, refrigerant-free cooling technologies, which are currently in the prototype phase, would be progressively adopted ten years from now. Among these are advanced evaporative cooling, advanced desiccants and solid-state cooling technologies. In the Faster Innovation Case, advanced space cooling technologies would account for more than 30% of global cooling capacity in 2050, allowing the average energy efficiency rating of the buildings stock to more than double to 9 by 2050, up from around 4 in 2019. Coupled with other measures to make buildings more energy efficient, refrigerant-free cooling technologies would lead to energy savings from 2030 to 2050 relative to the Sustainable Development Scenario equivalent to more than the current final energy consumption of the buildings sector, with two-thirds of these savings concentrated in the residential sector. In turn, spillovers from the faster growing demand for advanced cooling technologies could benefit technology development for heating services.

Electrification

As in the Sustainable Development Scenario, electrification is a key strategy in the Faster Innovation Case, which would see the share of electricity in total final energy demand grow by around one-quarter relative to the Sustainable Development Scenario and reach about half of total final energy in 2050 compared to nearly 20%

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today.[15] Transport and industry would be responsible for 95% of the additional electricity demand in the Faster Innovation Case with the electrification of road transport accounting for more than 30% of the total increase. Faster learning in battery manufacturing and in smart charging infrastructure is central to the Faster Innovation Case: so is the development and demonstration of advanced battery chemistries, particularly for heavy-duty vehicles. Without advances in alternative chemistries to Li-ion, it will be difficult for the use of batteries for transport to move beyond road vehicles and very short-distance shipping and aviation routes. In the Faster Innovation Case, the gravimetric energy densities (at cell level) would nearly triple from current levels in 2050 compared to a (still very rapid) growth of 70% it the Sustainable Development Scenario. At least two alternative battery chemistries – lithium-sulphur (Li-S) and lithium-air (Li-air) – have the potential to provide such advances: they are at small prototype and concept stage today. These developments would lead to more rapid uptake of electric vehicles: almost 90% of both light-duty and heavy-duty vehicles on the roads in 2050 would be battery electric in the Faster Innovation Case. In the case of heavy-duty vehicles, nearly seven-times more battery electric vehicles would be deployed than in the Sustainable Development Scenario.

To satisfy demand for electric vehicles in the Faster Innovation Case, about 17 TWh of battery manufacturing capacity would be required by 2050, meaning that more than one battery manufacturing plant of the size of the Tesla gigafactory would need to come online each month from today to 2050. The Faster Innovation Case would also require the rapid deployment of infrastructure for vehicle charging, particularly fast-charging stations capable of charging high battery capacities for electric trucks and buses through conductive or inductive dynamic charging on road and highways: such fast-charging stations are today at prototype stage. In the Faster Innovation Case, the number of fast chargers for electric heavy-duty vehicles would reach 19 million globally in 2050, more than twice the number in the Sustainable Development Scenario.

While the rapid battery developments envisioned in the Faster Innovation Case would transform road transport, and especially long-distance heavy-duty road operations, their impacts would be more muted in shipping and aviation. Due to the requirements for high-energy density fuels in shipping and aviation, battery electric powertrains only substitute for very short-range operations – the total weight of the battery restricts the range due to mass-compounding effects. Even by 2050, battery electric powertrains would account for only around 3% of freight movements in shipping and of passenger activity in aviation.

About 60% of the additional electricity demand in the Faster Innovation Case in 2050 compared to the Sustainable Development Scenario would come from industry. Large-scale electric heating would penetrate far more deeply into the industrial sector in the Faster Innovation Case than in the Sustainable Development Scenario. Rapid advances in the demonstration of large-scale high-temperature electric

[15] Electricity demand reported here refers to direct use of electricity only and excludes indirect uses such as for the production of electrolytic hydrogen.

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heating[16] for industrial processes that do not involve electricity-conducive materials would be required to enable such sizeable deployment levels in the Faster Innovation Case. Most of these technologies (e.g. electromagnetic) are at the concept validation stage today, but they would reach markets by no later than ten years from now in the Faster Innovation Case.

The commercialisation of the direct electrification of energy-intensive industrial processes such as primary steelmaking through iron ore electrolysis (currently at small prototype stage and thus outside the scope of the Sustainable Development Scenario) would also open new avenues for electrification in the Faster Innovation Case. This is based on the assumption that the time from small prototype to market for iron ore electrolysis is completed in record time (just below ten years), and that average deployment rises to 1 Mt (equivalent to half the capacity of a conventional steel mill) installed every two months in the period through to 2050, In the buildings sector, around 30 GW thermal capacity from integrated heat pump systems for heating and cooling (including storage systems) are installed every month on average in the period to 2050 in the Faster Innovation Case compared to just over 15 GW per month on average in the Sustainable Development Scenario.

Hydrogen

Demand for hydrogen, including for hydrogen-derived synthetic fuels such as ammonia, would increase by around 55% in the Faster Innovation Case in 2050, relative to the Sustainable Development Scenario, with around 60% of the demand from the transport and industry sectors. More than 95% of the hydrogen production in the Faster Innovation Case in 2050 would either be electrolytic or would be linked to CCUS, almost 10% larger share than the Sustainable Development Scenario in 2050. Electrolyser capacity would reach around 2 600 GW in 2050 in the Faster Innovation Case (120% more than in the Sustainable Development Scenario) and would absorb 45% of the additional electricity demand in that year (equivalent to one-third of today's consumption).

In industry, this increase would translate, for instance, into more than two new 1 Mt steel plants based on full hydrogen reduction being installed every month on average through to 2050 in the Faster Innovation Case, a pace of adoption that is more than twice as fast as in the Sustainable Development Scenario. Adoption at such a rapid pace necessarily means radical changes to the existing stock of steelmaking capacity; without such changes, more than a third of current global primary steelmaking assets would still be in operation in 2050. In shipping, more than 50 ammonia-fuelled large vessels would be put into service every month on average until 2050 in the Faster Innovation Case, almost twice the deployment rate in the Sustainable Development Scenario, in the context of a projected monthly market requirement of just over 80 large new vessels a month.

[16] High-temperature heating refers to heat delivered at 450°C or above, with some of the specific applications targeted requiring a temperature above 1 000°C.

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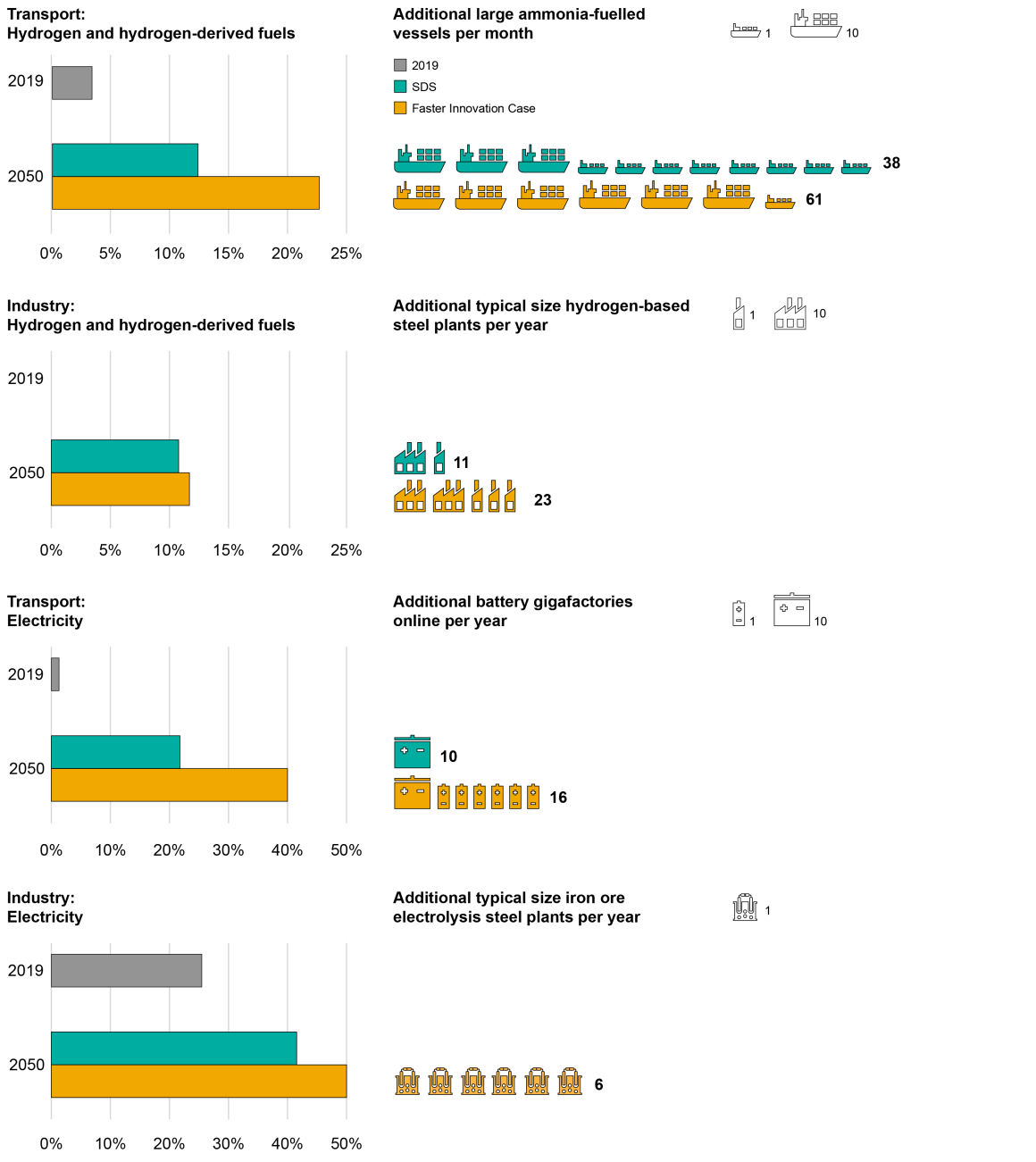
Figure 6.17 Global share of hydrogen and electricity in final energy demand by end-use sector (left) and selected adoption metrics of hydrogen technologies (right), 2019 and 2050



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Battery gigafactory capacity is assumed 35 GWh/yr. Final energy demand includes energy use for blast furnaces and coke ovens. Hydrogen includes direct demand of hydrogen and hydrogen-derived fuels for transport and buildings, and final energy demand required to produce hydrogen on-site for industrial processes. Typical size of steel plant considered is 1 Mt crude steel per year capacity. Typical maximum capacity for a large vessel considered is 50 kilotonnes of dead weight tonnage. Adoption rates show area average values for the period to 2050.

Electricity, hydrogen and other renewables see the highest growth in final energy demand, at the expense of fossil fuels, in the Faster Innovation Case relative to the Sustainable Development Scenario in 2050.

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Bioenergy

The share of bioenergy in total final energy demand would increase by around 20% in 2050 in the Faster Innovation Case relative to the Sustainable Development Scenario, mainly driven by industrial and transport-related applications. Such an increase would not present a technical challenge on the demand side, as biofuels are drop-in fuels for most applications, but it would put additional stress on biomass supply chains. Rapid innovation developments in biofuel conversion technologies and agricultural practices would be essential to unlock additional biomass sources and open new conversion routes to ensure the sustainability of supplies. Algae-based biofuels, which are currently only at small prototype stage today for most conversion routes, would be deployed at scale by 2050 in the Faster Innovation Case, but are not deployed in the Sustainable Development Scenario. The Faster Innovation Case would also require the rapid demonstration at scale of advanced biofuel production technologies such as biodiesel and biojet fuel through gasification and Fischer-Tropsch process, the aggregated production capacity of which would increase at an average rate around 40% faster than in the Sustainable Development Scenario through to 2050.

Carbon capture, utilisation and storage

The overall level of captured CO_2 emissions is almost 50% higher in the Faster Innovation Case in 2050 than in the Sustainable Development Scenario, at over 8 $GtCO_2$ per year, with the amount of CO_2 stored several hundred times larger than today (Figure 6.18). Negative emissions technologies, such as DAC and bioenergy carbon capture and storage, would account for the bulk of this. Both technologies would become even more critical in offsetting residual emissions from long-distance transport and heavy industry than in the Sustainable Development Scenario: emissions captured through these techniques in 2050 would almost triple relative to the Sustainable Development Scenario. Almost 16 DAC facilities of 1 Mt capture capacity would need to be commissioned every year on average from today through to 2050 in the Faster Innovation Case compared with around five such facilities per year in the Sustainable Development Scenario. The largest DAC plant currently being designed is 1 Mt capture capacity; only pilot-scale units of 0.4% that size have been operated so far. For bioenergy carbon capture and storage, almost 90 plants of 1 Mt capture capacity would be needed each year, almost three- times as much as the capacity projected in the Sustainable Development Scenario.[17] Accelerated innovation in CCUS would also enable direct emissions reduction in heavy industry. For example, the Faster Innovation Case would see more than five carbon capture

[17] 1 Mt capture capacity is equivalent to the largest biofuel plant with CO_2 capture in operation today, which was commissioned in 2017 in the United States to produce ethanol.

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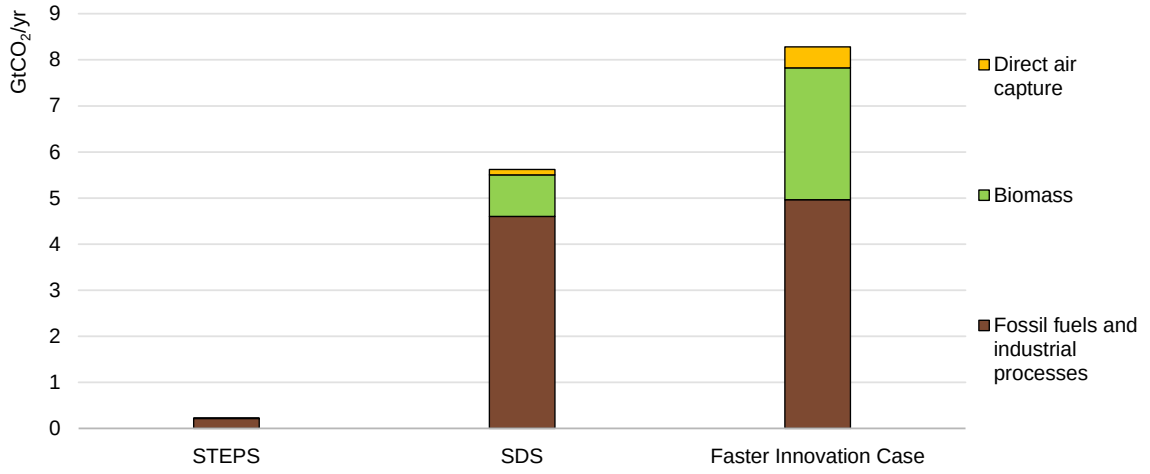
facilities of 1 Mt capacity built each month in the cement sub-sector through to 2050, compared to around four in the Sustainable Development Scenario.

Figure 6.18 Global captured CO_2 emissions by source, 2050



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Notes: SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario. Captured emissions are from fuel combustion and emissions released in industrial processes from carbon contained in the raw materials used.

Total CO_2 capture volumes would be almost 50% higher in 2050 in the Faster Innovation Case driven by almost a tripling in negative emissions technologies deployment relative to the Sustainable Development Scenario.

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References

Aghion, P. et al. (2016), Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry, Journal of Political Economy, Vol. 124/1, pp. 1-51, https://doi.org/10.1086/684581.

Archibugi, D., A. Filipetti and M. Frenz (2013), The impact of the economic crisis on innovation: Evidence from Europe, Technological Forecasting and Social Change, Vol. 80/7, pp. 1247-1260, https://doi.org/10.1016/j.techfore.2013.05.005.

Ballard (2019), Ballard to work with ABB on design and launch of fuel cell-powered river push boat in France, (press release), https://www.ballard.com/about-ballard/newsroom/news-releases/2019/05/21/ballard-to-work-with-abb-on-design-and-launch-of-fuel-cell-powered-river-push-boat-in-france (accessed May 2020).

Bennett, S. (2019), Accelerating clean energy innovation means tailoring R&D policy to technology scale and risk, (commentary), IEA, Paris, https://www.iea.org/articles/accelerating-clean-energy-innovation-means-tailoring-r-and-d-policy-to-technology-scale-and-risk.

Bento, N., C. Wilson and L. D. Anadon (2018), Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies, Energy Policy, Vol. 119, pp. 282-293, https://doi.org/10.1016/j.enpol.2018.04.015.

Bergek, A. et al. (2008), Analyzing the functional dynamics of technological innovation systems: A scheme of analysis, Research Policy, Vol. 37/3, pp. 407-429, https://doi.org/10.1016/j.respol.2007.12.003.

Bloomberg LLP (2020), Bloomberg Terminal, (accessed June 2020).

Breakthrough Energy (2020), Our investment portfolio, (web page), https://www.b-t.energy/our-investment-portfolio (accessed June 2020).

Bresnahan, T. and M. Trajtenberg (1995), General purpose technologies “Engines of growth”? Journal of Econometrics, Vol. 65/1, pp. 83-108, https://doi.org/10.1016/0304-4076(94)01598-T.

Brohi, E.A. (2014), Ammonia as fuel for internal combustion engines?: An evaluation of the feasibility of using nitrogen-based fuels in ICE, Master's Thesis in Sustainable Energy Systems, Chalmers University of Technology, Gothenburg, Sweden, http://publications.lib.chalmers.se/records/fulltext/207145/207145.pdf.

Calvino, F. and M. Virgillito (2017), The innovation-employment nexus: A critical survey of theory and empirics, Journal of Economic Surveys, Vol. 32/1, pp. 83-117, https://doi.org/10.1111/joes.12190.

Cleantech Group (2020), i3 database, www.cleantech.com/i3 (accessed May 2020).

Cornell University, INSEAD and WIPO (2018), The Global Innovation Index 2018: Energizing the World with Innovation, https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2018.pdf.

IEA. All rights reserved.

Díaz Anadón, L. (2012), Missions-oriented RD&D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States, Research Policy, Vol. 41/10, pp. 1742-1756, https://doi.org/10.1016/j.respol.2012.02.015.

EPO and IEA (European Patent Office) (International Energy Agency) (2020 forthcoming), Innovation in Batteries and Electricity Storage: A Global Analysis.

European Cement Research Academy (2012), ECRA CCS project: Report on phase III, TR-ECRA-119/2012, European Cement Research Academy, Dusseldorf, Germany, https://ecra-online.org/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_III.pdf.

Fleming, L. et al. (2019), Government funded research increasingly fuels innovation, Science, Vol. 364/6446, pp. 1139-1141, https://doi.org/10.1126/science.aaw2373.

Gaddy, B., V. Sivaram and F. O'Sullivan (2016), Venture capital and cleantech: The wrong model for clean energy innovation, MIT Energy Initiative Working Paper, MIT Energy Initiative, Cambridge, Massachusetts, https://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.

Gallagher K. et al. (2012), The energy technology innovation system, Annual Review of Environment and Resources, Vol. 37, pp. 137-162, https://doi.org/10.1146/annurev-environ-060311-133915.

Gross, R. (2018), How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end-use technology, Energy Policy, Vol. 123, pp. 682-699, https://doi.org/10.1016/j.enpol.2018.08.061.

Grubler, A. et al. (2012), Policies for the energy technology innovation system, Chapter 24 in: Global Energy Assessment: Toward a Sustainable Future, Cambridge University Press, Cambridge, United Kingdom and New York, NY, United States and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1665-1744, https://doi:10.1017/CBO9780511793677.030.

Grubler, A. and C. Wilson (2013), Energy Technology Innovation: Learning from Historical Successes and Failures, Cambridge University Press, Cambridge, https://doi.org/10.1017/CBO9781139150880.

Hekkert, M. et al. (2007), Functions of innovation systems: A new approach for analysing technological change, Technological Forecasting and Social Change, Vol. 74/4, pp. 413-432, https://doi.org/10.1016/j.techfore.2006.03.002.

Hoppmann, J. (2018), The role of interfirm knowledge spillovers for innovation in mass-produced environmental technologies: Evidence from the solar photovoltaic industry, Organization & Environment, Vol. 31/1, pp. 3-24, https://doi.org/10.1177%2F1086026616680683.

IEA (International Energy Agency) (2020a), Energy Technology Perspectives Special Report on Clean Energy Innovation, IEA, Paris, https://www.iea.org/reports/clean-energy-innovation.

IEA. All rights reserved.

IEA (2020b), Global Energy Review 2020, https://www.iea.org/reports/global-energy-review-2020.

IEA (2020c), World Energy Investment 2020, IEA, Paris, https://www.iea.org/reports/world-energy-investment-2020.

IEA (2020d), Energy Technology RD&D Budgets 2020, IEA, Paris, https://www.iea.org/reports/energy-technology-rdd-budgets-2020.

IEA (2019), World Energy Outlook 2019, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2019.

IEA (2017), Early-stage Venture Capital for Energy Innovation: Financing Models, Trends and Implications for Policy, Insights Series, IEA, Paris, https://webstore.iea.org/insights-series-2017-early-stage-venture-capital-for-energy-innovation.

IEA (2011), IEA Guide to Reporting Energy RD&D Budget/Expenditure Statistics, IEA, Paris, https://www.iea.org/reports/iea-guide-to-reporting-energy-rd-and-d-budget-expenditure-statistics.

IPCC (Intergovernmental Panel on Climate Change) (2018), Global Warming of 1.5°C, World Meteorological Organization, Geneva, Switzerland, https://www.ipcc.ch/sr15/

Izsak, K. et al. (2013), The impact of the crisis on research and innovation policies, Study for the European Commission DG Research, Technopolis Group Belgium and Idea Consult, https://ec.europa.eu/research/innovation-union/pdf/expert-groups/ERIAB_pb-Impact_of_financial_crisis.pdf.

Kim, Y. and C. Wilson (2019), Analysing energy innovation portfolios from a systemic perspective, Energy Policy, Vol. 134, https://doi.org/10.1016/j.enpol.2019.110942.

Kohl, A. and R. Nielsen (1997), Gas Purification, Gulf Professional Publishing, Oxford, https://doi.org/10.1016/B978-0-88415-220-0.X5000-9.

Kraftwerk Forchung (2013), CO2RRECT: Storing electricity while simultaneously capturing CO_2, (news report), http://kraftwerkforschung.info/en/co2rrect-storing-electricity-while-simultaneously-capturing-co2/page/0.

Matsunaga, M., F. Tatsuya and O. Kuniaki (2009), Powertrain system of Honda FCX Clarity fuel cell vehicle, World Electric Vehicle Journal, Vol. 3/4, pp. 820-829, https://doi.org/10.3390/wevj3040820.

Mazzucato, M. (2018), Mission-oriented innovation policies: Challenges and opportunities, Industrial and Corporate Change, Vol. 27/5, pp. 803-815, https://doi.org/10.1093/icc/dty034.

Molino, A. et al. (2018), Biofuels production by biomass gasification: A review, Energies, Vol. 11/4, pp. 811, https://doi.org/10.3390/en11040811.

Nemet, G.F. and D.M. Kammen (2007), US energy research and development: Declining investment, increasing need, and the feasibility of expansion, Energy Policy, Vol. 35/1, pp. 746-755, https://doi.org/10.1016/j.enpol.2005.12.012.

IEA. All rights reserved.

Nuber, D., H. Eichberger and B. Rollinger (2006), Circored fine ore direct reduction, Millenium Steel 2006, pp. 37-40, https://www.millennium-steel.com/wp-content/uploads/articles/pdf/2006/pp37-40%20MS06.pdf.

OECD (Organisation for Economic Co-operation and Development) (2020), Innovation in environment-related technologies, technology development, Environment Database, https://stats.oecd.org.

OECD (2015), Emerging technologies & firm dynamics: The implications of green growth, OECD, Paris, https://issue.com/oecd.publishing/docs/ggsd_2015_issuepaper2_finalpdf.

OECD (2009), Responding to the economic crisis: Fostering industrial restructuring and renewal, OECD, Paris, www.oecd.org/sti/ind/respondingtotheeconomiccrisis-fosteringindustrialrestructuringandrenewal.htm.

Pellens, M. et al. (2018), Public investment in R&D in reaction to economic crises: A longitudinal study for OECD countries, ZEW – Centre for European Economic Research, Discussion Paper No. 18-005, https://dx.doi.org/10.2139/ssrn.3122254.

Roberts, C. and F. Geels (2018), Political acceleration of socio-technical transitions, in Jenkins, K. and D. Hopkins (eds.), Transitions in Energy Efficiency and Demand: The Emergence, Diffusion and Impact of Low-Carbon Innovation, Routledge, pp. 177-194, https://doi.org/10.4324/9781351127264.

Ruttan, V. (2008), General purpose technology, revolutionary technology, and technological maturity, Staff Papers 6206, University of Minnesota, Department of Applied Economics, http://dx.doi.org/10.22004/ag.econ.6206.

Schafer, A. et al. (2019), Technological, economic and environmental prospects of all-electric aircraft, Nature Energy, Vol. 4, pp. 160-166, https://doi.org/10.1038/s41560-018-0294-x.

TATA Steel (2017), The HIsarna ironmaking process, (presentation), https://iea.blob.core.windows.net/assets/imports/events/245/ISTRM_Session3_HISARNA_201117.pdf (accessed May 2020).

Thackeray, M., C. Wolverton and E. Isaacs (2012), Electrical energy storage for transportation: Approaching the limits of, and going beyond, lithium-ion batteries, Energy & Environmental Science, Issue 7, pp. 7854-7863, https://doi.org/10.1039/C2EE21892E.

Wilson, C. and Y.J. Kim (2019), Analysing energy innovation portfolios from a systemic perspective, Energy Policy, Vol. 134, https://doi.org/10.1016/j.enpol.2019.110942.

Zemships (2008), One hundred passengers and zero emissions: The first ever passenger vessel to sail propelled by fuel cell, https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=Zemships_Brochure_EN.pdf.

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Chapter 7. Making the transition to clean energy

- More than 125 governments have formally discussed net-zero emissions targets, and over a dozen of countries and the European Union, accounting for around 10% of global energy-related CO_2 emissions, have formulated these ambitions in law or proposed legislation. Many companies have also announced carbon-neutral targets. Achieving net-zero emissions depends critically on accelerating clean energy technology development and deployment.
- Making a path to net-zero emissions requires governments to establish a long-term vision for their energy sector to guide future expectations and build investor confidence, and to support the strategy by tracking progress, re-prioritising as necessary, and communicating expectations and progress effectively.
- Long-term visions need to be supported by clean energy transition strategies and actions tailored to local infrastructure and technology needs. Effective policy toolkits must be built around five core areas:
    1. **Tackle emissions from existing assets.** Much of the existing capital stock will remain in operation decades into the future, but there is scope to retire some assets early or re-purpose them, taking advantage of investment cycle timetables.
    2. **Strengthen markets for technologies at an early stage of adoption.** It is for governments to set the framework for markets; they can maximise the contribution from private capital with appropriate instruments and incentives.
    3. **Develop and upgrade infrastructure that enables technology deployment.** Careful strategic planning is necessary to avoid bottlenecks in the deployment of clean energy technologies.
    4. **Boost support for research, development and demonstration.** Achieving net-zero emissions requires rapid progress in developing new early stage technologies. Options range from increased public R&D funding to support for large-scale demonstrators.
    5. **Expand international technology collaboration.** The scale and urgency of the challenges mean that there is a strong case for international co-operation which can make use of existing multilateral forums.
- Economic stimulus measures and recovery plans in response to the Covid-19 pandemic offer an opportunity to take action that would boost the economy while supporting clean energy and climate goals, including action in these five areas.

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Introduction

The global energy system today relies heavily on the unabated use of fossil fuels that emit around 35 gigatonnes of carbon dioxide ($GtCO_2$) each year. Today the challenge we face is to transform this system within half a century to one that delivers ample energy services to a growing number of people without emitting any CO_2 on a net basis. This is an unprecedented challenge, but the severity of the threat posed by the climate crisis means that success is essential.

The preceding chapters of this *Energy Technology Perspectives* (*ETP*) demonstrate that many clean energy technologies already are available and that they are often able to compete on costs in markets. Others need to progress from the demonstration stage to full commercialisation and down the learning curve for costs to fall, performance to improve and to be economically viable. Technology alone cannot resolve the climate crisis, but it is clear that it has a vital role to play: without the further development and deployment of new and emerging clean energy technologies on a massive scale, it will not be possible to meet the goals of an energy sector with net-zero emissions while underpinning economic development and providing access to modern energy services for all.

Past experience suggests that the energy sector can rise to the challenge, provided that the right framework is put in place (see Chapter 1). The highly capital-intensive and long-term nature of energy investment brings with it a great deal of risk, particularly for investment in technologies that are at an early stage of commercialisation. Companies of all sizes and across all sectors need visibility about governments' commitments and timelines if they are to calibrate their business strategies to the needs of a net-zero emissions pathway. Investors and consumers also need a clear vision of the strategy and framework if they are to effectively participate.

The Covid-19 pandemic makes the role of governments more important than ever. As the Covid crisis took hold in early 2020, the state of play for the clean energy transition was that the pace of adoption of clean energy technologies and investment in research and development (R&D) was not sufficient to meet the scale of the challenges, especially in sectors that currently have limited opportunities in commercial and scalable low-carbon options. As governments and stakeholders are designing and implementing response and economic recovery packages, there is a fortuitous window to accelerate the deployment of clean energy technologies, systems and infrastructure that will boost economic recovery, job creation, affordable energy services and other benefits while at the same time advancing the pathway to net-zero emissions from the energy sector to strive towards climate and sustainable development goals.

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This chapter reviews emerging plans and targets by governments to achieve net-zero emissions in the long term. It also sets out some guiding principles for the future deployment of clean energy technologies for policy makers: these principles draw on the analysis and findings in this report. The aim is to assist governments in developing and delivering clean energy technology strategies for net-zero emissions.

Government targets for net-zero emissions

Most energy producing and consuming assets have long lifetimes and require large-scale investment. This makes long-term planning very important in the energy sector. Governments have long been active in setting frameworks, regulations and targets for the energy sector to ensure security of supply and to support goals such as emissions reduction, affordability, access to modern energy services, and environmental protection. Such long-term planning has taken on more significance since the Paris Agreement in 2015. It has a vital role to play in establishing expectations about future policy action to deliver the commitments in the Agreement, and in shaping the direction and development of investment in energy innovation in that context.

By August 2020, 14 countries and the European Union had adopted formal net-zero emission targets[1] in national law or proposed legislation to that effect, with a target date in 2030, 2045, 2050 or beyond (Table 7.1). Most of these commitments are very recent: the targets set by France, United Kingdom and New Zealand were adopted during the second half of 2019, while the targets proposed in Chile and Hungary were set out in legislative plans in January and June 2020 respectively. Together, the countries adopting or proposing these targets represent around 10% of current energy-related global CO_2 emissions. Nineteen other countries, responsible for an additional 10% of global emissions, have also set net-zero emission targets in policy documents. Similar targets are under discussion in about 100 other countries with a combined emissions share of around 5%.

[1] This section tracks net-zero energy-related CO_2 emissions targets, excluding emissions related to international transportation and trade. Therefore, country commitments may be broader, and may, for example, include all greenhouse gases.

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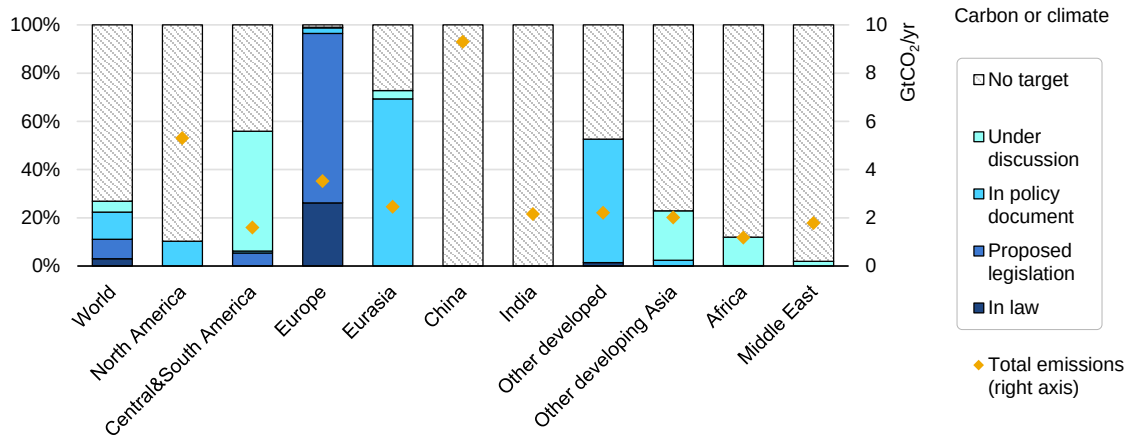
Figure 7.1 Share of energy-related CO_2 emissions covered by national and supra-national public net-zero emissions targets today



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Notes: The emissions coverage by national and supra-national targets excludes sub-national commitments (e.g. commitments from Australian or US states, Chinese provinces, cities). Following the European Union Climate Law, EU member states are classified in the category "proposed legislation" unless the country has a target already in domestic law (Denmark, France and Sweden). The category "in policy document" includes targets that have not been proposed as legislation, but that have been described in policy documents such as long-term strategies submitted to the United Nations Framework Convention on Climate Change. A number of countries have climate neutrality targets (net-zero greenhouse gas emissions), which are stronger than carbon-neutral commitments (net-zero CO_2 emissions).

Countries responsible for around one-fifth of global energy-related CO_2 emissions have formulated net-zero emissions ambitions in laws, legislation or policy documents.

How these targets are intended to be met varies across countries, notably with respect to the use of international carbon credits. Sweden, Norway, Chile and Switzerland plan to make use of international carbon offsets to meet their targets, while France, Fiji and Costa Rica do not. The rules on using international carbon markets to reduce emissions have yet to be finalised in UN Climate Change Conference (COP) discussions. Quantifying the need for these international markets would help to avoid both a potential lack of supply and a delay in national decision making about decarbonisation (Falduto et al., 2020).

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Table 7.1 Government carbon or climate neutral targets by legal status

Legal status	Year	National and supra-national entities	Selected sub-national entities (non-exhaustive)
	Already achieved	Bhutan, Suriname	
In law	2030	Norway	
	2045	Sweden	California, Hawaii, Australian Capital Territory, Scotland
	2050	Denmark, France, Netherlands,[2] New Zealand, United Kingdom, Hungary	New York State, Tasmania, South Australia, Queensland, Victoria, Melbourne, Sydney, New South Wales, Catalonia, Galicia, Basque Country
Proposed legislation	2050	Chile, European Union, Fiji, Spain, Slovenia, Ireland, Luxembourg	Washington State, Massachusetts, Catalonia, etc.
In policy document	2030	Uruguay	
	2035	Finland	
	2040	Iceland, Austria	
	2050	Canada, Costa Rica, Cyprus,[3] Germany, Latvia, Liberia, Marshall Islands, Papua New Guinea, Portugal, Slovakia, Switzerland	Nevada
	2070	Ukraine	
	"As early as possible in the second half of the century"	Japan, Singapore	
	2100	Russian Federation	

Note: European Union countries are mentioned explicitly when their commitment is more advanced or more ambitious than that of the European Union, for example in terms of legal status, implementation plans or definitions.

Among the countries that have adopted or are considering net-zero emissions targets, several have announced their intention to submit an enhanced climate action plan and/or a long-term strategy by the end of 2020. They include the members of the Climate Ambition Alliance (Annex II) and the signatories of the Carbon Neutrality Coalition, both of which bring together a group of countries, cities and organisations that have committed to take concrete and ambitious action to achieve the aims of the Paris Agreement. The members of these two groups together account for around

[2] The Climate Act sets a target of 95% greenhouse gas emissions reduction in 2050, compared with a 1990 baseline. (www.iea.org/policies/8632-climate-act).

[3] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

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20% of current global CO_2 emissions. More recently, the Covid-19 crisis has led to government spending pledges in support of economic recovery, and these could spur additional commitments to net-zero targets and action plans (Box 7.1).

Box 7.1 Covid-19 government recovery packages in support of net-zero emissions targets

The European Commission has proposed a Covid-19 recovery plan focused on a reinforced long-term EU budget and on "Next Generation EU", a EUR 750 billion recovery instrument. To make it consistent with its 2050 net-zero emissions ambition (Figure 7.1), the EU budget is currently organised around the European Green Deal work programme and its key pillars (building a circular economy, rolling out clean energy technologies, green mobility and alleviating socio-economic impacts for the most affected workers and communities). Next Generation EU could become the largest decarbonisation package so far, provided that agreement on the details can be reached between the European Parliament and the 27 member states. The program is also designed to attract at least hundreds of billions of euros of additional public and private investment in the coming years, as EUR 1.5 trillion will be needed in 2020-21 to achieve Europe's green and digital transition (EC, 2020).

Examples of decarbonisation measures part of EU's proposed recovery plans

EU green deal pillar	Examples of concrete targets	Targets in the Sustainable Development Scenario
Circular economy	Doubling annual renovation rates of existing buildings.	A third of the existing buildings stock renovated by 2050.
Clean energy technologies	6 GW of renewable hydrogen electrolysers by 2024, 40 GW by 2030.	Around 40 GW of renewable hydrogen electrolysers by 2030.
Green mobility	Installing 1 million electric vehicle charging points.	6 million electric vehicle charging points by 2030.
Alleviate socio-economic impacts	Support re-skilling, create new opportunities (EUR 40 billion Just Transition Fund).	Decline of coal, oil and gas use by 40% by 2050, while renewable use jumps 60%.

Note: This list is illustrative, not exhaustive, of the European Union's commitment to make concrete progress to decarbonise its economy in the wake of the Covid-19 pandemic. EU targets and supporting programmes still need to be approved by its decision making bodies (including the European Parliament).

Other countries are also considering emissions reductions as part of their economic recovery packages. For instance, Canada has announced several funds to support the oil and gas industry in order to reduce methane emissions and clean inactive wells (Government of Canada, 2020). Japan is considering "adaptive recovery" in the context of ensuring that infrastructure is resilient to natural disasters (UNDRR, 2020). In most countries, climate-friendly measures proposed so far as part of recovery packages nonetheless fall short of addressing the net-zero emissions challenge.

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In addition to net-zero emissions targets set at national level, regional or state targets have been set in Australia, Brazil, Spain and United States. California and New South Wales in Australia have adopted net-zero emission targets, for example. A number of cities are also planning targets for emissions reductions or climate neutrality, including some members of C40's[4] "Deadline 2020" initiative and members of the Global Neutral Cities Alliance. Commitment to achieving net-zero emissions is also rising in private companies, utilities and other businesses, (Box 7.2) while the Climate Ambition Alliance (Annex II), an initiative launched by Chile in 2019, brings together cities, companies, organisations and investors to push for a co-ordinated decarbonisation effort across various sectors of the economy.

Box 7.2 Corporate net-zero emission targets

Some companies have embarked on efforts to decarbonise their operations. Some have announced carbon-neutral targets, generally for their own operations by 2050. A few companies have set targets that extend up and down the value chain, covering the use of the commodity being sold. For example, Toyota, Volkswagen and Mercedes aim to decarbonise their passenger vehicle fleet. ThyssenKrupp's climate neutrality target includes the use of its elevator and steel and cement plant technology. BP and Repsol intend to include emissions from the final combustion of the fuels they sell. A few companies, such as DHL Express, have set targets that extend to their contractors. Arrangements for accounting for these emissions will be important, although the scope of the emissions taken into account varies from company to company.

Decarbonisation strategies take a variety of forms. They can broadly be categorised into three main areas:

- **Fuel switching using commercially available technologies.** A number of vehicle manufacturers (e.g. Toyota, Volkswagen and Groupe PSA), air conditioner manufacturers (e.g. Daikin and BROAD Group) and rail operators (e.g. Deutsche Bahn, SNCF and Indian Railways) have announced intentions to switch to CO_2-free electricity for their operations. Others, including Bosch, aim to increase their on-site renewables-based power production. Many car manufacturers also plan to increase the share of electric and hydrogen-powered models in their sales, for example, Daimler AG aims to produce only zero emission passenger cars by 2039. SSAB, a Swedish-Finnish steel company, aims to demonstrate fossil fuel-free steel production using electrolytic hydrogen by 2025. Other steel companies

[4] C40 is a network of the world's megacities committed to addressing climate change.

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such as ArcelorMittal Europe, Liberty Steel and Tata Steel Europe are considering their approach. These corporate commitments depend on the availability of decarbonised electricity sufficient to meet company needs. The RE100 initiative, which brings together more than 200 influential businesses committed to 100% renewable electricity through on-site production or market purchases, aims among other things to highlight and address policy and market barriers to corporate sourcing of renewable electricity.

- **Developing innovative clean technologies.** This is the main strategy where emissions are particularly challenging to reduce, including shipping, aviation and heavy industry sectors. It implies a strong commitment to invest in R&D. For instance, Maersk, the world's largest container ship and supply vessel operator, aims to adopt carbon-neutral vessels by 2030 (Maersk, 2019). The International Airlines Group, born from a merger agreement between British Airways and Iberia, plans to invest USD 400 million over the next 20 years in developing sustainable aviation fuels and infrastructure development (IAG, 2020). Dalmia Cement is aiming for new blends using less limestone and, like Heidelberg Cement, is also developing on-site carbon capture, utilisation and storage (CCUS) projects.
- **Buying carbon offsets.** This approach is being used by some companies as a way of offsetting their emissions and is under consideration by others. For instance, Google has claimed carbon neutrality in its operations since 2007 mainly on the strength of agricultural methane capture, landfill gas capture and forestry projects. Air France and British Airways have announced carbon-neutral domestic flights from 2020[5] on the back of offsets coming mostly from projects related to forest protection and reforestation or cook stoves. CO_2 removal is being considered by companies including Microsoft, which aims to become carbon negative by 2030 and to remove its historical emissions by 2050: this may help to drive investment in relevant technologies (Carbon Engineering, 2019). However, the use of carbon offsets does raise issues concerning their verifiability and additionality, especially when they are pursued in place of potential emissions reduction measures within a company. Concerns have been expressed, for instance, that the impact of 73% of the Certified Emission Reduction supply issued by the UNFCCC Clean Development Mechanism could be overestimated (EC, 2016).

[5] These two companies do not show in the figure below as they are not listed among the top ten companies in terms of scheduled passengers–kilometres flown in 2018.

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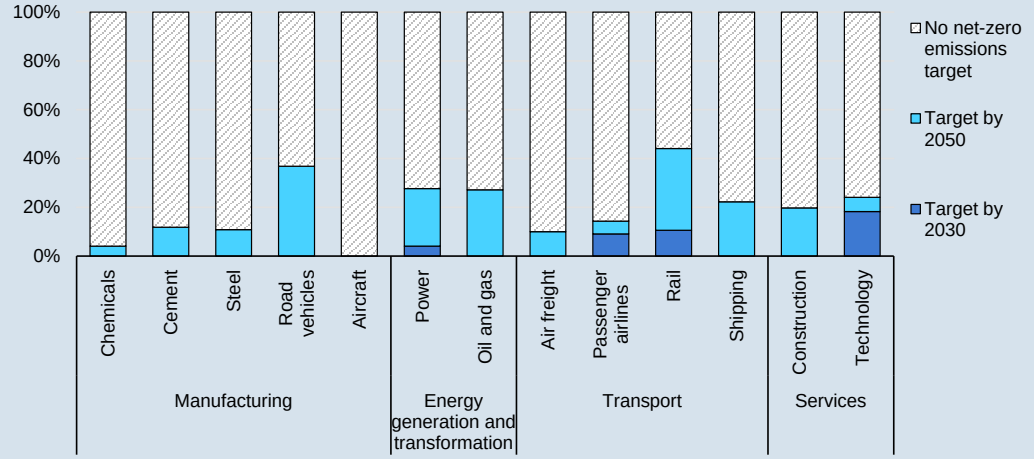
Share of activity covered by corporate carbon-neutral targets among the largest* corporate players



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* Each sector combines information on the 10 to 25 largest contributors to sectoral activity. Together, these players represent from 30% (for steel and power) to 76% (for car manufacturers) of the activity of their sectors.

Notes: Sectoral activity was assessed based on output production for steel and road vehicle manufacturers; output capacity for power generation, aluminium and cement; market revenues for chemicals, aircraft manufacturers, construction, rail operators and technology; scheduled passenger-kilometres flown for passenger airlines; freight tonne-kilometres flown for freight air operators, and cargo carrying capacity for maritime operators. The technology sector includes computer hardware, software, electronics, semiconductor, internet, telecom equipment, e-commerce and computer services. The targets encompass carbon and climate neutrality targets on operations or wider scopes by 2030, 2050 or in few cases earlier.

These targets are of vital importance given the central role that all types of businesses will have to play to achieve net-zero emissions in the energy sector. Corporate players have a key role in driving innovation and deployment of clean energy technologies both in their commercial activity and along the underlying supply chains. Commitments from consumer product companies could help to distribute potential extra costs across the value chain, drive markets for more sustainable raw materials and justify significant investment in upstream production.

Implementing strategies towards net-zero emissions

An energy transition to net-zero emissions begins with a peak in CO_2 emissions. Recent trends have been promising. CO_2 emissions remained at the same level over three consecutive years (2014-16), and although emissions rose again in 2017 and 2018, energy-related CO_2 emissions in 2019 were at the level of 2018.

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It is clear that the Covid-19 pandemic will result in a dramatic decline in CO_2 emissions: IEA analysis suggests that 2020 could see a drop in global energy-related CO_2 emissions of almost 8%, or around 3 Gt. This would be the largest reduction ever over the course of a year, more than six-times the size of the previous record reduction of 0.4 Gt in 2009 following the financial crisis. However, in 2020 this entire decline is due to curtailment in economic activity rather than structural changes in the way the world produces and consumes energy. This means that emissions are very likely to rebound as economies recover. The forthcoming 2020 edition of the *World Energy Outlook* will provide a deep dive into the projected course of the energy sector over the next ten years.

The good news is that there is no shortage of technologies or policy tools to bring about a structural peak in energy- and industry-related CO_2 emissions in the near-term and a steep decline thereafter. It clearly makes sense to maximise the scope for use of commercially available low-carbon technologies, in particular energy efficiency and renewables. As this report makes clear, however, a transition to net-zero emissions will require more than existing technologies alone can deliver (Figure 7.2). In the Sustainable Development Scenario, the bulk of the pre-commercial technologies that are widely deployed to reach net-zero emissions by 2070 are projected to be commercialised over the next ten years. In the Faster Innovation Case, technologies at demonstration and large prototype stage need to make it to market in about half that time and then to be deployed very rapidly in order to bring forward the year when net-zero emissions are achieved to 2050. The next decade is crucial for energy technology innovation in both cases.

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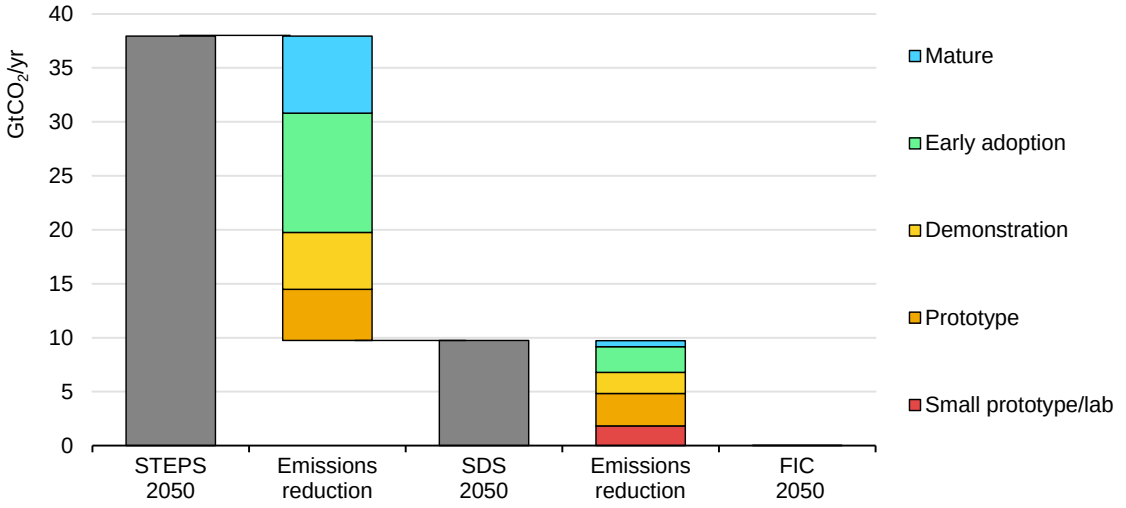
Figure 7.2 Global CO_2 emissions savings by current technology readiness category in the Faster Innovation Case relative to the Sustainable Development Scenario in 2050



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Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario; FIC = Faster Innovation Case. See Box 2.6 in Chapter 2 for the definition of the TRL categories large prototype, demonstration, early adoption and mature.

Reaching net-zero emissions requires a very rapid uptake of technologies currently at the demonstration or prototype stage: such technologies account for almost 70% of emissions reductions in 2050 in the Faster Innovation Case relative to the Sustainable Development Scenario.

The transformation of the energy system that is needed to develop and deploy a broad portfolio of technologies will not happen at the scale or speed required without clearly formulated long-term government strategies, integrated into energy policy and system planning, to guide and reduce the risks of investment decisions. Such long-term strategies need to integrate near-term priorities and track progress against medium-term milestones to make them credible and to secure buy-in from businesses and investors. They also need to take account of other policy objectives including energy security and affordability and, in countries where relevant, achieving universal access to modern energy services.

Effective strategies will include a multitude of elements, yet three are of particular importance (Figure 7.3).

1. **Establish a vision of the future through road-mapping[6] processes.** High-level targets for carbon emission reductions in the energy sector as a whole should be

[6] Good roadmaps describe the journey and the destination in qualitative as well as quantitative terms. They also look at how the activities of the people and companies involved might change over time, so as to provide a foundation for a conversation about opportunities and trade-offs between relevant stakeholders.

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at the heart of the process, underpinned by the identification of realistic target markets for the deployment and development of particular technologies, and by long-term targets and interim milestones, developed in co-operation with technology experts, civil society and market analysts. There is not one recipe for success: plans will have to be designed in the context of the particular circumstances of individual countries. Given the challenges of decarbonising some end-use applications, there are strong arguments in favour of developing plans on a sectoral or application-specific basis that recognise what has to be provided to enable specific sectors to reach net-zero emissions (e.g. the supply of low-carbon steel or heat in buildings) and not just plans at the level of technology type (e.g. biofuels, wind power or heat pumps). As a result of this process, governments should develop a detailed view on:

- **Technology and infrastructure needs and identification of innovation gaps**. There is scope to map clean energy visions onto the existing technology landscape to identify where improvements in cost and performance are needed, and where there are cross-sectoral interactions. Tools such as the *Energy Technology Perspectives Clean Energy Technology Guide*[7] can be helpful in this process (see Chapter 2).
- **Priority technology areas and strategies for net-zero emissions**. Selecting the areas to prioritise is a difficult but essential exercise. There is scope for governments to share good practice in this area. Expertise, capacity, comparative industrial advantage and potential for spillovers are all important in this context. Analysis done for the Sustainable Development Scenario highlights the importance of considering cross-sectoral spillovers.

2. **Track progress towards stated policy goals, evaluate the impact of policies and establish processes for regular review of priorities (Box 7.3).** Committing to net-zero emissions means taking a long-term view and embracing uncertainty, but that does not diminish the importance of regular assessments of progress, and of adjusting priorities and policies as necessary in the light of these assessments. There is considerable potential for better data to help governments assess how their clean energy policies are performing, including by ensuring that the information needed for ex post evaluation is gathered along the way.
3. **Communicate the vision and progress to the public and build socio-political support.** The roll-out of enabling infrastructure, the adaptation and turnover of existing assets, and the development and deployment of new clean energy technologies are more likely to be successful if there is widespread public understanding of and support for what is being done. This requires transparency about the process, and early identification of possible areas of public concern and enthusiasm.

[7] For more information visit: www.iea.org/articles/etp-clean-energy-technology-guide.

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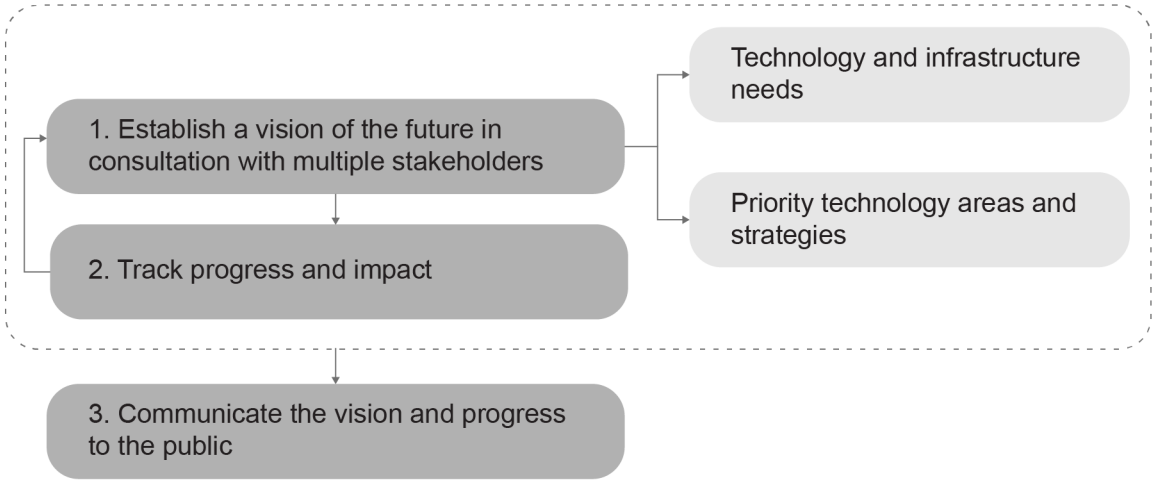
Figure 7.3 Governing process for a strategy towards net-zero emissions



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After establishing a vision of the future, governments need to continuously track progress and assess the impact of the adopted measures to deliver net-zero emissions, and to re-prioritise efforts as necessary along the way.

While multi-year priority setting is well established in places including the People's Republic of China ("China" hereafter), European Union and Japan, there is less experience with complementary processes to ensure flexibility and to evaluate outcomes with policy objectives.

Box 7.3 Tracking progress: A key element of net-zero emissions strategies

Tracking progress is vital to the success of net-zero emissions strategies. It helps to ensure that action is effective and that results are delivered, and it enables everyone to see what progress is being made. It also helps to identify technology areas that are struggling to keep up with requirements and enable timely adjustments to policies as and when needed.

Tracking overall progress in achieving clean energy policy goals needs to go well beyond traditional indicators such as the level of low-carbon technology investment and the emissions intensity per unit of energy demand and per unit of economic growth. Policy makers need to continuously monitor progress in all steps of critical value chains to avoid bottlenecks and to ensure that the innovation pipeline keeps producing new ideas and improved designs.

Tracking metrics need to be tailored to the level of maturity of each targeted technology. For technologies that have not reached markets yet, tracking efforts should focus on monitoring the pace at which such technologies go through the

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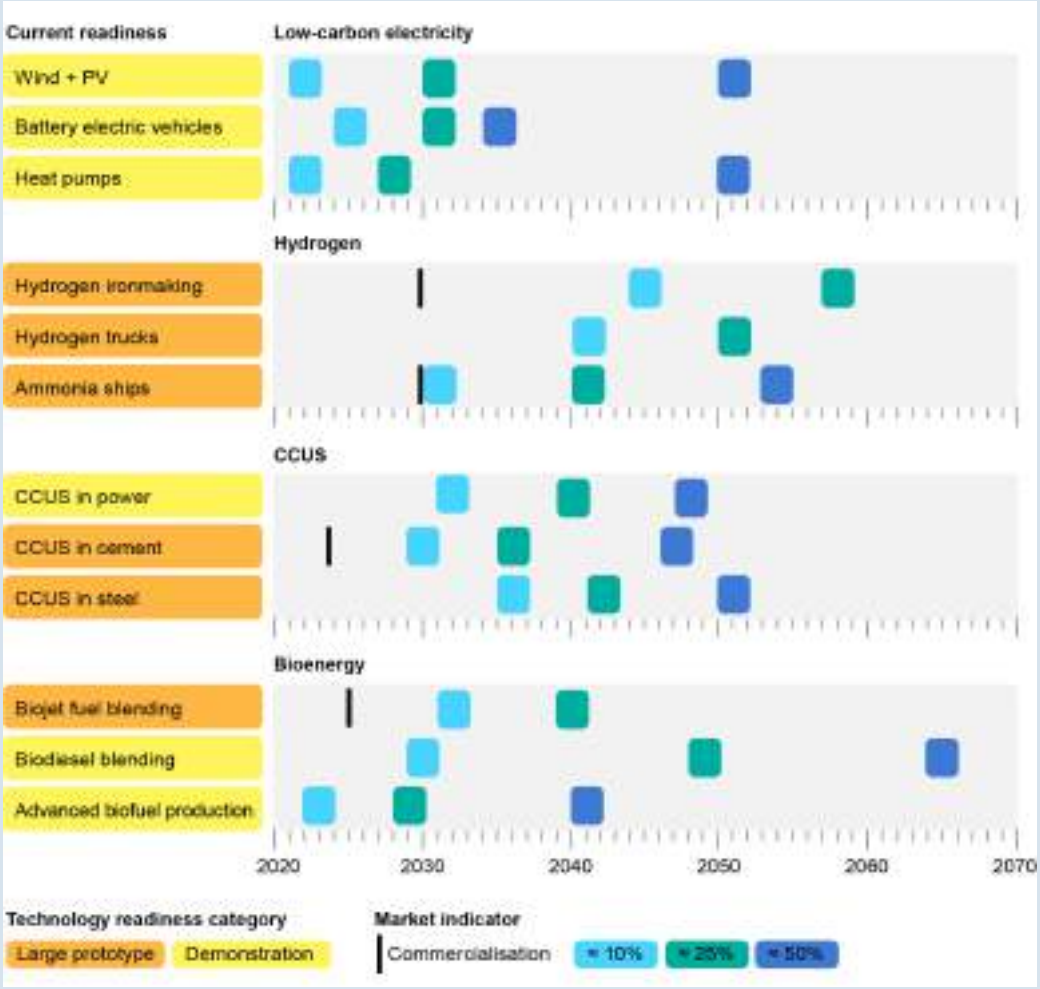
different development phases. The technology readiness level is a useful metric to use for this (see Chapter 2). For technologies already in the market place, tracking efforts should focus not just on the extent of their deployment but also on identifying other technologies with synergies and the extent of their deployment. Monitoring the expansion of manufacturing capacity for clean energy technologies and the progress of relevant infrastructure projects should also be part of the tracking exercise with a view to preventing technology deployment bottlenecks.

Global selected milestones of the transition to net-zero emissions in the Sustainable Development Scenario



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Notes: CCUS = carbon capture, utilization and storage. Commercialisation refers to the year when a given technology reaches markets. For technology families, the year of market introduction refers to the earliest year when a given technology design within that family is commercialised. For renewable power and fuels productions, market share refers to the share of generated electricity and produced fuels of total electricity generation and fuels production. For heat pumps, market share is the share of installed heating equipment in capital stock. For vehicles, market share is the share of vehicle sales. For industrial processes, market share refers to the share of production. For CCUS in power generation, market share refers to the electricity generation equipped with CCUS over that from thermal power plants (coal, gas, oil, and biomass).

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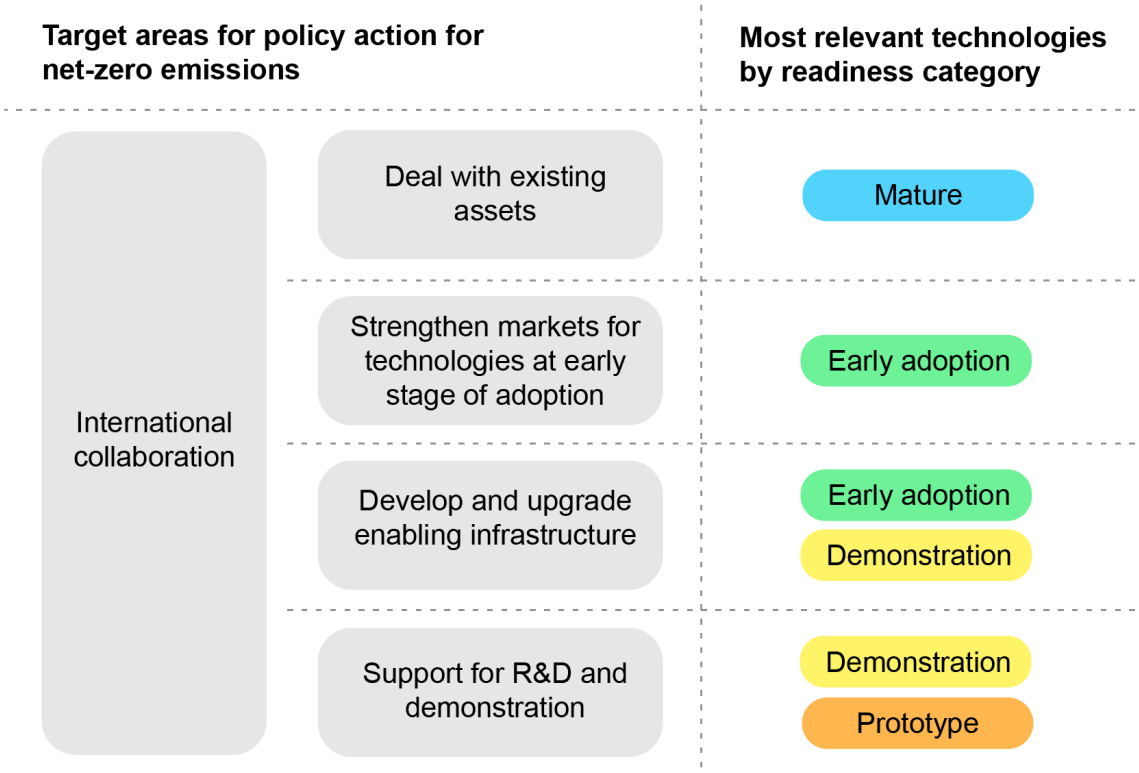
The IEA's Tracking Clean Energy Progress portal tracks global deployment progress at a technology-by-technology level.[8] The ETP Clean Energy Technology Guide maps the current level of maturity of more than 400 technologies for net-zero emissions across sectors. Both serve as means of calibrating progress against requirements for long-term pathways to net-zero emissions. The level of ambition at a technology-by-technology level will differ from country to country, but the collection and analysis of data will be important in all cases to track progress towards net-zero emissions. The IEA stands ready to assist all countries in that endeavour.

Figure 7.4 Core target areas for policy instruments to advance a net-zero emissions strategy by technology maturity level



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Governments need to design policies for technologies with various levels of maturity when they develop strategies to achieve net-zero emissions.

Whatever the emissions reduction target each country sets and the interim milestones in their accompanying roadmaps, achieving these depend on the policies and measures they adopt and the effectiveness of implementation. To be effective, policy measures need to be applied appropriately to a portfolio of technologies

[8] For details see: www.iea.org/topics/tracking-clean-energy-progress.

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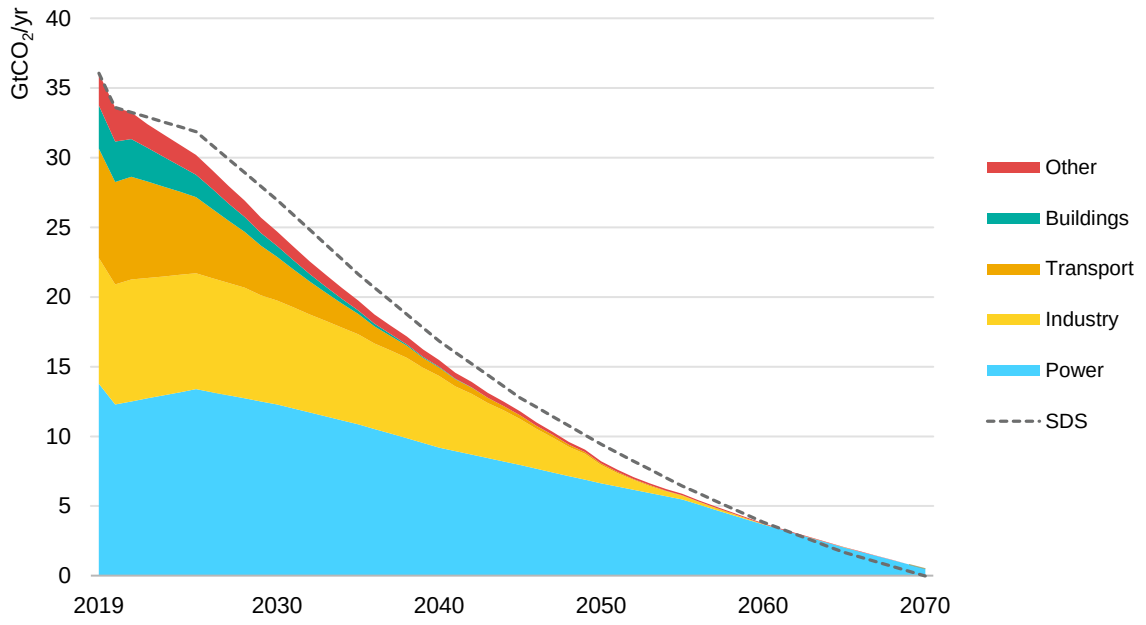
which are likely to be at various levels of maturity. Five core target areas for policy action can be defined that mirror the phases required to bring technologies from the laboratory to wider market deployment (Figure 7.4).

Tackle emissions from existing assets

For policy makers, the point of departure for drawing up a technology strategy for the clean energy transition should be an assessment of existing energy assets. To the extent that the existing capital stock and those assets currently under construction are expected to remain in operation decades into the future, the associated CO_2 emissions are often considered to be "locked in".

Figure 7.5 Global CO_2 emissions locked in by existing energy-related assets by sector measured against the CO_2 emissions trajectory of the Sustainable Development Scenario, 2019-70



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Notes: SDS = Sustainable Development Scenario. The sectors include assets under construction in 2019, the base year of this analysis. Analysis includes industrial process emissions which are accounted on a direct basis. Annual operating hours over the remaining lifetime remain as in 2019.

CO_2 emissions from the existing capital stock, including assets currently under construction, account for the majority of the remaining CO_2 budget for sustainability goals to be met.

The pace of the reduction in energy sector CO_2 emissions required by the Sustainable Development Scenario leaves very little room for adding new infrastructure that generates CO_2 emissions. This is because much of the existing energy capital stock – heating systems in homes, vehicles, airplanes, buildings, transport infrastructure

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and industrial equipment – will remain in use for decades, unless it is retired early or measures are taken to reduce emissions from those assets. We estimate that the global cumulative emissions that will arise from existing assets and those currently under construction until they stop operating amounts to nearly 750 Gt, equivalent to more than 90% of the cumulative CO_2 emissions in the Sustainable Development Scenario for reaching net-zero emissions by 2070 and above the emissions of a pathway that would make it possible for the energy sector to reach net-zero emissions by 2050 (Figure 7.5). Either way, virtually all new energy stock added in the coming decades will need to be carbon neutral, even after accounting for efficiency gains and CCUS.

However, there are several actions that can be taken and technologies that can be deployed to help unlock emissions from existing infrastructure:

- **Early retirement or repurposing of assets**, either because of a change in market conditions that makes them uneconomic or because of laws and regulations that force early closures or partial operation. Repurposing coal and gas power plants to provide balancing services or reserve capacity, rather than base load, is an interim strategy.
- **Refurbishment and retrofitting**, for example by insulating existing buildings, upgrading energy efficiency and applying emissions reduction technologies such as CCUS to the existing industrial and power infrastructure.
- **Fuel switching and incremental blending**, sometimes combined with some degree of retrofit, to allow the use of lower carbon fuels. Drop-in fuels (i.e. synthetic substitutes for conventional hydrocarbon fuels) for various transport modes and blending shares of waste and bioenergy into cement kilns are key examples that can be implemented with little modification to existing equipment. With only minor additional investments, biomass can be co-fired in existing coal power plants at levels up to 15-20%. For industrial processes and natural gas grids, there is scope to blend in small amounts of hydrogen or biomethane to reduce emissions intensity incrementally, ahead of more fundamental upgrades in coming years.

Modification to existing energy capital stock, even with readily available technologies, requires careful transition planning, in particular in the power and industry sectors, which are responsible for nearly 80% of all CO_2 emissions emitted by existing assets to 2070.

The scope for unlocking emissions differs significantly across regions, reflecting the landscape and age of their energy systems and existing infrastructure.

In general in advanced economies there is much more potential for early retirement of energy systems assets than in emerging economies: power stations and industrial plants are generally older, so the economic losses from early retirement would be

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lower. Planning would require careful consideration to ensure that energy security and international competitiveness are not compromised. Clear government signals would be needed to guide investment decisions towards low-carbon clean energy technologies so as to accelerate the decarbonisation of the industry concerned. Where the necessary clean energy technologies do not yet exist at the required scale, clear government signals indicating a commitment to address the emissions of the respective assets would help to facilitate innovation.

In emerging economies with more recently developed energy-related assets, the emphasis is likely to be more on retrofitting with more energy-efficient and less carbon-intensive technologies where it is economic to do so. In most cases, decarbonisation of such assets is likely to involve exploring technology opportunities for retrofit with CCUS or for repurposing them fully or partially to function with cleaner fuels and feedstocks. For instance, it may be possible to retrofit coal-gasification chemical or power plants and turn them into biomass-gasification assets in regions where sustainable biomass resources are available, once the relevant technology reaches successful demonstration.

The world's energy system cannot be transformed overnight, not least because low-carbon alternatives are simply not available at the scale required for this to happen. For example, even if all new car buyers today decided to opt for electric vehicles, there would not be enough supply to satisfy that demand, or enough charging stations to meet demand for recharging outside the home. Retooling factories to adapt to shifting demand and building new infrastructure will take time. Given this background, government strategies need to identify and promote opportunities for adapting existing assets over time through the effective deployment of clean energy technologies. Policies could, for example, support more widespread uptake of drop-in alternative low-carbon transport fuels that do not require the modification or scrapping of existing vehicles or fuel distribution systems, and could specify sustainability criteria to ensure that higher uptake yields real emissions reductions. Policies could also support the blending of low-carbon hydrogen into natural gas distribution pipelines so as to reduce emissions[9] while providing a base source of demand for hydrogen that could help bring down the cost of production.

In sectors where readily available alternatives for dramatic reductions in emissions intensity are lacking (i.e. those where emissions are hard to abate such as aviation or cement), decisions about whether or not to partially renew existing infrastructure are important (See Chapters 4 and 5). Incentivising early retirement or delaying investment could help avoid a new investment cycle occurring at the wrong time (Box 7.4).

[9] Arrangements would need to be made to ensure that pure natural gas continued to be supplied to chemical plants and other production processes that require it.

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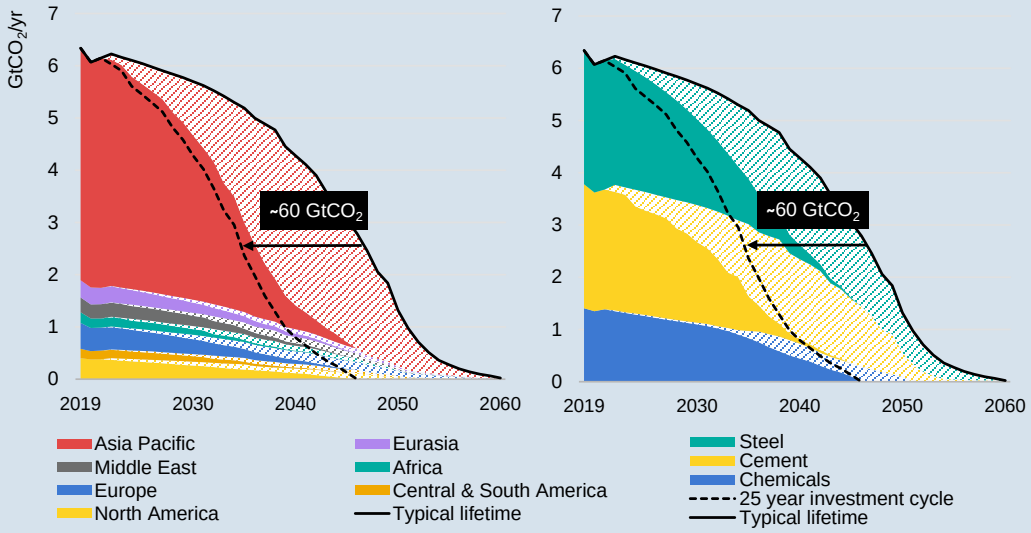
Box 7.4 Opportunities to unlock emissions from existing infrastructure

There is scope in a number of industrial sectors to reduce emissions at different stages of an asset's lifetime. In the steel sector, for example, the internal lining of a blast furnace typically needs to be replaced after 25 years. Doing so extends the life of the unit – and often the entire plant – by a further 25 years. For cement kilns the story is similar, while chemical plants tend to have more frequent cycles of major maintenance and more continuous expenditure. Investment cycles of this kind can be repeated multiple times, but the typical lifetimes of existing plants (30 years for chemicals, 40 years for steel and cement plants) suggests that 1-2 cycles is most common. Deciding not to invest at the end of the next investment cycle, and to retire or re-purpose plants at that stage, could reduce future emissions significantly: a reduction of 5-15 years in the operational period of assets in the steel, cement and chemicals sectors would bring a 40% reduction – nearly 60 $GtCO_2$ - in cumulative emissions from these sectors.

Unlocking CO_2 at the next investment cycle in key industrial sectors



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Notes: Typical lifetimes for steel, cement and chemicals assets are 40 years, 40 years and 30 years respectively. In the 25 year investment cycle case considered here, all assets are decommissioned after 25 years.

Intervening at the end of the next 25 year investment cycle could unlock around 60 $GtCO_2$ or around 40% of projected emissions from existing equipment in the steel, cement and chemical industries.

A parallel priority must be to avoid adding to the emissions trajectory in the coming years. With each new investment in a fossil fuel-based power plant, industrial boiler or conventional car or truck, an additional layer is added to the existing infrastructure

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emissions curve that stretches into the future, making it ever harder to keep cumulative emissions down to a level that is compatible with Paris Agreement climate goals.

Strengthen markets for technologies at an early stage of adoption

Effective government intervention is needed to accelerate the uptake of clean energy technologies at the early adoption stage. The key is to reduce their cost and performance gap relative to existing technologies by incentivising their deployment (see Chapter 6). Governments have a major role to play in making this happen, maximising the contribution from private capital through appropriate policies and measures and ensuring all links in clean energy technology value chains are addressed. Small, modular, mass-manufactured technology designs with high spillover potential offer valuable rapid learning dynamics and could have a particularly important role to play. Solar photovoltaics (PV) and lithium-ion (Li-ion) batteries are examples of how technology design has led to dramatic progress in the past: electrolysers, fuel cells, heat pumps and smart-home technologies all have the potential to do the same (IEA, 2020).

The two main types of instruments that governments can employ to create and nurture markets for clean energy technologies at an early stage of adoption are:

- **Market-pull instruments for clean energy technologies.** Stimulating demand for clean technologies, products and services facilitates their market uptake. Market deployment boosts economies of scale and learning-by-doing, which helps to improve the performance and reduce the cost of technologies. Different technologies will need various deployment incentive measures depending on value chain complexity and value for customers, among other factors (Table 7.2).
- **Continued R&D support after market introduction.** Supporting an evolving portfolio of competing designs at different stages of maturity for each priority area improves the chances of success: so does favouring options with rapid innovation potential. Historical evidence suggests that ongoing R&D is vital even after commercialisation to stimulate the further development of new designs and components and to bring down costs and improve performance. Diversity and competition help to spur progress and leave space for unexpected developments (IEA, 2020).

How market-pull instruments are applied, of course, will differ between technologies and technology categories. Though a general distinctions can be drawn between

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measures that will affect individual personal consumer choice, and those that will impact relevant decisions made by businesses and institutions, whether they be enterprises that provide energy services or operate manufacturing plants, or businesses and institutions that purchase technologies and energy services. While some policies can be aimed at both groups, policy formulation for the two groups may differ somewhat given differences in the priorities of the actor (businesses focused primarily on economics, personal consumers consider personal preferences and convenience), the nature of the actor (fewer number of corporates that can be directly regulated compared to large number of diffuse consumers), and the stage of the supply chain (businesses have more influence on the design of and inputs to products, consumers focus on service provision and must choose from available options).

For **personal consumers,** subsidies such as tax exemptions or rebates or direct purchase incentives can help to reduce an initial price premium for a new lower-emission technology or product, making it more affordable. Bans and phase outs of particularly high-energy consuming or CO_2 emitting technologies can steer consumers away from those technologies and open space for cleaner technologies to compete. CO_2 taxes at an appropriate level, which increases the cost of using carbon emitting technologies or the cost of products whose production is fossil fuel intensive, can also influence consumer choice towards more efficient and clean technologies. Efforts to raise awareness about energy consumption and emission levels such as energy efficiency labelling have also proven to be effective in pulling emerging technologies into the market.

Table 7.2 Examples of market-pull policy instruments by targeted group

Targeted group	Policy instruments	Examples
Personal consumers	Purchase incentives and tax exemptions	Tax rebates for household heat pump installations, purchase rebates for low or zero emission vehicle purchases.
	CO_2 pricing	CO_2 taxes, fuel taxes.
	Dynamic pricing	Time-of-use electricity pricing.
	Phase out inefficient and high emission technologies	Bans on incandescent light-bulbs, phase out of fossil fuel internal combustion engine vehicles.
	Standards and codes	Green building codes, vehicle fuel economy performance standards.
	Energy and sustainability labelling and certification	Energy efficiency labelling of household appliances, green building certification.
	Awareness raising and providing relevant information to influence choice for clean energy technologies	Public information campaigns about the benefits and ease of electric vehicles, heat pumps and other technologies.

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Targeted group	Policy instruments	Examples
Businesses, industry, and institutions	Average CO_2 performance standards (by technology type or sector)	Electricity and vehicle CO_2 intensity standards, industry sectoral CO_2 performance standards, CO_2 performance requirements in building codes.
	Flexible minimum market share requirements	Near-zero emission vehicle mandates, requirements for an average minimum share of near-zero emissions steel sales or purchases achieved through tradeable compliance certificates.
	CO_2 pricing	CO_2 taxes, emissions trading systems.
	Subsidies	Feed-in tariffs or feed-in premiums for low-carbon power, contracts-for- differences for low-carbon materials, industry tax credits for development of CCUS.
	Phase out inefficient and high emission technologies	Phase out of coal-fired power plants without CCUS.
	Public procurement of clean technologies	Purchase electric vehicles for government use, legislated requirements for low emission materials in publicly funded projects.
	Sustainability labelling and certification	Green steel or cement certification labelling.
	Financing for clean technology projects	Low interest and concessional loans, blended finance, sustainable finance taxonomies.

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For the **businesses and industry**, mandatory policies applied to energy providers, material producers, product and equipment manufacturers, and construction companies can be used to accelerate the deployment of new and emerging clean energy technologies. For example, CO_2 performance standards for a sector or technology area can be set which require a declining average CO_2 performance of sales or production, or minimum market share regulations can be adopted that require an increasing share of low-emissions sales or production. Designing these policies with flexibility in mind, for example by allowing the trading of compliance certificates, can further incentivise innovation efforts and reduce the overall costs of achieving the policy objective.

Businesses may be able to pass on any additional costs to consumers in many cases, for example through cross-subsidisation in vehicle markets or through slightly higher electricity prices. Where cost-pass through is more difficult, particularly in competitive international markets, other policies such as contracts-for-differences may help overcome competitiveness challenges. For example, a government could issue a tender for near-zero emission materials (e.g. steel, cement) and fund the cost difference for production relative to conventional high-emitting production for a guaranteed volume of materials; this is similar to a feed-in tariff for renewables generation thus offsetting additional cost of innovative technologies for low-carbon materials production.

Other forms of enterprise-focused incentives can be used, including green materials labelling targeted at product manufacturers and construction companies, and public

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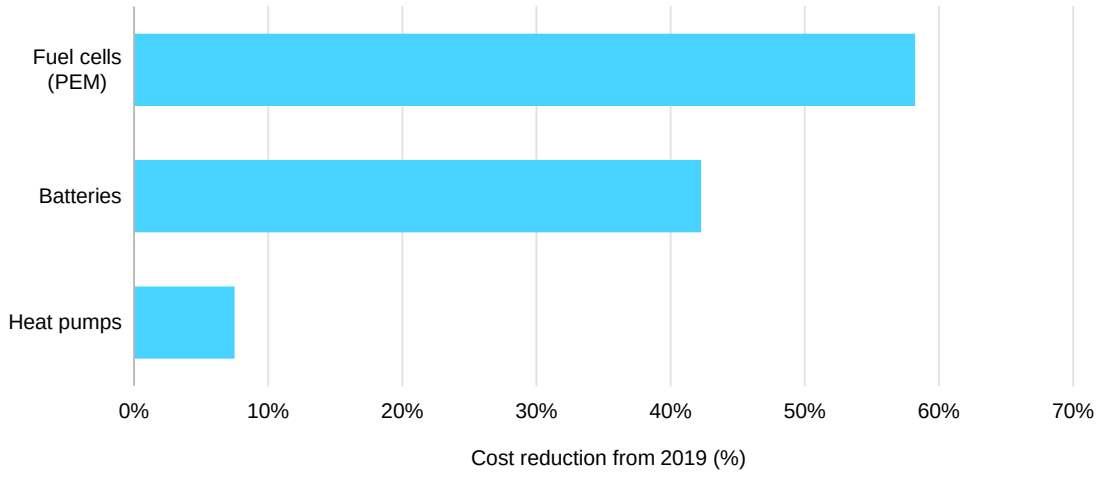
financing for clean technology projects. Public procurement can also play an important role, in that the government directly creates a market for clean technologies via demand from public institutions and enterprises. Broader policies like CO_2 taxes could also help pull producers towards low-carbon technologies, but may not suffice on their own, especially at the early stages of adoption or if the tax is set at a low level.

It is often difficult to draw analogies between various technologies in terms of accelerating market uptake as many have quite specific characteristics. Nonetheless, a considerable body of experience is available that draws from market deployment policies for specific clean energy technologies. A careful assessment of these experiences provides useful lessons for developing policy support for emerging clean energy technologies.

At the early adoption phase, the fundamental challenge is to move beyond initial applications to a point where market forces increasingly lead to cost reductions and generate a dynamic environment for the technology to thrive in the market and no longer need support. Early stages of adoption are also the ones where rewards are highest: the technology learning curve is steepest at this point, so that each doubling of new installations can bring significant cost reductions, building confidence in industry and investors about the future competitiveness of the technology. A focused and concerted drive now to adopt clean energy technology market-pull policies could help make the 2020s the decade of falling clean energy technology costs across the board (Figure 7.6).

Figure 7.6 Capital cost reductions of selected clean energy technologies at early stages of adoption in the Sustainable Development Scenario, 2019-30



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Notes: Fuel cells refer to proton-exchange membrane fuel cell types. Heat pumps here do not include geothermal applications.

Market-pull instruments for technologies at early stages of adoption can yield rapid cost reductions and build investor confidence in the prospect of them becoming competitive.

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Even after a new technology has overcome the barriers of early deployment and reached relative market maturity, a cost differential between low emission technologies and incumbent technologies may remain. Governments may wish to modify the policy approach at this stage, for example by phasing out subsidies. However, policy support is likely to need to be sustained over the long term, which may include through CO_2 taxes to reduce the price advantage of higher emitting technologies, technology phase-out policies for the highest emitting technologies (e.g. unabated coal-fired power phase out), and the provision of access to finance, among other options.

Develop and upgrade infrastructure that enables technology deployment

Achieving net-zero emissions requires significant investment in new infrastructure or upgrades to existing networks so as to provide smart electricity grids, alternative fuel distribution, CO_2 transport and storage, and communications networks for connected appliances and vehicles.

- Electric grids need to be upgraded and expanded to facilitate the integration of larger amounts of variable renewables in power generation, which will require more flexibility to deal with intermittent fluctuations in supply (see Chapter 3); to maintain necessary ancillary services; and to handle increased electricity demand arising from the electrification of road transport and other end-uses. The impending surge in electric vehicles, in particular, will create additional needs for recharging infrastructure (including fast-charging facilities) and catenary (overhead) lines on highways for electric trucks or ground-based feed rails for trucks, buses and cars.
- The adoption of alternative fuels in sectors where emissions are otherwise hard to abate requires the adaptation of existing infrastructure and the development of new infrastructure for their production and distribution. Each sub-sector has specific fuel requirements and each country its specific resource and technology opportunities. Potential alternative fuels include advanced biofuels, hydrogen, ammonia and other hydrogen-related synthetic fuels. International trade in these fuels would create a need for new ships and terminals.
- The large-scale deployment of CCUS depends on the construction of infrastructure to either permanently store or use CO_2 as feedstock for fuel or chemical products. Optimal initial locations for CCUS infrastructure are likely to be in or close to places where major emission sources coincide geographically with sites that are suitable for long-term storage or facilities that could use CO_2 in their operations. Industrial hubs, in particular around ports, could offer the best locations, enabling the CO_2 captured from multiple sources (such as hydrogen

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production in refineries or petrochemical facilities) to be transported through shared pipelines and stored in shared facilities, lowering costs for all parties. In the longer term, the development of direct air capture (DAC) would bring significant low-carbon energy supply infrastructure needs, and DAC facilities should ideally be located close to CO_2 storage sites to minimise CO_2 transport infrastructure requirements.

- District heating networks would have to convert from the traditional high-temperature operation mode to more efficient low-temperature operations and integrate low-carbon energy sources into the supply mix including intermittent ones, for which storage capacity would be needed to sustain a continuous heat supply.

Such infrastructure investments have strong public good elements by virtue of being natural monopolies and having large returns to adoption, meaning that later adopters often face lower costs and obtain higher benefits. Once infrastructure is in place, it can be a platform for innovation, encouraging new ideas for how to make best use of it, especially if third-party access is guaranteed. The need for new infrastructure however can be a major barrier to adoption if project promoters bear the risks of putting it in place while also bearing the risks of developing other elements of the value chain. There is therefore a strong case for governments to ensure that enabling infrastructure is put in place in line with demand for clean energy technologies. The timelines involved in developing new enabling infrastructure as well as the difficulties that often come with large-scale infrastructure projects mean that strategic and early development planning will be essential to ensure economies of scale and to maximise utilisation. The key requirements are to:

- **Incentivise network owners and operators to adapt and enhance existing enabling infrastructure** by integrating clean energy technologies into existing grids, pipelines and communication systems. Clear signals from governments about their commitment to reduce emissions could stimulate private investment in this area, which could be supplemented by direct financial support. Existing infrastructure could also be used to test new clean energy technologies and help accelerate their development. Regulated network operators are usually obliged to minimise risk, which reduces their capacity to incorporate new technologies into existing infrastructure, but new regulatory models are emerging to provide more scope for experimentation.
- **Mitigate investment risk in new enabling infrastructure projects that present a high-cost barrier** by providing some or all of the initial investment needed for enabling infrastructure projects that are essential for the achievement of net-zero emissions. Projects of this kind tend to have very high costs and risks: subsequent entrants are able to benefit from the infrastructure that these projects develop. This provides a rationale for direct government investment in the initial phase, in

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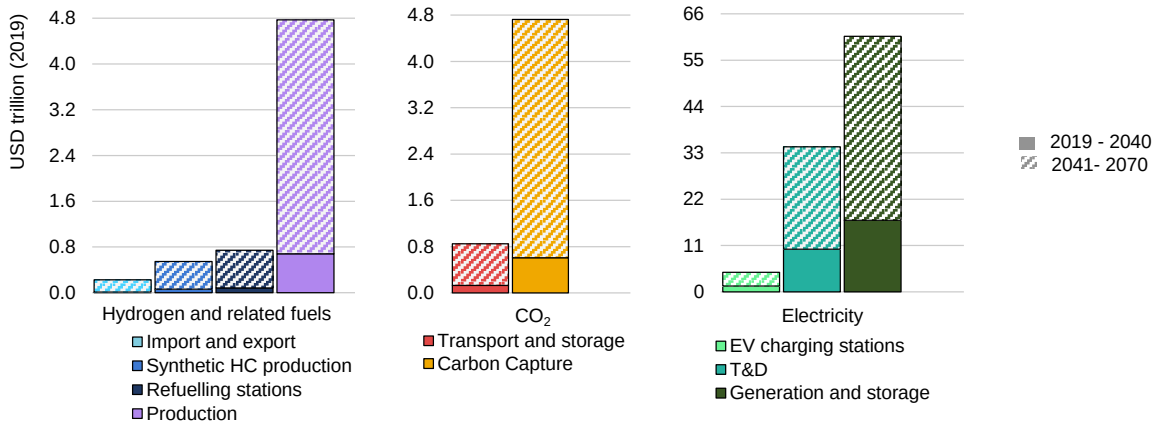
tandem with action to promote the use of the assets, for instance by establishing incentives for users during the first years of operation. Such projects are typically highly capital-intensive – together they require more than USD 100 trillion of cumulative investment worldwide through to 2070 in the Sustainable Development Scenario, about 90% of which relates to electrification, of which about 30% is needed by 2040 (Figure 7.7).

Infrastructure planning is critical to put in place targeted de-risking mechanisms at the right time to benefit from investment opportunity windows and prevent technology deployment bottlenecks. This can take many forms, but leveraging the current phase of the low cost of capital financing for the appropriate infrastructure development for new technologies can be an attractive opportunity for governments. Key industrial suppliers will need to ensure that their energy strategies are aligned with the innovation strategies of governments (and vice versa), and take due account of public acceptance.

Figure 7.7 Global cumulative investment in selected energy infrastructure in the Sustainable Development Scenario



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Notes: EV = electric vehicles; HC = hydrocarbons; T&D = transmission and distribution. Investments are undiscounted.

Electricity-related infrastructure dominates cumulative capital expenditure on energy infrastructure needed in the Sustainable Development Scenario.

Boost support for research, development and demonstration

The policies discussed to incentivise investment in clean energy technologies and supporting infrastructure would not only drive progress in technologies that are currently at an early stage of adoption, but also stimulate innovation by encouraging market competition and by providing a spur for the generation of new ideas on the part of researchers working on early-stage innovation. These policies, however, are

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not sufficient on their own to meet the challenges of achieving net-zero emissions: they need to be complemented by resources devoted to clean energy R&D and demonstration by both the public and private sectors (IEA, 2020).

While it is not possible to specify the precise amount that should be spent on R&D for clean energy technology or who is best placed to spend it in each country, the innovation system needs sufficient funding to generate a steady pipeline of new ideas in line with sectoral net-zero emissions visions. The proponents of these ideas need to be able to access funding to reach prototype and large-scale demonstration stage. The key requirements are to:

- **Support R&D activities for an evolving portfolio of competing designs at different stages of maturity for each priority**, favouring options with rapid innovation potential such as small, modular, mass-manufactured technology designs with high spillover potential (see Chapter 6).
- **Ensure that knowledge arising from publicly funded R&D is rapidly and openly shared** with the research community, and that taxpayer value is maximised. This is good practice for knowledge sharing purposes, for example, open access publishing is a condition of receiving EU R&D grants. Such transparency may also increase public support for R&D initiatives.
- **Mitigate the investment risks of key large-scale demonstrations for new clean energy technologies**. These may include CCUS for industrial facilities, fossil fuel-free iron and steel processes, new nuclear designs and floating offshore wind power – all of which face high capital costs for the first commercial projects. Public funding for such projects could be focused in particular on sectors that are hard to decarbonise, and could be conditional on the lessons learned from the projects being widely shared. Results-oriented public-private partnerships, international demonstration testbeds and conditional finance for international consortia from multilateral finance institutions are all worth exploring.

Given the critical importance of action during the next ten years and the time that it typically takes for emerging technologies to get from the laboratory to market, governments cannot afford to wait for market incentives to deliver the level of change required. The private sector is unlikely to have the ability to take these innovation risks on their own or to act with the urgency that is required.

Public R&D is expected to hold up better than private R&D in the wake of the Covid-19 pandemic. Governments of major economies may seek to boost innovation funding in response to the crisis. Companies face lower revenue and a lack of cash flow for R&D and capital investment to meet near-term growth targets, but there is little sign at this point of backing off from those who have made commitments to reduce their emissions intensity and test new energy technologies. For a rapid assessment of the likely impacts of Covid-19 crisis on their ability to support innovation towards longer

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term goals, we surveyed industrial contacts in May 2020. Responses indicated no change in long-term commitments, but they did indicate doubts among experts about whether companies would be able to keep their innovation pipelines flowing over the next couple of years (IEA, 2020).

Early-stage energy venture capital (VC) deals decreased by about 30% relative to 2018-19 levels in the first half of 2020. Declines are expected around the world in the second half of 2020 as a result of the financial risks, travel and other restrictions and policy uncertainty during the Covid-19 pandemic. This could put a brake on financing for innovative entrepreneurs at a time when several major governments are seeking to rely heavily on VC financing to bring clean energy technologies to market. It could also stimulate a policy discussion about the clean energy technology types that are best suited to VC financing and about potential models for bringing other types of technologies to market. With the exception of consumer products, for example, hardware often struggles to attract early-stage VC because it typically involves long development timescales and entails regulatory risks.

At a global level, successful energy innovation policies aim for a heterogeneous portfolio of technology designs and to facilitate competition between various options in real-world conditions. Successful energy innovation policies also differentiate between the types of support needed by various technology designs – in terms of their scale, manufacturing, value chains and spillover attributes – and at different stages of development. Successful government innovation programmes are clear about the part of the technology value chain they are targeting and realistic about what can be achieved at the national level given the size of their economies and their institutional capacity (IEA, 2020).

Expand international technology collaboration

The climate challenge is a global one, and technological progress to meet the challenge will be most efficient if countries are able to share some of the burden and opportunities internationally. Multilateral platforms for co-operation between governments already exist and are useful in this regard. As well, they can be strengthened to hasten the pace and wide disbursement of clean energy technologies. The key requirements are to:

- **Exchange good policy practice experience among relevant policy makers.** Several of the recommendations in this chapter concern actions that would have positive impacts but where there is not yet consensus on how best to implement them. It can include best practice lessons in how to prioritise clean energy policy approaches, how to tailor funding instruments and how to assess the impact of those measures and make course corrections where needed. Governments differ in their approaches reflecting their specific circumstances and cultures, some of

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which may not be directly transferable, yet there is plenty of scope for policy makers to adapt successful practice from elsewhere. For example, Japan has processes that lead to well documented prioritisation and road-mapping and provide clear guidance for R&D spending. China has a highly centralised multi-year planning framework that provides clear indications of national innovation priorities. Korea and Japan stand out for successfully exploiting synergies in their promotion of electrochemical technologies across different sectors from batteries to fuel cells. Some US programmes provide examples of good practice in embedding evaluation in innovation policy objectives in policy design (Pless, Hepburn and Farrell, 2020).

- **Harmonise performance standards and codes across countries.** Co-operation to strengthen existing energy performance standards and foster international applicability, as well as to develop new standards and codes for emerging clean energy technologies, can accelerate cost reductions in manufacturing and installation, and thus market deployment. Clear and transparent international labelling standards for sustainable materials and fuels including auditing protocols can facilitate market adoption of these commodities. There is potential to build on the wealth of existing international energy standards (e.g. ISO 50001 for energy management systems) and on experience at national level in developing and applying standards. There is also potential to strengthen and expand existing international platforms such as the International Partnership for Hydrogen and Fuel Cells in the Economy, and regional ones such as the International Platform on Sustainable Finance in the European Union.
- **Co-ordinate action among countries and research institutions** to ensure that no essential technology areas lag because of risks that are too big to be borne by one country. The risks of developing a new clean energy technology can sometimes be too high for one country if the market players are multinational, the outlook uncertain and the support particularly costly. Different economies have various approaches to creating markets that support early-stage commercialisation of clean energy technologies for public policy purposes, but there are some similarities between the approaches taken that could help co-ordination. For example, targets for renewable electricity, biofuels and electric vehicles are common in many major economies. Public procurement also plays a role in creating niche markets in some countries. In India, it is used to create dependable local markets for products, such as light-emitting diodes (LEDs), appliances and electric vehicles. Norway's approach to decarbonisation of maritime transport links R&D and public procurement (DNV-GL, 2019). In many cases co-ordination may mean a variety of countries providing support for the same technology but in different ways. The European Union has the highest explicit carbon price and also the most numerous deployment targets for clean

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energy technologies. China's combination of rapid prototyping, public procurement, low-cost finance for manufacturing and internal market deployment has effective for improving mass-produced products. In Japan, strong standards in energy efficiency and other areas drive market-led innovation, while well-designed requirements for evaluating R&D projects, programmes and planning help to improve them.

- **Support networks that facilitate the rapid exchange of knowledge** between manufacturers, networks operators and researchers in overlapping fields and that promote cross-fertilisation between sectors. The benefits of knowledge sharing are getting increasing attention across the world. The European Commission now requires recipients of funding to publish results with open access. Technology programmes co-ordinated by the US Department of Energy regularly publish their findings in detail. There is a similar requirement for CCUS projects in Alberta (Canada). In China, the creation of specific zones for the development and deployment of certain technologies, including electric vehicles and hydrogen production, facilitates knowledge exchange. The benefits of knowledge and application spillovers can be maximised by exploiting synergies internationally, while international networks for knowledge exchange, including public-private partnerships and cross-sectoral coalitions, can help avoid duplication of effort and identify gaps not yet addressed. Existing multilateral platforms for co-operation provide a sound basis for deepening collaboration. They include the Clean Energy Ministerial and Mission Innovation. A notable example is the IEA Technology Collaboration Programme[10] which supports the work of independent, international groups of experts in 38 technology areas that enable governments and industries from around the world to lead programmes and projects on a wide range of energy technologies and related issues. The experts in these collaborations work to advance the research, development and commercialisation of energy technologies.

[10] www.iea.org/areas-of-work/technology-collaboration.

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References

Carbon Engineering (2019), CE expanding capacity of commercial Direct Air Capture plant, (press release), Carbon Engineering, https://carbonengineering.com/news-updates/expanding-dac-plant/ (accessed 20 February 2020).

DNV-GL (2019), Someone has to go first (webpage), https://www.dnvgl.com/expert-story/maritime-impact/Someone-has-to-go-first.html.

EC (European Commission) (2020), The EU budget powering – The recovery plan for Europe, https://ec.europa.eu/info/sites/info/files/factsheet_1_en.pdf.

EC (2016), How additional is the Clean Development Mechanism? Oko Institute for European Commission, Directorate-General Climate Action, https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf.

Government of Canada (2020), Canada's Covid-19 Economic Response Plan, https://www.canada.ca/en/department-finance/economic-response-plan.html.

Falduto, C. and M. Rocha (2020), Aligning short-term climate action with long-term climate goals: Opportunities and options for enhancing alignment between NDCs and long-term strategies, OECD/IEA Climate Change Expert Group Papers, No. 2020/02, OECD Publishing, Paris, https://doi.org/10.1787/7c980fce-en.

IAG (International Airlines Group) (2020), IAG Sustainability (webpage), https://www.iairgroup.com/en/sustainability (accessed July 2020).

IEA (International Energy Agency) (2020), Energy Technology Perspectives Special Report on Clean Energy Innovation, IEA, Paris, https://www.iea.org/reports/clean-energy-innovation.

Maersk (2019), Towards a zero-carbon future, (news article), https://www.maersk.com/news/articles/2019/06/26/towards-a-zero-carbon-future, (accessed 20 February 2020).

Pless, J., C. Hepburn and N. Farrell (2020), Bringing rigour to energy innovation policy evaluation, Nature Energy, Vol. 5, pp 284–290, https://doi.org/10.1038/s41560-020-0557-1.

UNDRR (United Nations Office for Disaster Risk Reduction) (2020), Japan calls for "adaptive recovery" in response to climate crisis, UNDRR - Office in Japan and Regional Office for Asia and Pacific, (webpage), https://www.undrr.org/news/japan-calls-adaptive-recovery-response-climate-crisis.

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Annexes

Regional and country groupings

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus,[1,2] Malta and Romania.

Africa: Algeria, Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Tunisia Zambia, Zimbabwe and other African countries and territories.[6]

Americas: North America and Central and South America regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, China, India, Japan, Korea, Democratic People's Republic of Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3] Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Emerging economies: All other countries not included in the "advanced economies" regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel,[5] Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey and Ukraine.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus,[1,2] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia,

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Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

IEA (International Energy Agency): OECD regional grouping excluding Chile, Iceland, Israel,[5] Latvia, Lithuania and Slovenia.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development): Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Country notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Lao People's Democratic Republic (Lao PDR), Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

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[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

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Acronyms and abbreviations

3D	3-dimensional
AC	alternate current
AIM	Aviation Integrated Model
ASEAN	Association of Southeast Asian Nations
ASTM	American Society of Testing and Materials
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicle
BF	blast furnace
BFO	biofuel oil
BOF	basic oxygen furnace
BTL	biomass-to-liquid
BTX	benzene, toluene and mixed xylenes
BWB	blended wing-body
CAAA	Clean Air Act Amendments
CAPEX	capital expenditure
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CFSF	cold-formed steel framing
CNG	compressed natural gas
CNR	catalytic naphtha reforming
CO	carbon monoxide
CO_2	carbon dioxide
COP	Conference of Parties
COP	coefficient of performance
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	direct air capture
DACS	direct air capture and storage
DCS	data collection system
DRI	direct reduced iron
EAF	electric arc furnace
EC	European Commission
ECA	emission control area
EEDI	energy efficiency design index
EOR	enhanced oil recovery
EPC	engineering, procurement and construction
ERS	electric road system
ETP	Energy Technology Perspectives
ETS	Emission Trading Scheme

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EU	European Union
EV	electric vehicle
FAME	fatty acid methyl esters
FC	fuel cell
FCEV	fuel cell electric vehicle
FIC	Faster Innovation Case
FLH	full load hours
FT	Fischer-Tropsch
GDP	gross domestic product
GFEI	Global Fuel Economy Initiative
GHG	greenhouse gas
GVW	gross vehicle weight
H_2	hydrogen
HDT	heavy-duty truck
HEFA	hydroprocessed esters and fatty acids
HEV	hybrid electric vehicle
HFO	heavy fuel oil
HFT	heavy-freight truck
HPCCV	high-power charging for commercial vehicles
HRS	hydrogen refuelling station
HVC	high-value chemical
HVDC	high-voltage direct current
HVO	hydrotreated vegetable oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICE	internal combustion engine
IEA	International Energy Outlook
IGCC	integrated gasification combined cycle
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LCSF	Low Carbon Fuel Standard
LCV	light commercial vehicle
LDV	light-duty vehicle
LED	light-emitting diode
LHV	lower heating value
LMDI	Logarithmic-Mean-Divisia-Index
LNG	liquefied natural gas
LPG	liquefied petroleum gas
Li	lithium
MEPC	Marine Environment Protection Committee
MFT	medium-freight trucks
MRV	monitoring, reporting and verification
NASA	National Aeronautics and Space Administration

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NDC	nationally determined contribution
NGL	natural gas liquid
NH_3	ammonia
NO_x	nitrogen oxides
NZEB	near-zero energy building
OEM	original equipment manufacturer
OPEX	operating expenditure
PEM	polymer electrolyte membrane
PHEV	plug-in hybrid electric vehicle
PPP	purchasing power parity
PM	particulate matter
$PM_{2.5}$	particulate matter with a diameter less than 2.5 micrometres
PNG	piped natural gas
PSA	pressure swing adsorption
PV	photovoltaic
R&D	research and development
R&DD	research, development and demonstration
RFS	Renewable Fuel Standard
S	sulphur
SAF	sustainable aviation fuel
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SEEMP	ship energy efficiency management plan
SIP	synthetic isoparaffin
SMR	small modular reactor
SMR	steam methane reforming
SO_2	sulphur dioxide
STE	solar thermal electricity
STEPS	Stated Policies Scenario
SUV	sport utility vehicle
T&D	transmission and distribution
TFC	total final consumption
TRL	technology readiness level
UHBR	ultra-high-bypass-ratio
US	United States
USD	United States dollar
VC	venture capital
VLSFO	very low sulphur fuel oil
VRE	variable renewables
WEO	World Energy Outlook
ZEV	zero-emission vehicle

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Units of measure

°C	degree Celsius
bcm	billion cubic metre
EJ	exajoule
gCO_2/kWh	gramme CO_2 per kilowatt hour
GJ	gigajoule
GJ/t	gigajoule per tonne
GJ/yr	gigajoule per year
Gt	gigatonne
Gt/yr	gigatonne per year
$GtCO_2/yr$	gigatonne of carbon dioxide per year
Gtoe/yr	gigatonne of oil equivalent per year
GW	gigawatt
GW/yr	gigawatt per year
h	hour
kg	kilogramme
kgH_2	kilogramme of hydrogen
km	kilometre
km^2	square kilometre
kt	kilotonne
kt/yr	kilotonne per year
$ktCO_2/yr$	kilotonne of carbon dioxide per year
kW	kilowatt
kW_e	kilowatt electric
kW_{H2}	kilowatt hydrogen
kWh	kilowatt-hour
L	litre
L/100 km	litre per 100 kilometres
Lde	litre of diesel equivalent
m^2	square metre
mb/d	million barrels per day
mboe/d	million barrels of oil equivalent per day
MBtu	million British thermal unit
MJ	megajoule
mm	millimetre
Mt	million tonnes
Mt/yr	million tonnes per year
Mtce	million tonnes of coal equivalent
$MtCO_2$	million tonnes of carbon dioxide
$MtCO_2/yr$	million tonnes of carbon dioxide per year
MtH_2	million tonnes of hydrogen

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MtH_2/yr	million tonnes of hydrogen per year
Mtoe	million tonnes of oil equivalent
Mtoe/yr	million tonnes of oil equivalent per year
MW	megawatt
MWh	megawatt-hour
ppm	parts per million
rpk	revenue passenger-kilometres
t/day	tonne per day
t/year	tonne per year
tce	tonne of coal equivalent
tCO_2	tonne of carbon dioxide
tCO_2/cap	tonne of carbon dioxide per capita
tCO_2/t	tonne of carbon dioxide per tonne
tkm	tonne-kilometres
toe	tonne of oil equivalent
TWh	terawatt-hour
TWh/yr	terawatt-hour per year
USD/bbl	United States dollar per barrel
USD/kgH_2	United States dollar per kilogramme of hydrogen
USD/km	United States dollar per kilometre
USD/MWh	United States dollar per megawatt-hour
USD/t	United States dollar per tonne
vkm	vehicle kilometres
Wh/kg	watt-hour per kilogramme

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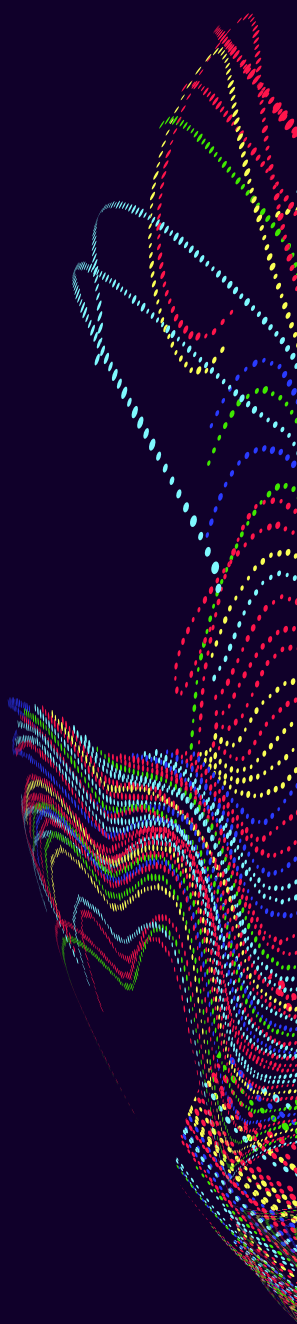
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