IRENA
International Renewable Energy Agency

REACHING ZERO WITH RENEWABLES

Eliminating CO_2 emissions from industry and transport in line with the 1.5°C climate goal

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Foreword

In planning for global emissions reductions, government attention first focused on the power sector, leaving industry, transport and other end-use sectors to be tackled later. That initial focus on electricity has proven effective. Thanks to the dramatic fall in cost of renewables and the increasing scale of their uptake, there is now a credible, cost-effective pathway towards fully decarbonising power production.

However, as the scientific understanding of climate change has deepened and as societal and political awareness has grown, the urgency of tacking all carbon dioxide (CO_2) emissions has also become evident. With attention focused increasingly on the 1.5°C limit, holding the line on rising global temperatures means eliminating emissions in all sectors of the economy.

Energy decarbonisation, therefore, has to move quickly beyond the power sector to fully tackle end-use emissions. This must include the most difficult, energy-intensive sectors, such as heavy industry and long-haul transport.

Low-carbon options, including electric vehicles and clean fuels based on renewables, have become familiar in many countries. But current options for some sectors are not yet sufficient. We need to start developing – and proving – viable solutions for those sectors immediately, in the early 2020s, and be ready to scale them up massively in the 2030 and 2040s.

To be in line with the 1.5°C goal, decision makers in both the public and private sectors need a clearer view of what needs to be done. They must know what is realistic, what it could cost, and what needs to happen first.

This *Reaching Zero with Renewables* study brings together a wide range of knowledge about how to decarbonise the most challenging industrial and transport sectors. Encouragingly, renewables and associated energy-transition technologies offer viable options in every case. Some of those looked impossible just a few years ago. But falling technology costs and proven synergies have now opened a credible path to cut emissions to zero. Renewable energy uptake would provide at least half of the emission cuts needed in the seven toughest sectors, the analysis indicates.

The assessment builds on the *Global Renewables Outlook* published by the International Renewable Energy Agency (IRENA) in April 2020. Since then, the COVID-19 pandemic has engulfed the world. Yet energy and climate goals, along with the sustainable development agenda, have only gained urgency. Long-term investments in renewables, efficiency and electrification need to be at centre stage in the investment package for the transformative decarbonisation of our societies.

With the right plans and sufficient support, key transport and industry sectors can be fully decarbonised. Reaching zero is possible. Let’s work together and do it.

Francesco La Camera
Director-General
IRENA

Executive Summary

Limiting the rise in average global temperatures to 1.5 degrees Celsius (°C) requires all sectors of the economy to reach zero carbon dioxide (CO_2) emissions early in the second half of this century. Doing so presents significant technical and economic challenges, particularly in some highly energy-intensive sectors of industry and transport.

These challenges, however, cannot be deferred any longer. The Paris Agreement, in calling for rapid decarbonisation, has focused attention on the energy sector as a major source of global emissions. The latest studies from the Intergovernmental Panel on Climate Change (IPCC) show the window of opportunity closing fast for meaningful action to counter the global climate threat.

Options that would deliver only partial emission reductions, therefore, are not sufficient. Policy makers and industry investors need to focus unerringly on scaling up the few options consistent with reaching the zero-emission goal. Most of those options rely on renewable energy technologies.

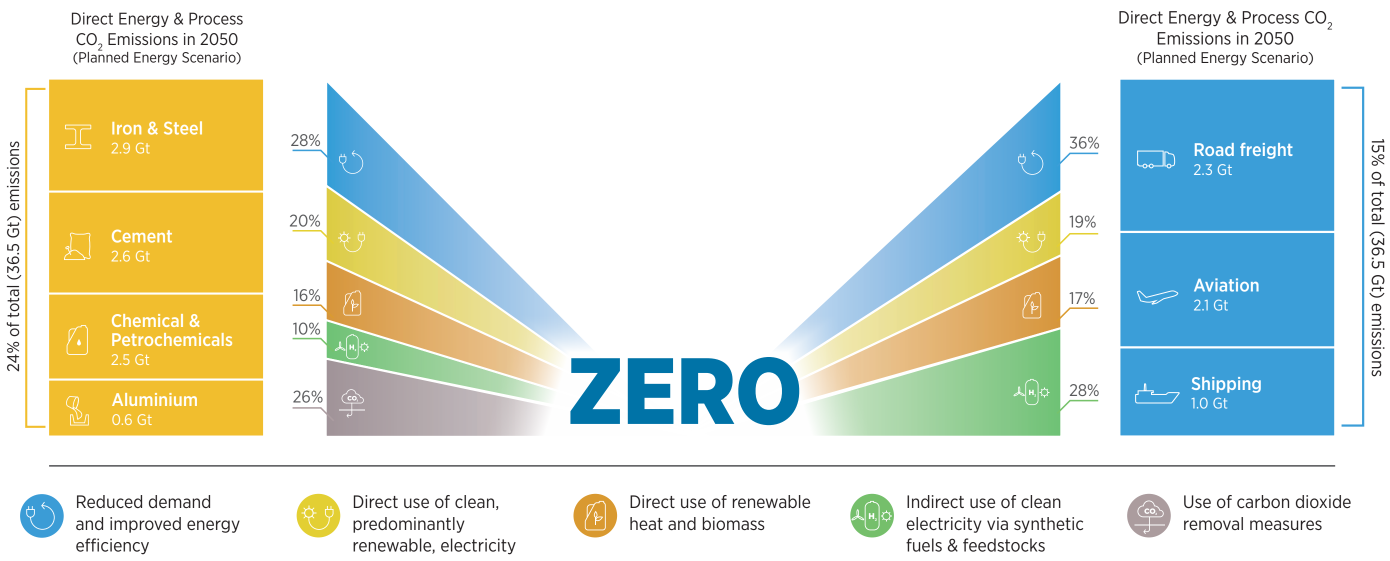
Four of the most energy-intensive industries and three key transport sectors stand out as the hardest to decarbonise. Together, those seven sectors could account for 38% of energy and process emissions and 43% of final energy use by 2050 unless major policy changes are pursued now.

This *Reaching zero with renewables study* outlines the best available deep decarbonisation options for those sectors. Prepared by the International Renewable Energy Agency (IRENA), it supports the aim of holding the global temperature rise at 1.5°C this century, compared to pre-industrial levels.

Progress in these sectors has been limited to date. But two changes in recent years should allow for faster and deeper cuts in emissions. Firstly, societies worldwide have come to recognise the need for deep decarbonisation across all sectors, despite the challenges involved. Secondly, steady and continuing cost reductions for renewable energy open up a wider range of technology options.

Renewable energy technologies, along with batteries and other enabling technologies, are now proven to be effective and affordable, in every country, for a growing range of applications. Renewables show more potential – whether for direct energy use or as feedstocks – than ever before. This makes them crucial to reach zero emissions.

A combination of five emission reduction measures could, if applied at scale, reduce industry and transport CO_2 emissions to zero.



None of the options identified, however, is commercially mature or ready for wide adoption quite yet. Uncertainties remain about their potential and optimum use, and none will be easy to scale-up. The reasons are varied and complex. But to begin with, they include: high costs for new technologies and processes; the need for enabling infrastructure ahead of demand; highly integrated operations and long-established practices; uneven, large and long-term investment needs; gaps in carbon accounting; and business risks for first-movers, including added costs and consequent "carbon leakage" in favour of competitors.

Addressing these challenges demands far more attention and creativity than is currently being applied. Sector-specific and cross-cutting actions are also needed urgently. One of the first steps must be a renewables-based strategy for industry and transport with the clear end goal of zero emissions.

This, in turn, calls for inter-linked sector-level strategies at the local, national and international levels, built on the five technology pillars of demand reduction and energy efficiency, renewable electricity, renewable heat and biofuels, green hydrogen and e-fuels, and carbon-removal technologies. Renewables, together with demand reduction and energy efficiency, could account for over 80% of the CO_2 emission reductions needed.

Contents

Figures

Tables

Boxes

Abbreviations

°C	Degree Celsius
AUD	Australian dollar
BAU	business as usual
BECCS	bioenergy with carbon capture and storage
BECCU	bioenergy with carbon capture and utilisation
BES	Baseline Energy Scenario
BET	battery electric truck
BF	blast furnace
BFO	bio-fuel oil
BioMCN	BioMethanol Chemie Nederland
BOF	basic oxygen furnace
BP	best practice
BTX	benzene, toluene and xylenes
$CaCO_3$	calcium carbonate
CaL	calcium looping
CaO	calcium oxide (lime)
CAPEX	capital expenditure
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and/or storage
CDR	carbon dioxide removal
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide-equivalent
CORSIA	Carbon Offsetting Scheme for International Aviation
CSP	concentrating solar power
CST	Clean Skies for Tomorrow
DAC	direct air capture
DDP	Deeper Decarbonisation Perspective
DHC	district heating and cooling
DKK	Danish krone
DME	dimethyl ether
DRI	direct reduced iron
EAF	electric arc furnace
EJ	exajoule
EOR	enhanced oil recovery
EU	European Union
EUR	euro
FAME	fatty acid methyl esters
FCEV	fuel cell electric vehicle
FT	Fischer-Tropsch
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
H_2	hydrogen
HEFA	hydroprocessed esters and fatty acids
HPSR	hydrogen plasma smelting reduction
HT DAC	high-temperature direct air capture
HVO	hydrotreated vegetable oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Association
ICE	internal combustion engine

ILUC	indirect land use change
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
km	kilometre
kWh	kilowatt-hour
LBG	liquefied biogas
LCOE	levelised cost of electricity
LEILAC	Low Emissions Intensity Lime and Cement
LNG	liquified natural gas
LPG	liquified petroleum gas
LT DAC	low-temperature direct air capture
m^3	cubic metre
MDEA	methyl diethanolamine
MDO	marine diesel oil
MEA	monoethanol amine
MGO	marine gasoil
Mt	megatonne
MW	megawatt
N	nitrogen
NDC	Nationally Determined Contribution
NGCC	natural gas combined cycle
NH_3	ammonia
NSP	new suspension preheater (kiln)
OPEX	operating expenditure
PBAT	polybutylene adipate terephthalate
PBS	polybutylene succinate
PEM	proton exchange membrane
PES	Planned Energy Scenario
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoates
PLA	polylactic acid
PTT	polytrimethylene terephthalate
PV	photovoltaic
PVC	polyvinyl chloride
R&D	research and development
RD&D	research, development and demonstration
SCMS	supplementary cementitious materials
SNG	synthetic gas
SOEC	solid oxide electrolyser cells
SPK	synthetic paraffinic kerosene
SR	smelting reduction
t	tonne
TES	Transforming Energy Scenario
TFEC	total final energy consumption
TPC-ET	thermoplastic polyester elastomers
TWh	terawatt-hour
ULCOS	Ultra-Low Carbon dioxide Steelmaking programme
US	United States
USD	United States dollar
VRE	variable renewable energy
yr	year
ZEV	zero-emission vehicle

REACHING ZERO WITH RENEWABLES

a summary for decision makers

Reaching zero with renewables: A summary for decision makers

Focusing on the goal

Limiting the global average temperature rise to no more than 1.5°C above pre-industrial levels will require all sectors of the economy to reach zero carbon dioxide (CO_2) emissions early in the second half of this century. Doing so will be very challenging, particularly in some key industry and transport sectors. Reaching zero requires a completely different mindset to that mostly adopted to date. Actions that deliver only partial emission reductions will not be sufficient, and some may actually hinder reaching zero. The focus of policy makers and industry investors must unerringly be on a pathway that progressively scales up those few options that are consistent with reaching the zero-emission goal.

Many of the options discussed in this report have been known about, debated and experimented with for 20 years or more, but in general that research and those discussions have not translated into deployment, and only relatively modest improvements have been made. Two things have, however, changed recently that potentially shift the paradigm and should allow for far more rapid progress in the next decade and beyond. Firstly, there is strong and widening societal recognition, and increasing political consensus, on the need for all sectors to make deep cuts in carbon emissions, despite the challenges in doing so. Secondly, renewable energy, and some enabling technologies such as batteries, have developed significantly and are now proven to be a credible and increasingly affordable option in all countries and in many applications.

The use of renewables both for energy and for feedstocks will be central to the pathway to zero emissions. The rapid decline in the costs of renewables over the past decade, and the future potential for further cost reductions and scaling, opens up options for the use of renewable energy that were previously dismissed. As this report shows there is a high potential for renewables use, much more than previous analysis has identified. Renewable electricity (from solar, wind, ocean and geothermal energy) and renewable heat and renewable fuels (from biomass and renewable electricity (producing synthetic fuels)) can address energy needs in industry and transport, and biomass and synthetic renewable fuels can provide industrial feedstocks, displacing fossil fuel sources. Renewable-based solutions have not been explored to date with the rigor and urgency that is needed.

While the solutions and policy measures needed for some sectors – including power and passenger vehicles – look relatively clear (although still challenging), there are seven industry and transport sectors which will be the hardest to decarbonise. Those seven sectors (shown in the graphic below) will account for 38% of energy & process emissions and 43% of final energy use by 2050 unless major policy changes are pursued. In all cases renewables could play a far larger role now. Renewables must grow to become the principal source of energy and feedstocks in the next few decades and could contribute circa two thirds of the reductions to direct emissions needed across these seven sectors.

Energy-intensive industrial sectors

Iron and steel

In 2017:
- Consumed 32 exajoules (EJ) of energy
- Only 4% was from renewables
- Emitted 3.1 gigatonnes (Gt) of CO_2

Chemicals and petrochemicals

In 2017:
- Consumed 46.8 EJ of energy
- Only 3% was from renewables
- Emitted 1.7 Gt of CO_2

Cement and lime

In 2017:
- Consumed 15.6 EJ of energy
- Only 6% was from renewables
- Emitted 2.5 Gt of CO_2

Aluminium

In 2017:
- Consumed 4.5 EJ of energy
- 16% was from renewables
- Emitted 0.4 Gt of CO_2

Energy-intensive freight & long-haul transport sectors

Road freight

In 2017:
- Consumed 32.3 EJ of energy
- Only 1.5% was from renewables
- Emitted 2.3 Gt of CO_2

Aviation

In 2017:
- Consumed 13.5 EJ of energy
- A negligible share was from renewables
- Emitted 0.9 Gt of CO_2

Shipping

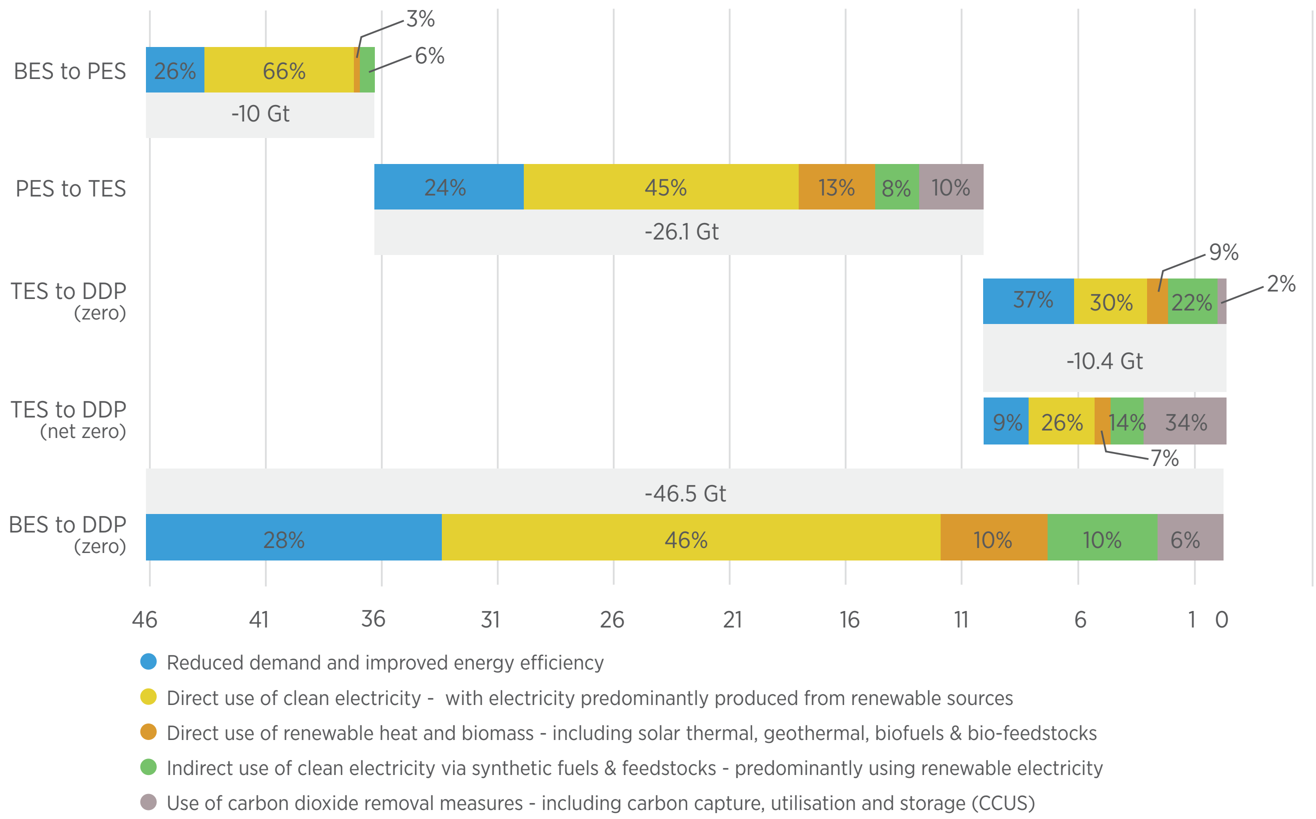
In 2017:
- Consumed 11.3 EJ of energy
- A negligible share was from renewables
- Emitted 0.9 Gt of CO_2

Potential solutions are available for each of these sectors, but none of them are commercially mature and ready for wide adoption, and many uncertainties remain about their potential and optimum use. Analysis of options is often too siloed with the full life cycle of products not adequately considered, and the interdependencies, synergies and trade-offs between sectors are not well understood. Much deeper analysis and debate, and many more pilot projects to build evidence and experience, is needed. Actions to deliver those projects must be prioritised more highly by all stakeholders and must move more quickly towards scale-up over the coming decade.

This report explores what is possible. It has a twin focus: examining how the world could achieve zero emissions in key industry and transport sectors by around 2060, and assessing the potential role of renewables-based technologies in doing so. The report aims to provide both an accessible overview of the topic and a source of the latest key insights and data. It draws on insights from across IRENA's technology analysis to date, as well as bringing together and summarising current expert understanding of key details including status, challenges, costs and potentials of the options. It signposts where further detailed discussions can be found and highlights gaps in our knowledge that should be the focus for further detailed work. By doing so this report can serve as a starting point for the more comprehensive and informed discussions that are needed among policy makers and other stakeholders.

Reaching zero by 2060

IRENA's *Global renewables outlook* report (IRENA, 2020a), published in April 2020, focused on a pathway to 2050 consistent with a goal of limiting global temperature rise to "well below 2-degrees Celsius". The report, however, also explored the additional abatement, beyond the Transforming Energy Scenario, needed to eliminate energy-related and industrial process CO_2 emissions. That Deeper Decarbonisation Perspective (DDP) is not a full scenario but does provide guidance on the areas for accelerated action to reduce energy and process-related CO_2 emissions to zero by 2060. The bottom bar in the figure below summarises the balance of reductions identified in the DDP analysis across different emission reduction measures in order to reach zero. This report builds on that analysis to explore how that DDP can be delivered, a prerequisite to limiting temperature rise to 1.5 °C from preindustrial levels.



Each of the sectors discussed in this report is in the early stages of exploring emission reduction strategies, but many of the options being looked at will only partially reduce emissions and are not consistent with the sector eventually reaching zero. In order to not waste resources, lose time or lock in emissions, a clearer focus is needed on the end objective of zero CO_2 emissions when evaluating which options to pursue. Technologies and processes that cannot eventually lead to zero or close-to-zero emissions are only worth pursuing if they either greatly reduce the scale of the challenge for true zero-emission solutions, or if they will be replaced in the next 40 years or are a stepping stone to successfully implementing zero-emission solutions.

When these criteria are applied, only a very small number of currently conceived options in each sector are consistent with a zero CO_2 emissions objective; those options are listed in the sector chapters that follow. Approaches will differ across sectors, but the majority of emission reductions will be achieved through a combination of five "emission reduction measures", three of which rely primarily on renewable energy.

The application of these measures in each sector is explored throughout the report, but in each case a variety of other factors and trends will aid their use. Key among them is the continuous decline in renewable power costs and a rapidly widening field of deployment which opens up the potential for wider electrification. At the same time there is growing understanding of the value of demand-side flexibility as an enabler for higher shares of variable renewable energy (VRE) sources (such as solar and wind), which the industry and transport sectors can both contribute to and benefit from. (That flexibility potential is explored in IRENA's 2019 report *Innovation landscape for a renewable-powered future* (IRENA, 2019a) and the upcoming report *Electrification with renewables: Driving the transformation of energy services* (IRENA, forthcoming a).)

Reduced demand and improved energy efficiency
Reduce energy and material demand and intensity of use through a range of actions including: energy efficiency, behavourial and process changes, relocation and the application of circular economy principles.

Direct use of clean electricity – predominantly produced from renewable sources
Directly use clean electricity, sourced predominantly from renewables, to provide energy requirements. Can both replace existing fossil fuel-based electricity use and replace other energy demand through "electrification".

Direct use of renewable heat and biomass – including solar thermal, geothermal, biofuels and bio-feedstocks
Directly utlise renewables for energy and feedstocks. Includes the use of solar and geothermal for some heat requirements and the use of sustainable biomass including through the direct use of bioenergy for heat and the production and use of biofuels and bio-feedstocks. This may also include the combination of biomass use with carbon capture and storage (BECCS).

Indirect use of clean electricity via synthetic fuels and feedstocks – predominantly using renewable electricity
Source energy and feedstocks from hydrogen or from fuels or feedstocks produced from hydrogen (synthetic fuels or feedstocks) using CO_2 captured from non-fossil fuel sources. The hydrogen should be "clean" and preferably "green", i.e., sourced from renewables.

Use of carbon dioxide removal measures – including carbon capture, utilisation and/or storage (CCUS)
Capture most or all CO_2 emissions from fossil fuel-based energy production or other processes and either store the captured CO_2 permenantly or utliise the CO_2 in ways in which it will not be later released. This can include the production of "blue" hydrogen or the capture of CO_2 from processes or the atmosphere specifically for use in creating chemical feedstocks or fuels.

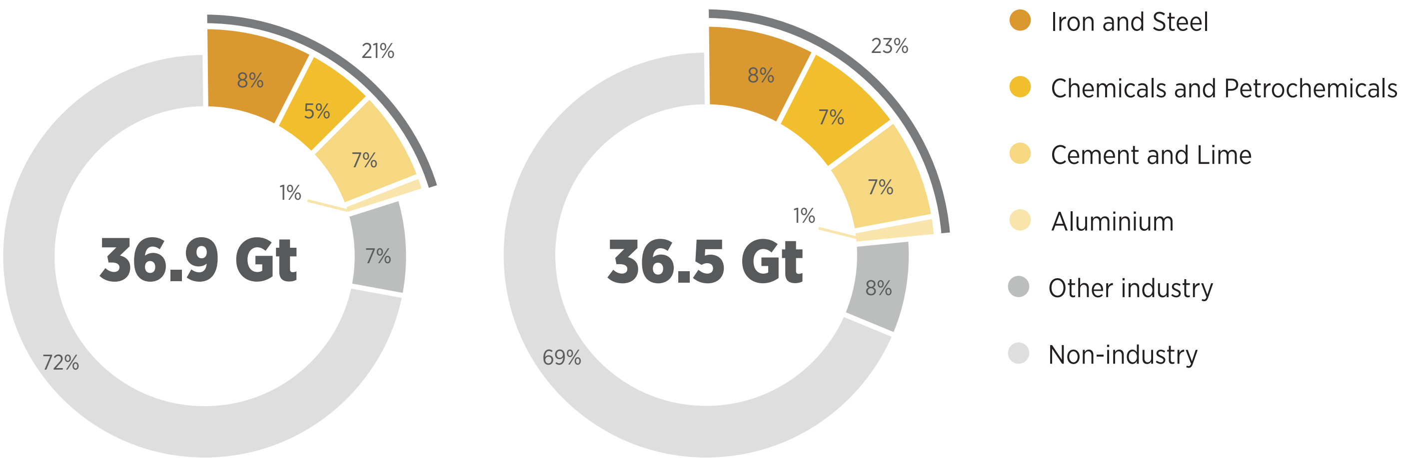
Note: In some specific sectors other strategies will contribute as well – for example, replacements for clinker, the use of alternative building materials or the relocation of plants to better utilise renewable resources.

Other examples of positive factors and trends include: the flexibility of some industrial processes to be relocated, opening up options to site them where there is the best access to low-cost renewables; the growing momentum behind green hydrogen with steadily improving technology and potential for declining costs; and the falling cost of batteries and rapidly growing supply chains for passenger electric vehicles with potential spill-over benefits for electric trucks. These and other trends explored in the report are opening up possibilities for industry and transport that make a zero-emission objective an achievable prospect.

Industry overview

Industry share of total energy and process-related CO_2 emissions in 2017 (Gt).

Industry share of total energy and process-related CO_2 emissions in 2050 Planned Energy Scenario (Gt).

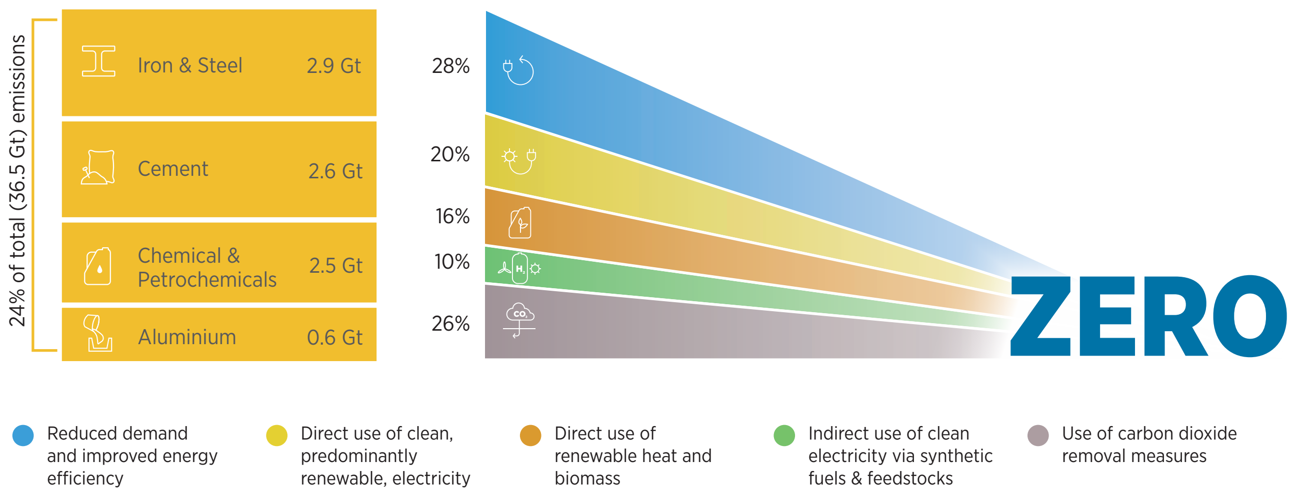


Source: IRENA, 2020a; IEA, 2017
The Planned Energy Scenario (PES) provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Energy-intensive industries: Options for reaching zero

Direct Energy & Process CO_2 Emissions in 2050 (Planned Energy Scenario)

Reaching zero in key industrial sectors

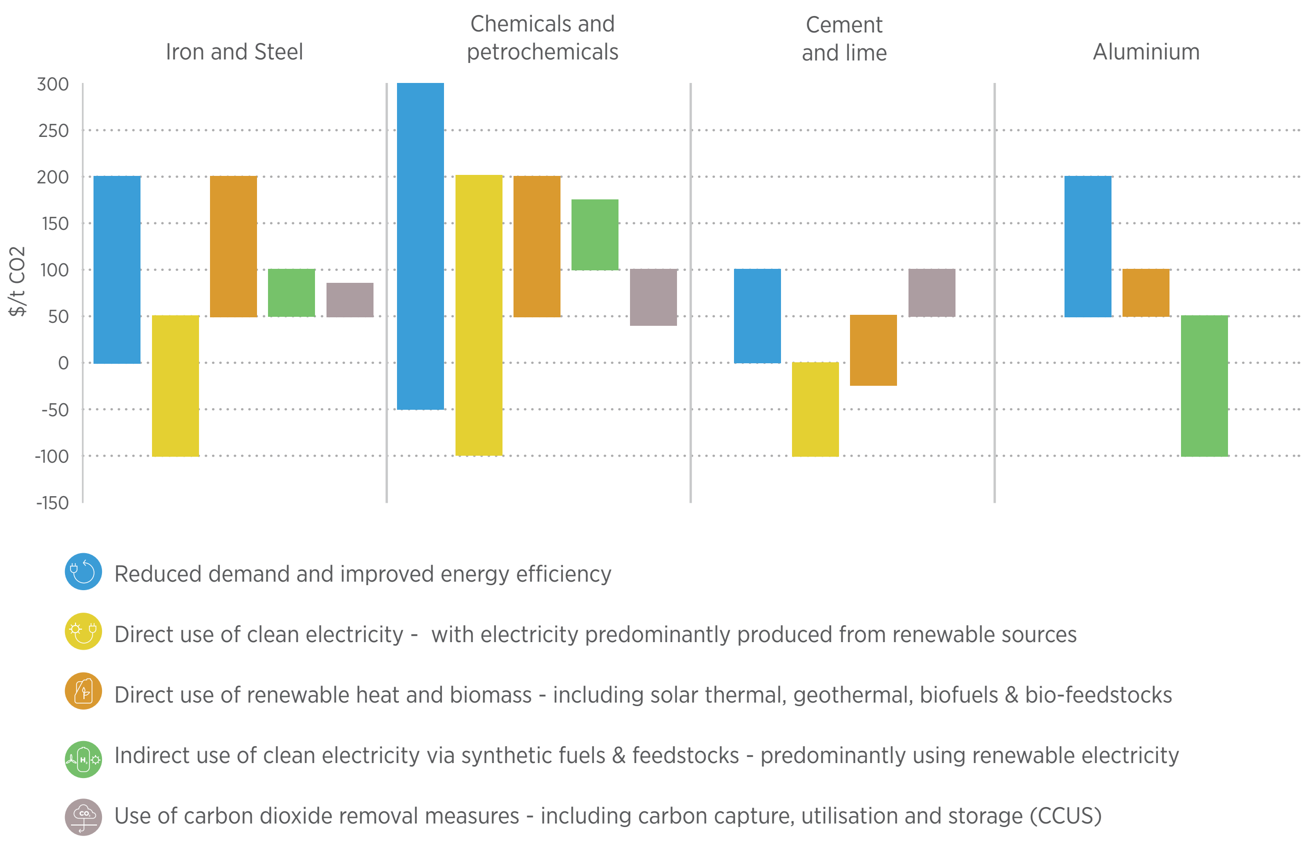


The industrial production of key materials is an essential enabler of modern economies. As countries develop, demand for such material continues to grow. However, that production currently comes with high CO_2 emissions. Industry accounts for around 28% of total global CO_2 emissions, but four industrial sectors in particular – iron and steel, chemicals and petrochemicals, cement and lime, and aluminium – account for almost three-quarters of total industrial emissions.

The majority of energy used in industry is currently sourced from fossil fuels. But energy use is not the only source of emissions in the industrial sector; CO_2 emissions must also be eliminated from production processes and from the life cycle of products. Reducing emissions and eventually reaching zero will require radical shifts in how such materials are produced, consumed and disposed of. To date, however, the need to drive long-term emission reductions in these four industrial sectors has not received the necessary policy attention.

A number of reasons account for this lack of action. Two in particular are key. Firstly, only a few economically viable CO_2 emission reduction solutions are currently available for these industrial sectors, and no consensus exists on which of the options are most suitable. Secondly, carbon leakage — that is, the transfer of production to other locations where emission reduction requirements are lower – is a deterrent in promoting decarbonising efforts.

Cost abatement ranges for industry sectors and measures

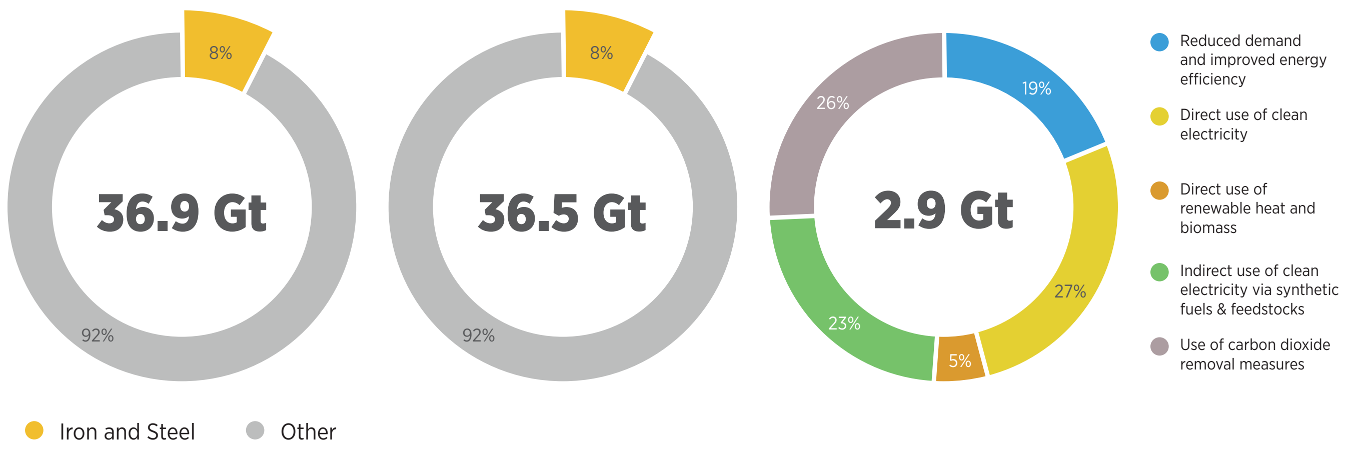


Iron and steel

Iron and steel share of total energy and process-related CO_2 emissions in 2017 (Gt).

Iron and steel share of total energy and process-related CO_2 emissions in 2050 Planned Energy Scenario (Gt).

Estimated role of key CO_2 emission reduction measures to reduce steel Planned Energy Scenario emissions to zero.



Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Steel is an alloy of iron and carbon that is widely used as an engineering and construction material. The iron and steel sector is a major energy user and a major emitter of CO_2. In 2017, the sector accounted for 32 EJ of final energy use and produced 8% of total global energy and process-related CO_2 emissions. Almost three-quarters of the energy and feedstocks used in global iron and steelmaking processes in 2017 were coal, coke and other coal products (IEA, 2020a).

Over 70% of global steel is produced via the blast furnace / basic oxygen furnace (BF-BOF) route which relies mostly on metallurgical coal as the chemical reducing agent. Most of the remaining steel is produced from direct reduced iron (DRI) or steel scrap in an electric arc furnace (EAF), mainly with fossil fuels providing both the reducing agent and energy for DRI and the electricity for the furnace.

Improving the energy efficiency of processes, further improving material efficiency and applying the principles of a circular steel economy (to ensure that even higher proportions of steel scrap are recycled) can all play useful roles in reducing emissions. But those measures will not on their own be sufficient. A structural shift in iron and steelmaking is needed with renewables displacing fossil fuels for both energy and reducing agents.

There are two primary options to achieve this: switching to alternative processes that can utilise renewable energy and clean, preferably green, hydrogen; or utilising clean, preferably renewable, energy and capturing CO_2 emissions from existing processes with carbon capture, utilisation and/or storage (CCUS) technologies. Some other emission reduction routes include, for example, the use of biomass, renewable-based hydrogen and waste plastics in blast furnaces, but while these may assist in the short to medium term, they do not look likely to be able to deliver zero or near-zero emissions in the long term.

2 options compatible with reaching zero emissions

Hydrogen-based direct reduction of iron and electric arc furnace-based steel production

- Produce iron via the direct reduction process using clean, preferably green, hydrogen as a reducing agent.
- Produce steel using electric arc furnaces.
- Source all heat and electricity inputs from renewables.

Capturing and storing process and waste emissions, and using renewables for energy

- Apply CCUS to existing iron and steel production processes.
- Source all heat and electricity inputs from renewables.

Key insights

- The DRI-EAF route with green hydrogen is making progress. At least six plants are being piloted, mainly in Europe. Renewable hydrogen-based DRI can become a viable alternative to traditional blast furnaces at a carbon price of around USD 67 per tonne of CO_2, subject to the availability of low-cost renewable electricity.

- If the BF-BOF route is to continue to be used, then it will need to be combined with cost-effective CCUS technologies. Currently one operational steel plant is using CCUS (a natural gas-based DRI-EAF steel facility equipped with CCUS in the United Arab Emirates).

- Coupling iron ore mining and green ironmaking in places with abundant and low-cost renewable resources, such as Australia, while decoupling the ironmaking and steelmaking process in countries heavily reliant on fossil fuels, such as China, Japan and the Republic of Korea, could create new value and supply chains while also delivering emission reductions.

- China's current dominance in global steelmaking, and the expected increase in production capacity in a limited number of other developing or emerging economies, means that actions taken by those countries will be crucial for reducing global CO_2 emissions in this sector.

Priorities for action

- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).

- Create early demand for "green" steel despite higher costs early on (e.g., through public procurement, corporate sourcing and minimum percent requirements); creating a market can incentivise improvements in technologies and costs and reduce the risk of "carbon leakage".

- Increase public and private funding and cross-border collaboration for research, development and deployment (RD&D) into hydrogen-based DRI and BF-BOF-based designs with CCUS.

- Exploit cross-sectoral synergies to reduce the cost of green hydrogen; many sectors will need lower-cost green hydrogen, and improving electrolysers, scaling up demand and creating distribution infrastructure will help.

- Explore opportunities to relocate iron production to areas with potential for low-cost renewable energy; this can create new value and supply chains while also delivering emission reductions.

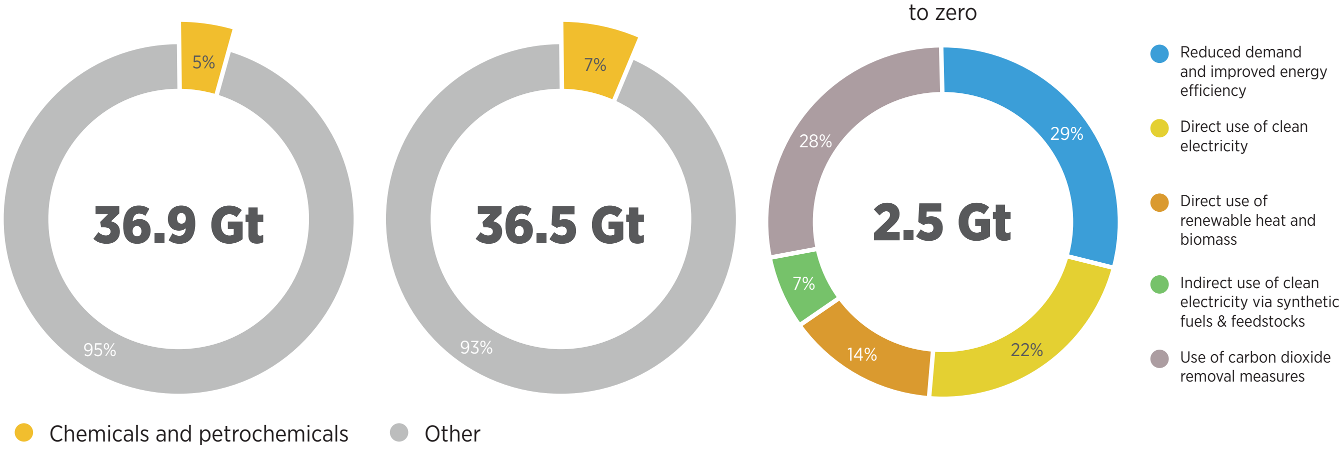
- Ensure that countries with large or expanding iron and steel production can utilise zero-emission-compatible production technologies; emerging economies will account for high shares of future production.

Chemicals and petrochemicals

Chemicals and petrochemicals share of total energy and process-related CO_2 emissions in 2017 (Gt).

Chemicals and petrochemicals share of total energy and process-related CO_2 emissions in 2050 Planned Energy Scenario (Gt).

Estimated role of key CO_2 emission reduction measures to reduce chemicals and petrochemicals Planned Energy Scenario emissions to zero



Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

In the petrochemical sector fossil fuel feedstocks are used to produce a range of "primary petrochemicals" which are the "building blocks" for a wide range of materials – for example plastics, synthetic organic fibres such as nylon, and other polymers, which have many uses.

Globally around 644 megatonnes (Mt) of petrochemicals were produced in 2018, and the sector continues to grow rapidly. Plastics, which account for the majority of product in volume terms, grew 20-fold in the past five decades to reach 360 Mt by the end of 2018 and could grow three-fold globally by 2050 in a scenario of unrestricted use.

The CO_2 emissions of petrochemical products come from different sources, including: direct energy and process emissions from production processes (around 1.7 Gt/yr); product use phase emissions (0.2 Gt/yr); and emissions from decomposition/incineration processes (around 0.24 Gt/yr). Additionally another 1 Gt per year is stored in hydrocarbon products which could be released depending on their end-of-life disposal. If left unchecked, total emissions could grow to 2.5 Gt per year by 2050.

Emission reductions can be achieved by: reducing demand for petrochemicals, reducing emissions from the energy used in the production processes, adopting renewables-based alternatives to fossil fuel feedstocks and permanently storing the carbon embedded in the products at the end of their life. Adopting the principles of the circular economy is an essential starting point that will assist the implementation of other approaches by reducing the scale of the challenge and is critical to managing other environmental concerns such as the impact of plastic waste on local ecologies.

3 options compatible with reaching zero emissions

Using biomass for feedstocks and renewables for energy

- Source all heat and electricity inputs from renewables.
- Use biomass for chemical feedstocks – replacing primary petrochemicals with bio-based chemicals or replacing fossil fuel-derived polymers (particularly plastics) with alternatives produced from biomass.

Using synthetic hydrocarbons for feedstocks and renewables for energy

- Source all heat and electricity inputs from renewables.
- Use synthetic hydrocarbons – produced from green hydrogen and clean CO2 sources – for chemical feedstocks.

Capturing and storing process and waste emissions, and using renewables for energy

- Apply CCUS to existing production processes.
- Source all heat and electricity inputs from renewables.
- Apply measures for the permanent storage of the carbon in products – *e.g.*, a highly efficient circular economy, the long-term storage of waste products or CCUS applied to end-of-life combustion.

Key insights

- The sector has made limited progress in reducing CO_2 emissions. Reasons for this include: much of the energy efficiency potential has been already realised; multiple conversion processes are integrated in large ageing industrial complexes, which limits the remaining energy efficiency potential; petrochemical production is increasingly integrated with refinery operations; and the cost of low-carbon alternatives, such as bioplastics, is currently high.

- Achieving a zero-carbon chemical and petrochemical industry will involve a complex transition. A life-cycle approach is needed to capture the full greenhouse gas emission impact and all mitigation opportunities. Front runners – consumers, governments, and chemical and petrochemical clusters and companies – will need to force this change.

Priorities for action

- Adopt a full life-cycle approach when considering the sector's emissions – one that accounts for the carbon in chemical-based products and their use and end-of life disposal.

- Transition to a truly circular economy, greatly increasing recycling and reuse rates and so reducing demand for new chemicals production.

- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).

- Create early demand for "green" chemicals and products (mandate if necessary); creating a market can incentivise improvements in process efficiency and costs and reduce the risk of "carbon leakage". Certification of green supply chains may be required.

- Increase public and private funding and cross-border collaboration for RD&D into bio-based or synthetic chemicals as drop-in replacements or alternative substitutes for existing products.

- Decouple fossil fuel refining from chemical production and establish stronger collaboration between the chemical industry and the clean energy sector to ensure complementary strategies and access to renewable energy.

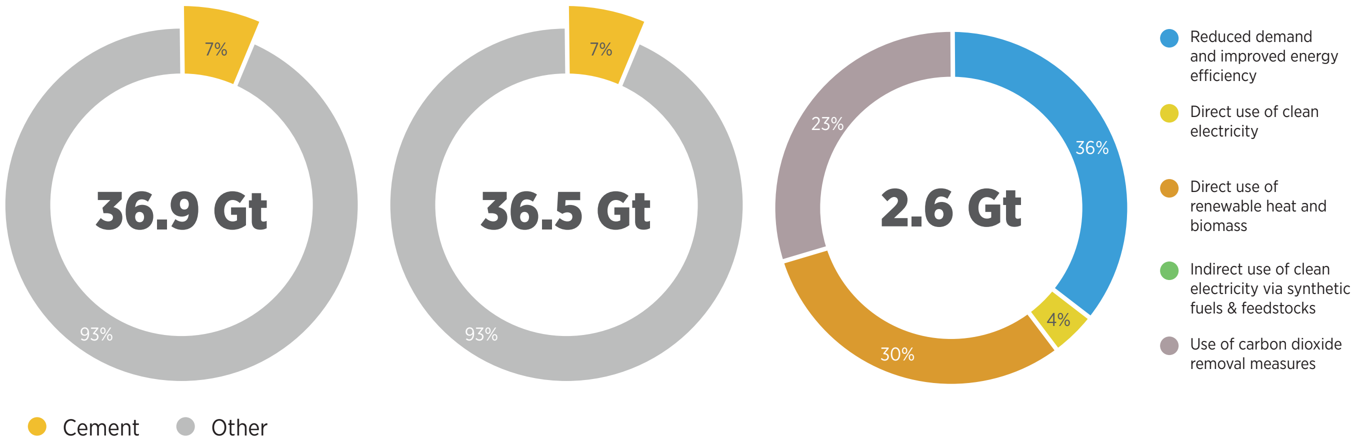
- Address issues in how carbon emissions are measured and accounted for – for example, need to consider the "storage" of carbon in materials and emissions resulting from waste incineration.

Cement and lime

Cement share of total energy and process-related CO_2 emissions in 2017 (Gt).

Cement share of total energy and process-related CO_2 emissions in 2050 Planned Energy Scenario (Gt).

Estimated role of key CO_2 emission reduction measures to reduce cement Planned Energy Scenario emissions to zero.



Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Cement is a fine, soft, powdery-type substance, used mainly to bind fine sand and coarse aggregates together in concrete. Although a variety of cement types exist, the most common is "Portland cement", which is produced by mixing clinker with smaller quantities of other additives such as gypsum and ground limestone.

Global cement production has grown by a factor of 3.5 between 1990 and 2019, reaching 4.1 Gt in 2019 with China accounting for 54% of global production. Cement and lime production produced 6.7% of total global energy and process-related CO_2 emissions in 2017. This share is expected increase slightly to 7.2% as other sectors decarbonise more quickly.

The production of clinker, the main constituent of cement, is responsible for the bulk of the sector's emissions, including both energy and process emissions.

No single option in this sector can reduce emissions to near zero. Full decarbonisation will require a consideration of the full life cycle of cement with several strategies pursued in parallel. These will include reducing demand for conventional cement (through lower amounts of cement in concrete and the lower use of concrete in construction), eliminating energy emissions (through a fuel switch to renewables), reducing process emissions from cement production (through lower amounts of clinker in the cement) and eliminating or offsetting the remaining process emissions (through CCUS and bioenergy with carbon capture and storage (BECCS)).

4 options compatible with reaching zero emissions

ZERO

Reducing clinker use

- Partially substitute clinker with alternative binders, *e.g.*, blast furnace slag or fly ash.

Reducing demand for conventional cement

- Use alternative construction techniques to reduce cement use, and/or use renewable building materials, such as wood, instead of cement.
- Avoid clinker emissions by using alternative cement formulations.

Fuel switching to renewables

- Use direct electrification or the use of biomass and waste for process energy.

Capturing and storing CO_2 emissions

- Apply CCUS to abate remaining energy and process emissions.
- Use biomass with CCS (BECCS) to produce negative emissions that can offset some uncaptured clinker emissions.

Key insights

- Renewable energy sources have been underutilised in the cement sector. Renewables could eliminate around 40-50% of emissions that are energy related. The remaining process emissions will need to be addressed via material efficiency, material replacement and carbon capture and storage (CCS).

- Reducing overall demand, reducing clinker use and offsetting some process emissions through other in-sector negative-emissions approaches (BECCS, concrete reabsorption, use of wood in construction) will reduce the amount of CCS needed.

- The cost of zero-carbon cement production is currently around double that of standard cement. Research into substitutes for clinker and cement is not translating into innovation in operational plants. More development and demonstration projects are needed.

- China's role is currently crucial, and a number of developing countries are likely to grow in significance. Production in those countries must start on the right (zero-carbon-compatible) track. Major developed economies can set an example and assist by showing leadership on projects as well as on demand, regulations, carbon border taxes, etc.

Priorities for action

- Explore a portfolio of options to eliminate the sector's emissions through a combination of approaches; offsetting emissions from some plants with carbon removal measures elsewhere will be needed.

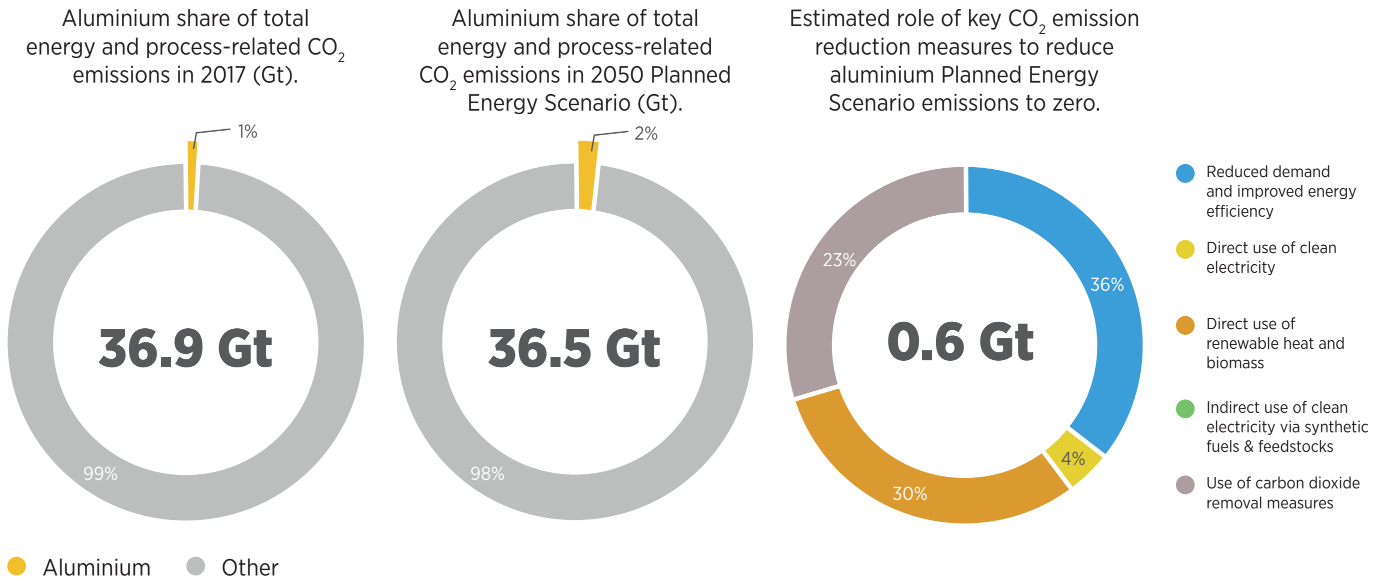
- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently very few examples of such projects exist worldwide).

- Create demand for "green" cement (despite higher costs early on) and incentivise the use of alternative building materials (*e.g.*, through public procurement, corporate sourcing and minimum percent requirements); creating a market will incentivise improvements in technologies and costs and reduce the risk of "carbon leakage".

- Increase public and private funding and cross-border collaboration for RD&D into clinker alternatives, alternative construction techniques and materials, and the use of carbon removal technologies including CCUS and BECCS.

- Ensure that countries with large or expanding cement demand and production can utilise zero-emission-compatible approaches; emerging economies already account for high shares of current production and will account for high future shares.

Aluminium



Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Aluminium is produced first through bauxite calcination for alumina production (the Bayer process) and then through smelting (Hall-Héroult processes) for aluminium production.

Direct emissions from aluminium production accounts for around 1% of global CO_2 emissions and demand for aluminium projected to rise 44% by 2050. Indirect emissions from electricity production accounts for 90% of all CO_2 emissions from aluminium. The remaining 10% is direct process emissions of which two-thirds are related to the use of carbon anodes in the Hall-Héroult process. Decarbonising aluminium production will therefore require decarbonising the energy used in the alumina and aluminium production stages by switching to renewable sources, and eliminating the use of carbon anodes. Options for the latter, however, are not fully developed or proven.

1 option compatible with reaching zero emissions

Renewable power and inert anodes

- Source all heat and electricity inputs from renewables.
- Develop and adopt use of inert anodes.

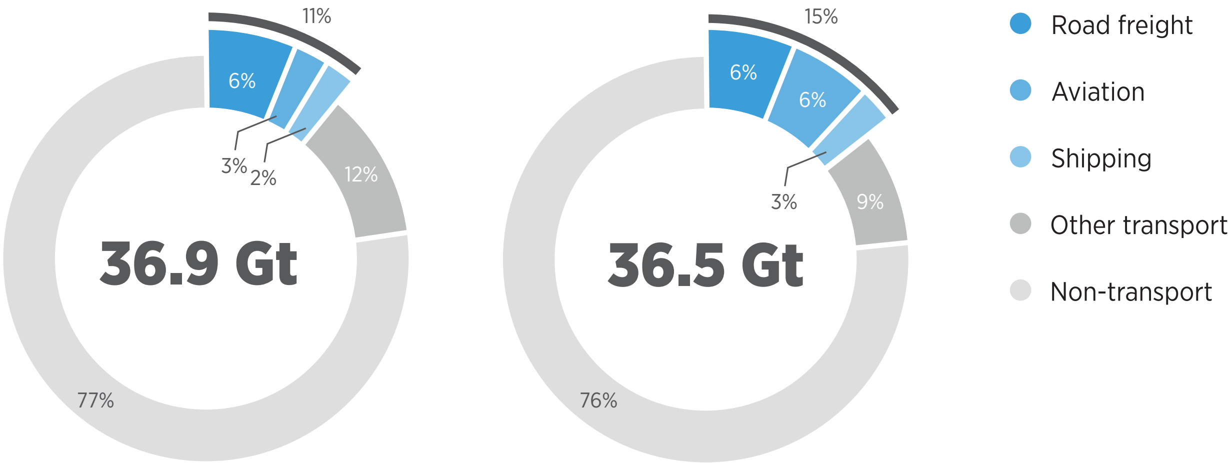
Priorities for action

- Establish many more demonstration / lighthouse projects that combine renewable electricity sources with aluminium production (including business models) to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).
- Create early demand for "green" aluminium (mandate if necessary); creating a market can incentivise improvements in process efficiency and costs and reduce the risk of "carbon leakage". Certification of green supply chains may be required.
- Establish closer collaboration between companies in the aluminium and power sectors – to ensure that plans are compatible and to exploit synergies, particularly around new business models that create value from flexibility in demand and so help manage the increased deployment of variable renewable energy sources, such as solar and wind.
- Increase public and private activities and cross-border collaboration for RD&D into alternative "inert" anode designs.
- Explore opportunities to relocate more aluminium production to areas with the potential for low-cost renewable electricity supply; this can reduce costs while delivering emission reductions.

Transport overview

Transport share of total energy and process-related CO_2 emissions in 2017 (Gt).

Transport share of total energy and process-related emissions in 2050 Planned Energy Scenario (Gt).

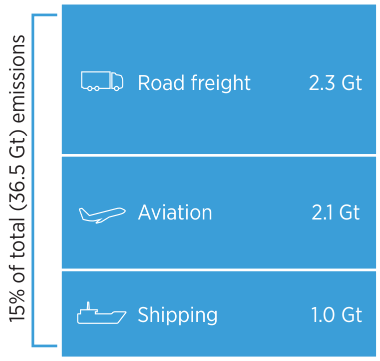


Source: IRENA, 2020a; IEA, 2017

The Planned Energy Scenario (PES) provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

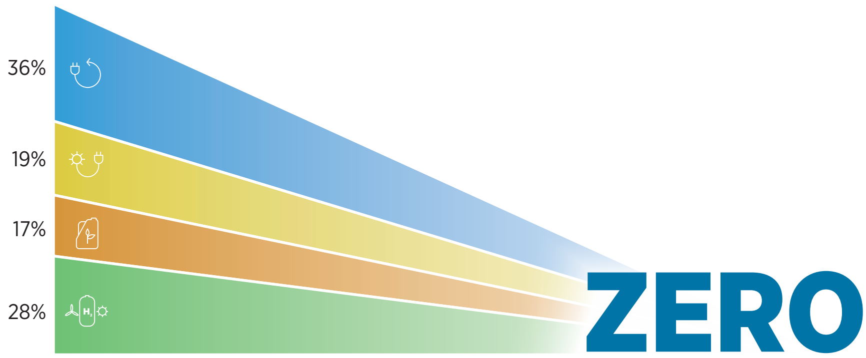
Freight transport: Options for reaching zero

Direct Energy & Process CO_2 Emissions in 2050 (Planned Energy Scenario)



*Emissions from energy

Reaching zero in key transport sectors



- Reduced demand and improved energy efficiency
- Direct use of clean, predominantly renewable, electricity
- Direct use of renewable heat and biomass
- Indirect use of clean electricity via synthetic fuels & feedstocks
- Use of carbon dioxide removal measures

Transport plays a vital role in the world's economy. It facilitates the movement of people and goods across the globe and enables modern life as we know it. This comes at a cost, however, as the transport sector is also a major source of emissions due to its current heavy reliance on fossil fuels. With the global demand for transport services expected to increase in future years there is an urgent need to identify ways to reduce emissions and advance towards the complete decarbonisation of the sector.

Transport emissions come from the combustion of fossil fuels in internal combustion engines and turbines. When combusting these fuels, a range of different greenhouse gases and pollutants are emitted, including CO_2, carbon monoxide, nitrogen oxides, hydrocarbons and other particulate matter. The transport sector, as a whole, accounted for nearly a quarter of global energy-related CO_2 emissions in 2017, with total CO_2 emissions of 8.5 Gt. An estimated 97% of transport-related emissions come from road, air and marine transport, while rail and other modes of transport account for the remaining 3%.

The preferable path to low CO_2 emissions has become clear for some but not all transport modes. Electrification with renewables is a viable option for rail and light-duty road transport (cars, sport utility vehicles (SUVs), small trucks), assuming that the electricity comes from renewable sources. In the case of rail transport, the use of electricity is already widespread, especially for passenger transport. In the case of light-duty road transport, battery electric vehicles have shown dramatic improvements in range (kilometres/charge), cost and market share in recent years.

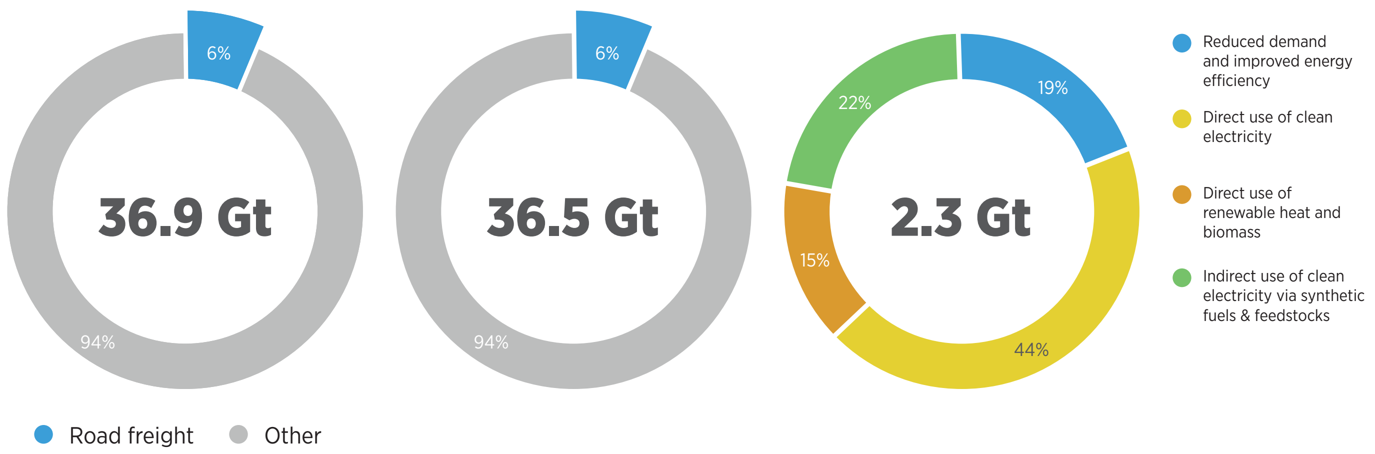
For other transport modes, however, the optimal pathway has yet to become clear. Road freight transport, aviation and shipping are significant energy users and CO_2 emitters, and driving their emissions to zero by 2060 will be a challenge. This report examines the challenges and options available to reduce and eventually eliminate direct emissions in these three harder-to-decarbonise sub-sectors.

Road freight

Road freight share of total energy and process-related CO_2 emissions in 2017 (Gt).

Road freight share of total energy and process-related CO_2 emissions in 2050 Planned Energy Scenario (Gt).

Estimated role of key CO_2 emission reduction measures to reduce road freight Planned Energy Scenario emissions to zero.



Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Road freight transport accounted for 27% of all transport-related emissions or over 6% of global energy-related emissions in 2017. Despite representing only 9% of the global vehicle stock, freight trucks accounted for around 39% of the life-cycle greenhouse gas emissions from road vehicles in 2017.

3 options compatible with reaching zero emissions

ZERO

Battery electric vehicles

- Use electric motors powered by a battery pack, charged with renewable electricity.

Fuel cell electric vehicles

- Use electricity produced by fuel cells powered by compressed (green) hydrogen.

Advanced biofuels

- Use biomass-based fuel substitutes, such as biodiesels and renewable diesels.

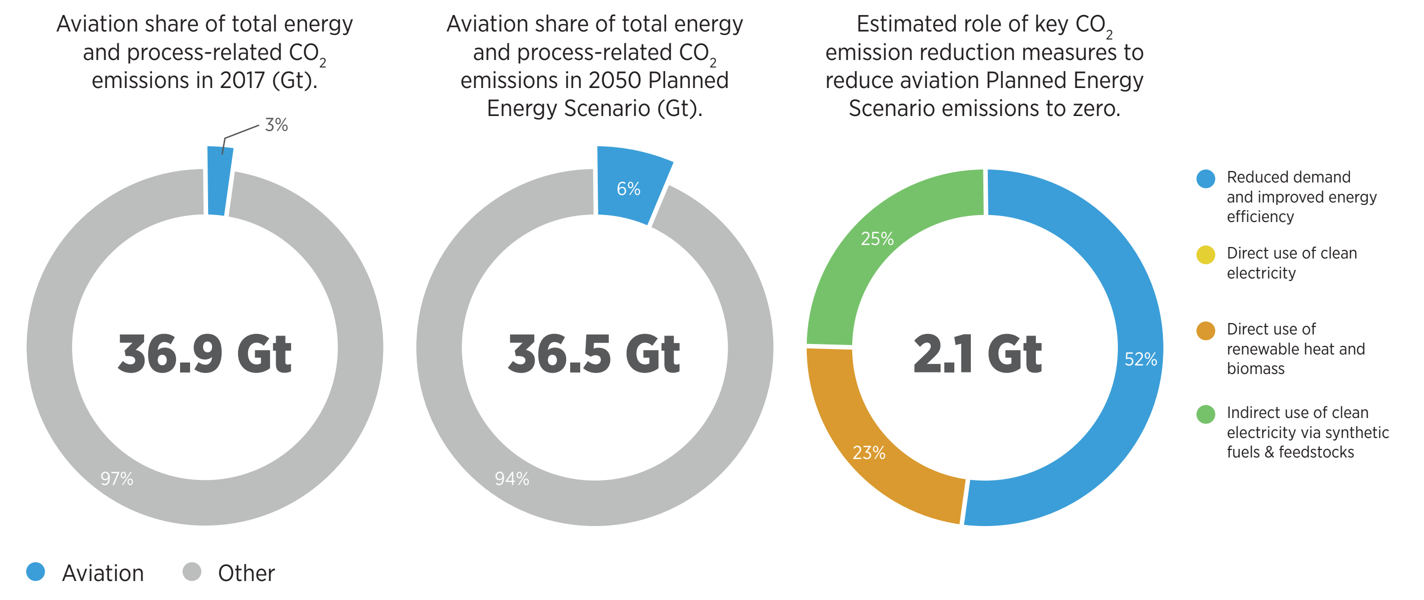
Battery electric vehicles are a feasible decarbonisation option for light-duty freight transport (*e.g.*, "last-mile" delivery vehicles). Due to their heavy loads and high power requirements, batteries are more difficult to implement in road freight transport. Their kilowatt-hour per kilometre (kWh/km) requirement is 1.1-1.3 kWh/km, compared to 0.2 kWh/km for light-duty vehicles.

Fuel cell electric vehicles are an emerging option for heavy-duty road transport, as they may allow for longer ranges than battery electric vehicles. Existing fuel cell electric long-haul trucks have a range of 1 100 kilometres, compared to the 400-800 kilometre range of their battery electric counterparts. A limited number of heavy-duty fuel cell electric vehicle fleets are already in operation. Biofuels are already used commercially in some markets; however, their limited production and relatively high cost remain barriers, and feedstock availability is a potential limitation.

Priorities for action

- Co-develop national and international roadmaps that have wide stakeholder support with clear milestones that show the sector-specific pathway towards full decarbonisation; a shared industry vision and a broad buy-in to the trajectory is a key enabler of investment.
- Establish many more demonstration / lighthouse projects involving small fleets of vehicles, to show what can be done and to collate and share the learning (some low-carbon freight vehicle designs are emerging, but they remain niche).
- Create incentives for low-carbon road freight deliveries (*e.g.*, through progressively tightening standards and through corporate commitments; creating demand can incentivise investment in technologies and so reduce costs.
- Increase public and private funding and cross-border collaboration for RD&D into battery performance improvements and cost reductions, vehicle designs, hydrogen, synthetic fuel, and biofuels production and supply.
- Exploit cross-sectoral synergies such as the need for lower-cost batteries, the need for lower-cost green hydrogen and hydrogen supply chains, and the need for expanded sustainable sources of biomass and biofuels, and the associated supply chains' infrastructure.

Aviation



Note: Energy efficiency includes modal shifts and behavioural changes.
Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

Aviation accounts for 11% of all transport emissions, or 2.5% of global energy-related emissions. Demand for aviation is expected to more than double by 2040, making decarbonisation of the sector a priority. Aviation is dependent on high-energy-density fuels due to mass and volume limitations of aircrafts. With current aircraft designs, this limits the options of alternative fuels suitable for replacing jet fuel to some advanced biofuels and synthetic drop-in fuels.

Advanced biofuels, in the form of biojet, are the most technologically straightforward pathway to decarbonise the aviation sector, but current production meets only 0.004% of global jet fuel demand. Perceived barriers for biofuels include regulatory shortcomings, availability of financing, and feedstock costs and accessibility. Synthetic aviation fuels produced from green hydrogen could play a role as drop-in fuels, but production is currently very limited and costs are very high, exacerbated by a lack of demand for the fuels at the current price point. Electric propulsion has some advantages over jet engines such as lower complexity and maintenance costs. However, due to technical limitations related to mass, weight and volume, the technology is currently only feasible for small planes and short-haul flights.

3 options compatible with reaching zero emissions

Biojet fuel

- Use fuels produced from sustainably sourced biomass.

E-fuels

- Use synthetic fuels produced from cleanly sourced CO_2 and green hydrogen.

Battery-powered aircraft

- Use propulsion systems powered by batteries charged with renewable electricity.

Priorities for action

- Maintain support for and implement industry-wide international agreements on emission reduction mechanisms and build on those to establish a shared zero-emission vision and strategy for aviation.

- Develop (and ideally mandate) goals for domestic (in-country) aviation and develop national roadmaps to reach zero emissions that are co-owned by all stakeholders.

- Establish many more demonstration / lighthouse projects involving low-carbon fuel use or new aircraft designs, to show what can be done and to collate and share the learning (some low-carbon aircraft designs are emerging, but they are currently small aircraft only).

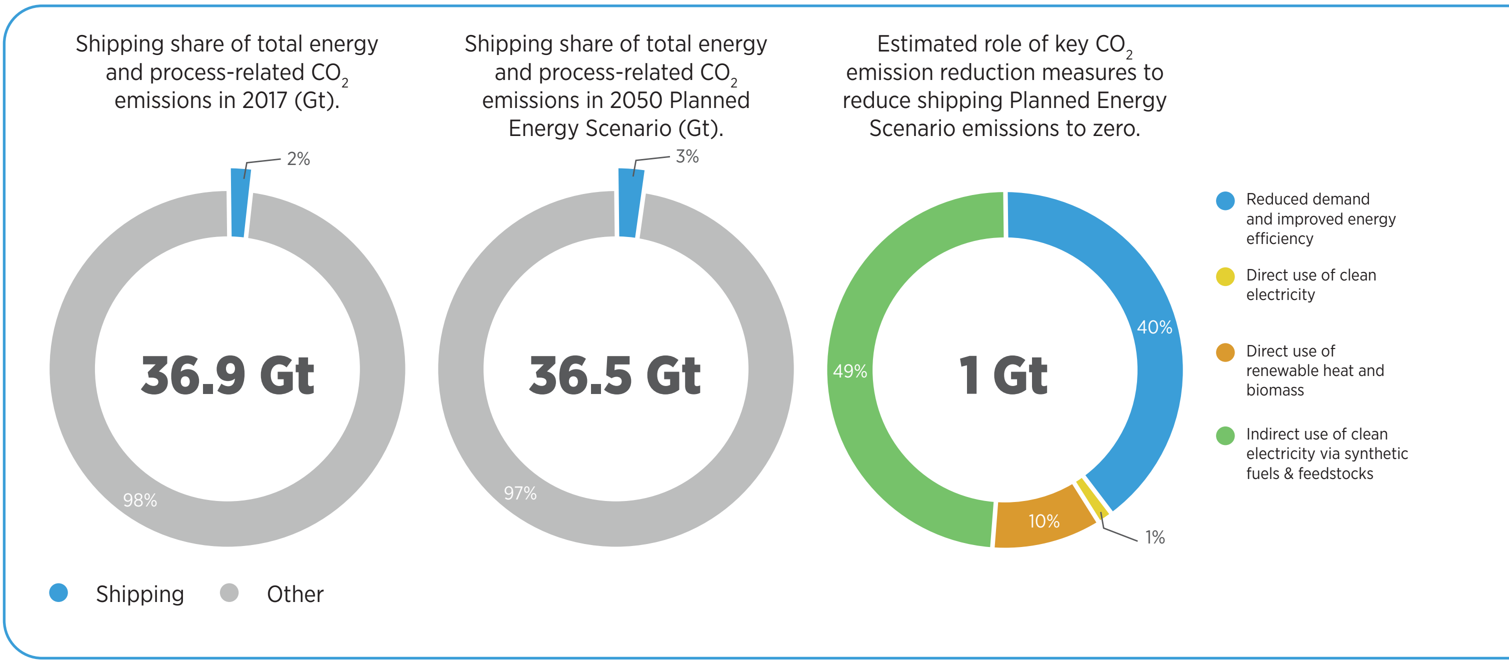
- Create incentives for low-carbon flights (*e.g.*, through progressively tightening standards, through corporate commitments and through consumer support); creating demand can incentivise investment in technologies and support scale-up which can reduce costs.

- Increase public and private funding and cross-border collaboration for RD&D into sustainable biomass supply, biofuels production, synthetic fuels production, electricity storage and alternative aircraft designs (particularly urgent to begin now because of very long development and licencing timelines of large aircraft).

- Develop a more detailed and shared understanding of the realistic potential future availability of key fuels (*i.e.*, biojet and synthetic fuels) in different locations and for different applications – to inform choices and trade-offs both in the aviation sector and across other sectors.

- Exploit cross-sectoral synergies such as the need for expanded sustainable sources of biomass and biofuels, the need for lower-cost green hydrogen and synthetic fuels production, and the associated supply chains' infrastructure.

Shipping



Note: Energy efficiency includes structural change.
Source: IRENA, 2020a; IEA, 2017
PES = the Planned Energy Scenario which provides a perspective on energy system developments if only current government energy plans and planned targets and policies were implemented and no additional measures.

International shipping is responsible for 90% of the world's trade (ICS, 2020), and the sector was responsible for 2.3% of annual global CO_2 emissions in 2017, or around 10% of global transport sector emissions. Around 20% of the global shipping fleet is responsible for 85% of the net greenhouse gas emissions associated with the shipping sector. Therefore, a limited number of interventions might have a large impact in decarbonising the shipping sector.

Improvements in energy efficiency can mitigate some emissions, but as trade volumes grow the sector will eventually need to shift to renewable fuels and to alternative means of propulsion. The sector is heavily dependent on inexpensive, low-grade refining residues, and although several lower-carbon alternatives exist that can function well technically, they all come at a considerable cost premium.

Electrification via batteries or fuel cells could play an important role for short-distance vessels (*i.e.*, ferries, and coastal and river shipping). Biofuels are an immediately available option to decarbonise the shipping sector either in blends or as drop-in fuels. However, their potential is currently limited by uncertainties in the industry regarding their availability, sustainability and cost. Hydrogen and e-fuels, produced from renewable power, could play an important role but their adoption would require substantial adaptations to existing onboard and onshore infrastructure, and thus costs. Ammonia, methanol and biomethane, produced from renewable power or biomass, are emerging as the most feasible low-carbon fuel pathways.

2 options compatible with reaching zero emissions

ZERO

Advanced biofuels

- Use biomass-based fuels such as biodiesel, renewable diesel, bio-methanol, bio-fuel oil and liquefied biogas.

E-fuels

- Use green hydrogen or synthetic fuels such as green methanol, ammonia and methane.

Priorities for action

- Maintain support for and implement industry-wide international agreements on emission reduction mechanisms and build on those to establish a shared zero-emission vision and strategy for shipping.
- Develop (and ideally mandate) goals for specific shipping routes and develop roadmaps to reach zero emissions that are co-owned by all stakeholders.
- Establish many more demonstration / lighthouse projects involving low-carbon fuel use on specific ships or on specific shipping routes and new ship propulsion designs, to show what can be done and to collate and share the learning (some projects are emerging, but they remain niche).
- Create incentives for low-carbon shipping (*e.g.*, through progressively tightening standards, and through corporate commitments including companies whose goods are shipped); creating demand can incentivise investment in technologies and support scale-up which can reduce costs.
- Increase public and private funding and cross-border collaboration for RD&D into sustainable biomass supply, biofuels production, synthetic fuels production and alternative ship propulsion designs.
- Develop a more detailed and shared understanding of the realistic potential future availability of key fuels (*i.e.*, biofuels, synthetic fuels) in different locations and for different applications – to inform choices and trade-offs both in the shipping sector and across other sectors.
- Exploit cross-sectoral synergies such as the need for expanded sustainable sources of biomass and biofuels, the need for lower-cost green hydrogen and synthetic fuels production, and the associated supply chains' infrastructure.

Realising a renewables-based strategy for reaching zero

1	**Pursue a renewables-based strategy for end-use sectors with an end goal of zero emissions.**	This involves developing linked sectoral strategies at the local, national and international levels built on the five technology pillars of demand reduction / energy efficiency, renewable electricity, renewable heat and biofuels, green hydrogen and e-fuels, and carbon removal technologies.
2	**Develop a shared vision and strategy and co-develop practical roadmaps involving all major players.**	To ensure engagement, national and international visions and roadmaps for the sector must be supported by all key actors – across political parties, across competing companies, by consumers and by the wider public. International and inter-governmental bodies and initiatives can assist in building consensus.
3	**Build confidence and knowledge among decision makers.**	Decision makers need to better understand the risks. Many more demonstration and lighthouse projects are needed. Those who can must lead – that is, developed countries, major economies, major companies, and public and private sector "coalitions of the willing" need to step up and show what is possible.
4	**Plan and deploy enabling infrastructure early on.**	New approaches will require substantial new infrastructure – to produce and deliver large amounts of renewable power, biofuels and e-fuels. Infrastructure investment needs to come ahead of the demand. Carefully co-ordinated planning coupled with targeted incentives will be needed.
5	**Foster early demand for green products and services.**	Creating early sources of demand for green fuels, materials, products and services – through public procurement, corporate sourcing, regulated minimum percent requirements, etc. – will help build the scale of production needed and help reduce costs. There are some good and bad examples of this that can be learned from.
6	**Develop tailored approaches to ensure access to finance.**	Considering the specificities of these sectors – i.e., high CAPEX, long payback periods, etc. – tailored financial instruments along the whole innovation cycle are needed. Co-operation between public and private financial institutions can help.
7	**Collaborate across borders.**	This is a global challenge, and the solutions needed are complex and expensive. Countries working alone will not be able to explore all options in the necessary depth. International collaboration can help countries share the burden.
8	**Think globally, utilise national strengths.**	Relocating industrial production to places with better access to low-cost renewable energy could reduce costs and create new trade opportunities. Countries with large or expanding production should be supported in getting on the right (zero-carbon-compatible) track early on.
9	**Establish pathways for evolving regulation and international standards.**	Regulations and standards are key enablers of change but can also be barriers – they require careful planning to ensure that they shift at the same pace as the technological changes.
10	**Support RD&D and systemic innovation.**	Large gaps in capability and large cost differences between new renewables and established fossil fuel options still remain. Investment in research, development and deployment (RD&D) is needed across a range of technologies to reduce costs, improve performance and broaden applicability. Innovation must be systemic – that is, technology innovation needs to go hand-in-hand with innovation in business models, in market design, in system operations and in regulation.

None of the options outlined in the *Reaching zero with renewables* report are commercially mature and ready for wide adoption; many uncertainties remain about their potential and optimum use, and none will be easy to adopt. The reasons are varied and complex but include: the high costs of new technologies and processes; the need for enabling infrastructure ahead of demand; highly integrated operations and long-established practices; uneven, large and long-term investment needs; gaps in carbon accounting; and competitiveness and carbon leakage risks for first-movers.

Addressing these challenges needs to be the focus of far more attention and creativity than is currently being applied. Sector-specific actions are explored in the report, but at the higher level there are a number of cross-cutting actions that should be addressed with urgency.

The world has made remarkable progress in the last decade in developing renewable energy sources and has made positive steps towards decarbonising power systems. Collectively it must now seek to make comparable progress in addressing carbon emissions in end-use sectors. That 40-year transition has barely begun, but it warrants far greater attention, planning, ingenuity and resources now if progress is to be made fast enough. There are significant challenges but also a range of promising options – particularly those that make use of low-cost and abundant renewable resources. With the right plans and sufficient support, the goal of reaching zero emissions in key transport and industry sectors is achievable.

To engage further on this topic:

Join IRENA's virtual Innovation Week 2020 (5-8 October) or view the recordings, at http://innovationweek.irena.org.

Visit http://irena.org/industrytransport for further reports including the upcoming *Reaching zero with renewables* – Briefing papers which will provide short, decision maker-focused insights on specific aspects of this topic.

1.

PATHWAYS TO ZERO

1 Pathways to Zero

1.1 Report overview

Limiting the global average temperature rise to no more than 1.5°C above pre-industrial levels will require the complete decarbonisation[1] of all sectors of the economy by early in the second half of this century. That will be very challenging, particularly in some key industry and transport sectors where viable options are currently limited. Renewables, supplemented with other technologies, can play a pivotal role in these sectors, but the potential of renewables has not been fully recognised to date.

Renewables, supplemented with other technologies, can play a pivotal role in these sectors, but the potential of renewables has not been fully recognised to date.

This report has **a twin focus**: exploring how the world could achieve **zero** emissions in key industry and transport sectors by around 2060, and assessing the potential role of **renewables** in doing so. The report aims to provide an accessible overview of the topic as a basis for a more detailed and informed discussion among policy makers and other stakeholders on the challenges, uncertainties and most critical gaps in capabilities that will need to be addressed if we are to facilitate a renewables-based pathway to zero carbon emissions by 2060. It brings together insights from technology analysis provided to date by the International Renewable Energy Agency (IRENA) and other sources, signposts where further detailed discussions can be found and highlights gaps in knowledge that should be the focus for further detailed work.

This chapter outlines the emission reduction challenges and what we currently know about pathways to reaching zero emissions. The subsequent two chapters identify and discuss the main options for eliminating direct carbon dioxide (CO_2) emissions from energy use and industrial processes in the most challenging industrial sectors, including iron and steel, chemicals and petrochemicals, cement and lime, and aluminium; and in the most challenging transport sectors, namely road freight, aviation and shipping. The final chapter discusses the way forward and proposes specific actions to begin the transition to eliminate CO_2 emissions in those sectors. The Annex provides additional context on the production, challenges and costs of the renewable energy carriers – including electricity, biofuels, hydrogen and synthetic fuels – that will be key to the transition to zero.

1 The term "decarbonisation" is used in this report to describe the reduction or elimination of the release of anthropomorphic carbon dioxide emissions into the atmosphere from energy production and use or from industrial processes. Carbon is an important element in many materials; decarbonisation in this context is not about removing carbon, but rather about preventing CO_2 emissions.

BOX 1: RECENT IRENA ANALYSIS

IRENA's recent analytical work provides insights into the role of renewables in driving CO2 reductions in these challenging sectors. The present report draws on these analyses and other sources to provide a broad perspective on the options available and to inform the development of more detailed plans. Key documents and meeting notes can be found on IRENA's website (https://irena.org/publications) and are summarised in Table 1.

TABLE 1: IRENA'S RECENT WORK ON RELEVANT SECTORS

Sector(s)	Report / Analysis	Brief description
Aviation	Advanced aviation biofuels – ready for take-off? (Gielen and Oksanen, 2019)	This article discusses the growing use of biojet and the factors needed to accelerate its adoption, including regulatory frameworks and/or significant carbon pricing.
Aviation	Biofuels for aviation – Proceedings of an event organised by IRENA at the European Biomass Conference and Exhibition (EUBCE) (IRENA, 2019b)	This meeting discussed the potential for and strategies to accelerate biojet development, including the economics of the technology, policies for accelerated production and current barriers for expansion.
Aviation	Economics of biojet fuels (IRENA, forthcoming b)	This upcoming report analyses the current and future development of biojet fuels as well as technological and market perspectives covering the biojet market, status, and outlook, and the production of biojet and other sustainable aviation fuels.
Aviation and shipping	The outlook for power-fuels in aviation, shipping (Gielen et al., 2020)	This article discusses the scale, economics, climate benefits and initiatives surrounding e-fuels use in challenging sectors including aviation and shipping. It builds on the synfuels webinar hosted by IRENA and dena and highlights the key role of green hydrogen in meeting our climate goals.
Cement	CO2 emission abatement for cement and concrete – a global perspective (Gielen, forthcoming)	This upcoming paper provides an overview of the cement sector and its main decarbonisation challenges while analysing eight key options to decarbonise by mid-century.
Chemicals and petrochemicals	Innovation outlook: Renewable methanol (IRENA, forthcoming c)	This upcoming report studies the role of renewable methanol, including the current and future development of the technology and market, and related challenges to overcome for expansion.
Chemicals and petrochemicals	Zero-emission pathway for the global chemical and petrochemical sector	This upcoming paper assesses the techno-economic potential of 20 options for decarbonising the chemical and petrochemical sector's product life-cycle CO2 emissions compared to planned policies and pledges.
Industry	Circular economy for the energy transition (Gielen and Saygin, 2019)	This commentary discusses the techno-economic potentials and measurements of progress needed for the circular economy to unleash significant energy and climate benefits.
Industry and transport	Hydrogen from renewable power: Technology outlook for the energy transition (IRENA, 2018c)	This report studies the role of hydrogen, including technical maturation and cost reductions needed to meet a range of energy needs which are difficult to address through direct electrification.

Sector(s)	Report / Analysis	Brief description
Iron and steel	Renewables-based decarbonisation and relocation of iron and steel making: A case study (Gielen et al., 2020)	This article assesses the future role of hydrogen-based iron and steel making and its potential impact on global material flows, based on a combination of technology assessment, material flow analysis and micro-economic analysis.
Shipping	Navigating the way to a renewable future: Solutions to decarbonise shipping (IRENA, 2019d)	This report explores the impact of maritime shipping on CO_2 emissions, the structure of the shipping sector and key areas that need to be addressed to reduce the sector's carbon footprint.
Shipping	Shipping: Commercially viable zero emission deep sea vessels by 2030 (Gielen and Roesch, 2019)	This article discusses the climate impacts of the shipping sector and the steps needed to decarbonise within the next decade.
Transport	Advanced biofuels: What holds them back? (IRENA, 2019e)	This report analyses current barriers to investment in advanced biofuels based primarily on a survey of industry executives and decision makers and captures the perspective of project developers aiming to nurture the market and to scale up advanced biofuels.
Transport	Hydrogen: A renewable energy perspective (IRENA, 2019c)	This report examines the potential of hydrogen as a fuel in sectors that will be hard to decarbonise, including energy-intensive industries, trucks, aviation, shipping and heating applications.

1.2 Emission reduction pathways

The Paris Agreement on climate change calls on countries to strengthen the global response to the threat of climate change by keeping the global temperature rise this century well below 2 degrees Celsius (°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C. Achieving that ambitious target of 1.5 degrees will require a concerted effort to reach or get very close to net-zero CO_2 emissions, in all sectors of the economy, by early in the second half of this century (Box 3).

To help inform the development of national and international strategies IRENA has developed a comprehensive, data-based, analytical framework that illustrates a path to achieving the Paris Agreement's 2050 goals. As described in IRENA's *Global renewables outlook* (IRENA, 2020a), released in April 2020, this Paris-aligned path, known as the Transforming Energy Scenario, shows that significant reductions in energy sector carbon emissions are technically and economically feasible and affordable.

BOX 2: IRENA SCENARIOS AND PERSPECTIVES

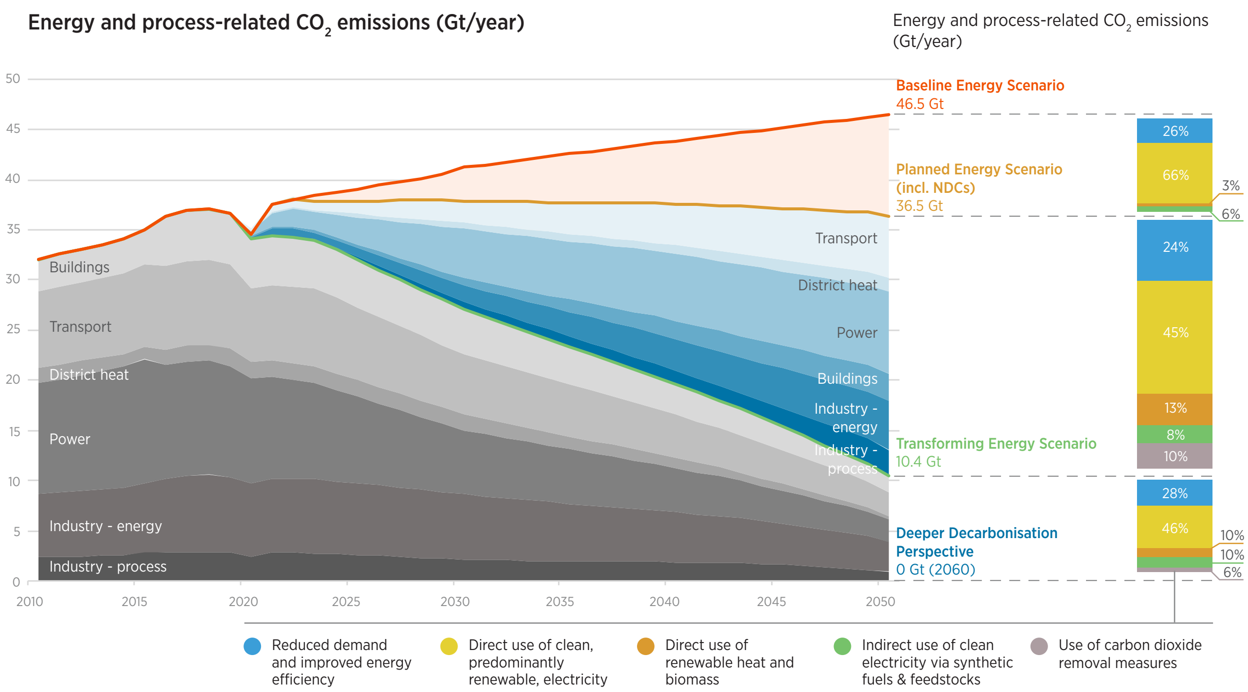
This report references several scenarios for the energy sector, developed by IRENA. These scenarios are described in full in IRENA's *Global renewables outlook: Energy transformation 2050*. In summary they are:

- The "Baseline Energy Scenario" (BES) reflects policies that were in place around the time of the Paris Agreement in 2015, adding a recent historical view on energy developments where needed.
- The "Planned Energy Scenario" (PES) is the primary reference case for this study, providing a perspective on energy system developments based on governments' current energy plans and other planned targets and policies (as of 2019), including Nationally Determined Contributions under the Paris Agreement unless the country has more recent climate and energy targets or plans.
- The "Transforming Energy Scenario" (TES) describes an ambitious, yet realistic, energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (although not limited exclusively to these technologies). This would set the energy system on the path needed to keep the rise in global temperatures to well below 2 °C and towards 1.5 °C during this century.
- The "Deeper Decarbonisation Perspective" (DDP) provides views on additional options to further reduce energy-related and industrial process CO_2 emissions beyond the Transforming Energy Scenario. It suggests possibilities for accelerated action in specific areas to reduce energy and process-related CO_2 emissions to zero in 2050-2060.

Figure 1 summarises the *Global Renewables Outlook's* scenarios. The Transforming Energy Scenario shows where emission reductions are needed and can be delivered across all sectors by 2050. However, even after significant emission reductions in the Transforming Energy Scenario are achieved, there are still 9.5 gigatonnes (Gt) of energy-related CO_2 emissions and 0.9 Gt of process-related CO_2 emissions remaining in 2050. Reaching zero carbon emissions will therefore require further action in power, buildings, transport and industry over and above the action in these sectors under the Transforming Energy Scenario.

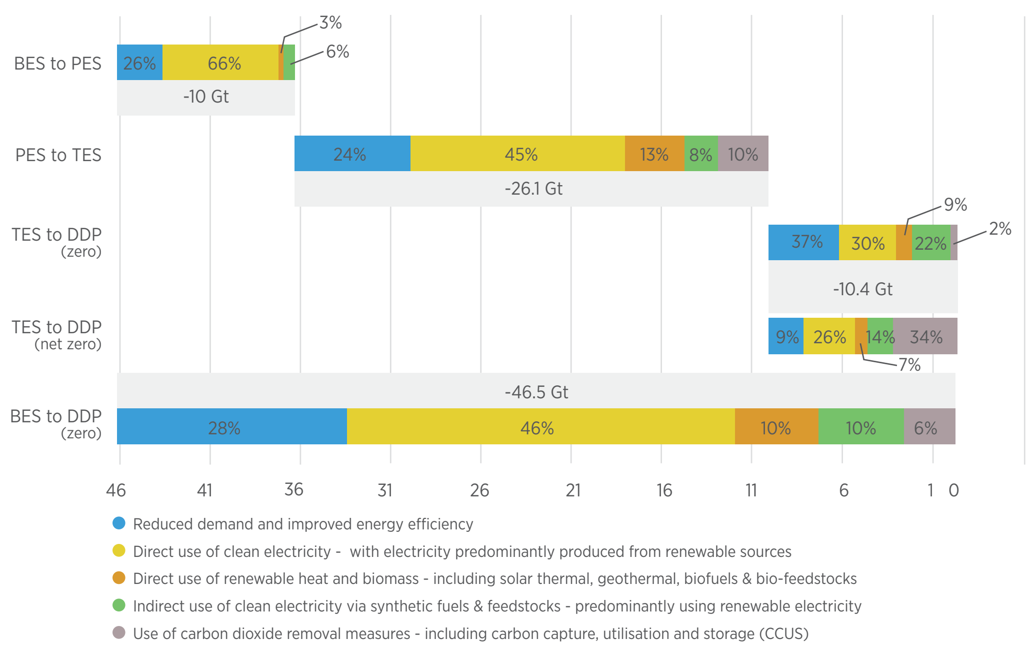
The focus of the *Global renewables outlook* was on the 2050 "well-below 2-degrees" goal; however, the report also explored the additional abatement needed to further reduce or eliminate energy-related and industrial process CO_2 emissions beyond the Transforming Energy Scenario. The Deeper Decarbonisation Perspective (DDP) is not a full scenario but a suggestion of possibilities for accelerated action in specific areas to reduce energy and process-related CO_2 emissions to zero by 2060. Figure 2 summarises the balance of reductions identified in the Deeper Decarbonisation Perspective analysis across different emission reduction measures in order to reach zero.

FIGURE 1: Energy- and process-related CO_2 annual emissions trajectories from 2010 till 2050



Note: Includes mitigation potential per technologies from IRENA's Baseline Energy Scenario to Planned Energy Scenario and Transforming Energy Scenario in 2050. The Transforming Energy Scenario includes 250 megatonnes (Mt) per year in 2050 of carbon capture, utilisation and storage for natural gas-based hydrogen production (blue hydrogen).
Source: Adapted from IRENA, 2020a

FIGURE 2: Contribution of emission reduction measures in different IRENA scenarios



Source: Adapted from IRENA, 2020a

1.3 The emission reduction challenge in industry and transport

IRENA's Transforming Energy Scenario leverages the recent dramatic reductions in the costs for renewable power generation – notably, for wind and solar photovoltaics (PV) – to make deep power sector emission reductions achievable by 2050. Meeting these goals in the power sector will be difficult, requiring large increases in global renewable power investment, accelerating the phase-out of fossil fuel use for electricity generation, and strong policy support aimed clearly at promoting direct renewable use (*e.g.*, solar thermal, biomass), energy efficiency (*e.g.*, thermal insulation of buildings, process improvement) and infrastructure investment (*e.g.*, power grids, flexibility measures such as storage).

The strategies needed to reach zero emissions in the power sector are at least reasonably clear: the technologies are readily available and market-proven, the costs are modest, and the policy tools are well-documented and effective. That is not the case in some end-use sectors.

Cost-competitive renewable power, combined with widening public acceptance and availability, is beginning to drive the electrification of some end-use sectors such as light-duty vehicles and buildings, and should lead to large reductions in energy-related carbon emissions. But in other end-use sectors a transition to renewables and towards zero emissions has barely begun.

This report focuses on those specific sectors in industry and transport where the options and potential for emission reduction are far less clear. These sectors are often described as "hard-to-decarbonise" or "hard-to-abate" because of the technological, logistical and economic challenges of reaching zero CO_2 energy and process emissions in these sectors and because options are currently limited.

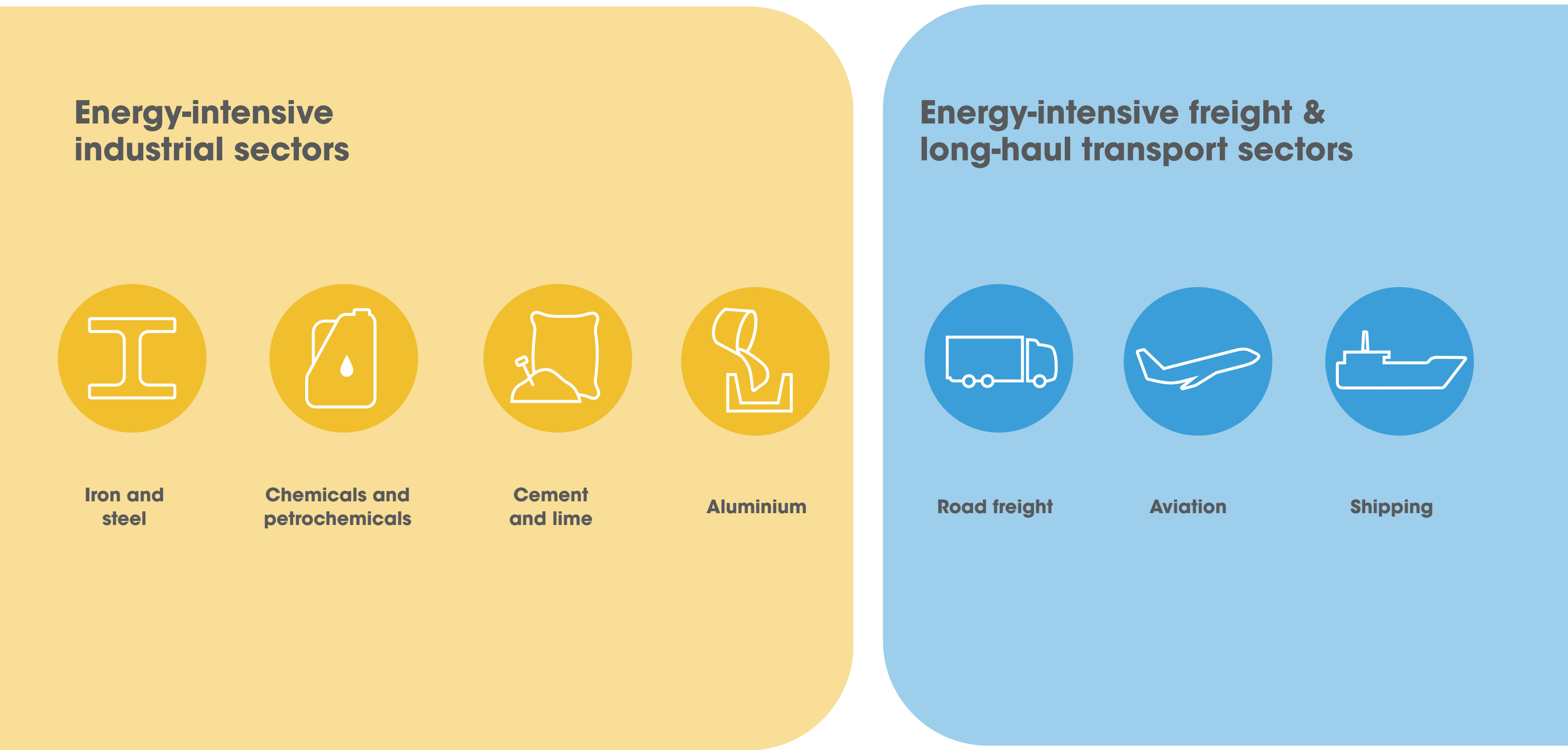
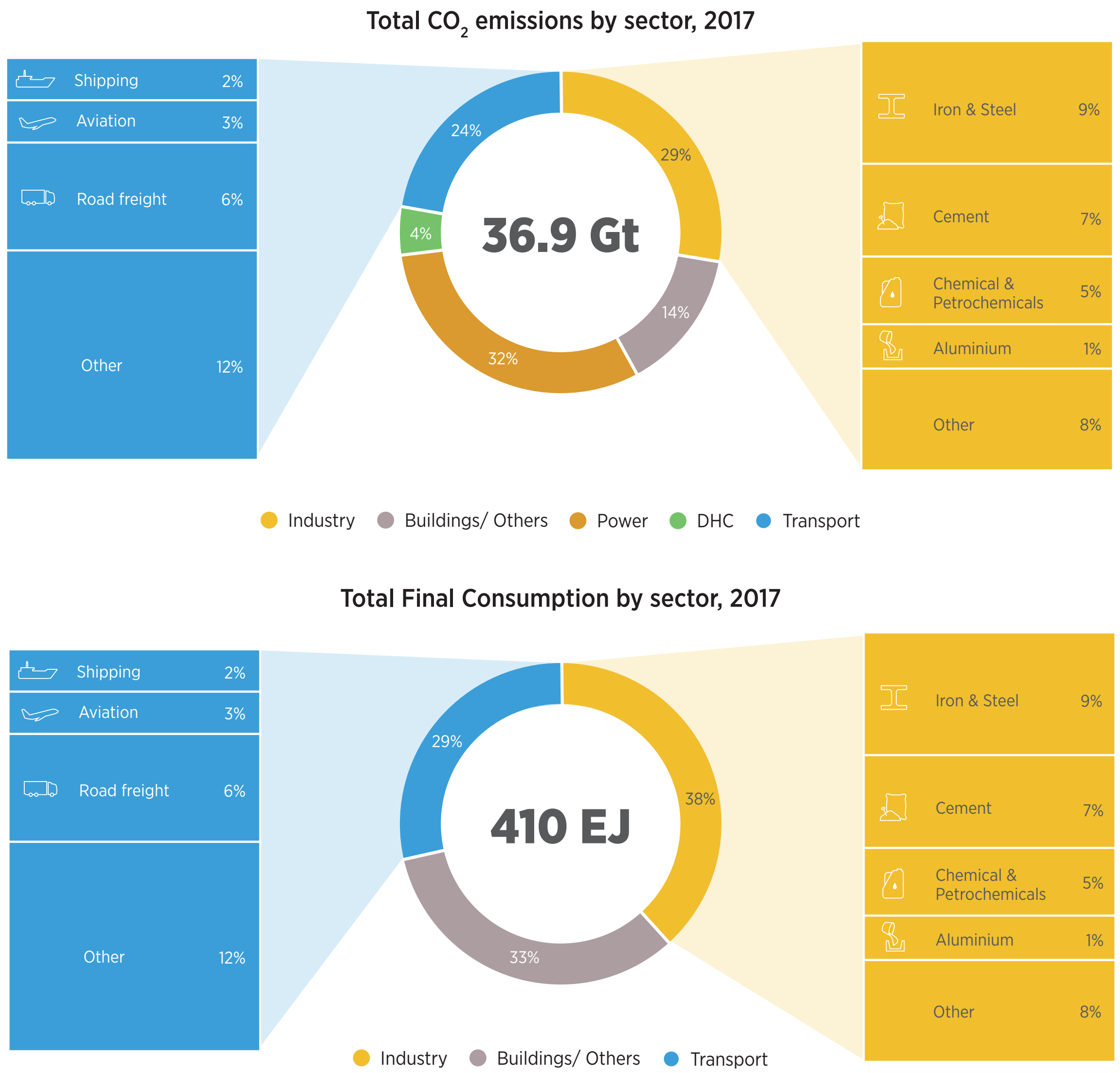


Figure 3 shows the breakdown of emissions and energy use in 2017. Together those seven sectors accounted for around a third of global energy and process-related CO_2 emissions in 2017. Iron and steel alone accounts for around 9% of energy and process CO_2 emissions, followed by cement (at 7%) and chemicals and petrochemicals (at 5%). Within transport, road freight emissions are more than twice those of aviation or shipping. However, aviation demand is growing faster than other sectors and is projected to become the more significant contributor to transport CO_2 emissions in the future, while being responsible for other greenhouse gas emissions.

In terms of energy use, industry and transport account for over two-thirds of total final energy consumption (TFEC). The chemical and petrochemical industry is the largest industrial energy consumer, accounting for 11% of TFEC, followed by iron and steel (8%) and cement (4%). In transport, out of the selected transport sub-sectors covered in this report, road freight is the largest energy consumer, accounting for 8% of TFEC, followed by shipping and aviation, both with 3%.

FIGURE 3: Total CO2 emissions and total final consumption by sector, 2017



Note: Total final consumption includes energy and non-energy uses for industry. STEEL = iron and steel, CEM = non-metallic minerals (e.g., cement), CHEM = chemicals, ALUM = aluminium, OTHER = other industry/transport sectors, SHIP = shipping, AVTN = aviation, ROAD_FR = road freight, DHC = district heating and cooling.
Source: IRENA calculations; IEA, 2017; IEA, 2019a

1.4 Reaching zero by 2060

The pathways to zero for the power sector, buildings and non-commercial transport sectors are reasonably clear, although challenging. Strategies for those sectors are explored in depth in a range of publications from IRENA and many others. The optimum pathways for other sectors, however, are less clear, look very challenging and have received comparatively little attention to date.

In principle a range of options are available that can help reduce emissions in these sectors. The challenge is to find the optimal mix of solutions that will result in zero carbon emissions by 2060 in the most practical and cost-effective way. The goal of reaching or at least coming close to zero in each sector requires a very different mindset compared to an objective of merely reducing emissions.

Each of the sectors discussed in this report is in the early stages of exploring emission reduction strategies, but many of the options being looked at will only partially reduce emissions and are not consistent with the sector eventually reaching zero. Some of those options – particularly demand reduction, energy efficiency and circular economy options – are still worth pursuing, for example if they make economic sense for the sectors or can assist in the later implementation of other options. In some cases, however, there is risk of locking in emissions that are then harder to eliminate later on. For example, "halving" efforts (*e.g.*, by replacing coal with natural gas) may halve emissions but will require further (potentially expensive and complex) actions to eliminate the remaining emissions.

In order to not waste resources, lose time or lock in emissions, a clearer focus is needed on the end objective of zero CO_2 emissions when evaluating which options to pursue. Technologies and processes that cannot eventually lead to zero or close-to-zero emissions are only worth pursuing if they either greatly reduce the scale of the challenge for true zero-emission solutions, or if they will be replaced in the next 40 years or if they are a stepping stone to successfully implementing zero-emission solutions.

A goal of reaching zero in each sector requires a very different mindset compared to an objective of merely reducing emissions ...

... there are only a very small number of currently conceived options in each sector that are consistent with a zero CO_2 emissions objective.

When these criteria are applied, only a very small number of currently conceived options in each sector are consistent with a zero CO_2 emissions objective. Most of those options are not yet sufficiently well-proven or cost-attractive to be a clear-cut choice for sectors. These options are discussed in Chapters 2 and 3.

BOX 3: ZERO OR NET-ZERO

Discussions of zero-emission strategies are usually focused on a goal of net-zero – that is, where some emissions are still produced but are offset by carbon dioxide removal (CDR) measures that remove emissions from the atmosphere. Examples of CDR measures include reforestation, afforestation, direct air capture, enhanced weathering, and bioenergy with carbon capture and storage (CCS).

IRENA's Deeper Decarbonisation Perspective explores both zero and net-zero goals because the optimum strategy is currently unclear given uncertainties in what technologies and policies can actually deliver.

Those countries that have adopted zero-emission goals usually refer to net-zero. That approach is likely appropriate when considering strategies at a national or international level where a system-wide view on emissions can be taken. At a sectoral level, however, it carries risks if the assumption in each sector is that it can continue to emit CO_2 that will be offset elsewhere. The premise of this report is that every sector should be aiming to reduce its emissions to zero or as close to that as possible. Problems will arise that mean zero emissions are not achieved in every case, in every country or where the pace of emission reductions is too slow. Negative emissions technologies will be needed in those circumstances, but their availability and use should not be assumed up front. There may also be synergies between sectors – such as the chemicals sector utilising CO_2 captured in other sectors. Accurately accounting for such synergies requires a full system-level analysis. Given those uncertainties this report focuses on exploring what can be achieved, consistent with a zero-emission goal for each sector.

1.5 Measures for zero emissions

The majority of emission reductions will be achieved through a combination of five "emission reduction measures", three of which rely primarily on renewable energy.

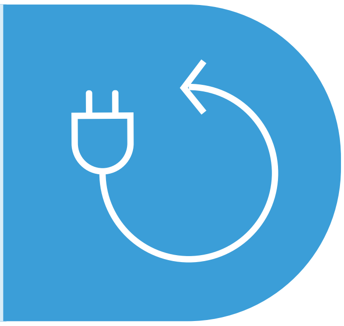
While each of the sectors explored in the subsequent chapters will require tailored and differentiated strategies to reach zero, they have a number of common elements. The majority of emission reductions will be achieved through a combination of five "emission reduction measures", three of which rely primarily on renewable energy.

Figure 4 and the remainder of this chapter summarise those measures. In practice, a combination of all measures will be needed in most sectors, but these five are listed in approximate order of preference based on maturity, practicality, complexity and cost.

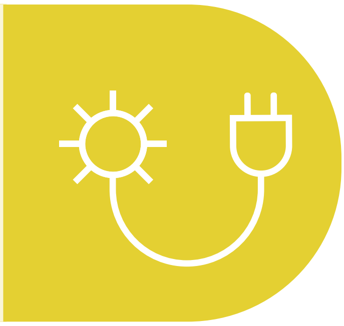
The Annex provides a fuller discussion of the renewable energy carriers that support these measures, including their production process, technology status, challenges and costs.

FIGURE 4: Emission reduction measures for reaching zero

Reduced demand and improved energy efficiency
Reduce energy and material demand and intensity of use through a range of actions including: energy efficiency, behavourial and process changes, relocation and the application of circular economy principles.

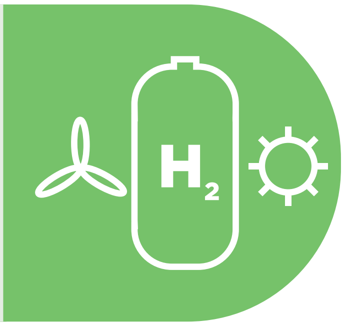


Direct use of clean electricity – predominantly produced from renewable sources
Directly use clean electricity, sourced predominantly from renewables, to provide energy requirements. Can both replace existing fossil fuel-based electricity use and replace other energy demand through "electrification".

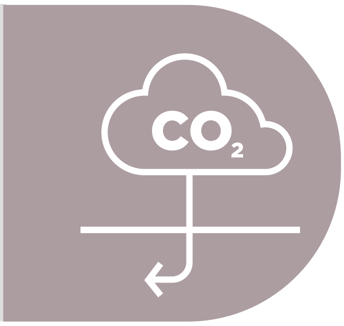


Direct use of renewable heat and biomass – including solar thermal, geothermal, biofuels and bio-feedstocks
Directly utlise renewables for energy and feedstocks. Includes the use of solar and geothermal for some heat requirements and the use of sustainable biomass including through the direct use of bioenergy for heat and the production and use of biofuels and bio-feedstocks. This may also include the combination of biomass use with carbon capture and storage (BECCS).

Indirect use of clean electricity via synthetic fuels and feedstocks – predominantly using renewable electricity
Source energy and feedstocks from hydrogen or from fuels or feedstocks produced from hydrogen (synthetic fuels or feedstocks) using CO_2 captured from non-fossil fuel sources. The hydrogen should be "clean" and preferably "green", i.e., sourced from renewables.



Use of carbon dioxide removal measures – including carbon capture, utilisation and/or storage (CCUS)
Capture most or all CO_2 emissions from fossil fuel-based energy production or other processes and either store the captured CO_2 permenantly or utliise the CO_2 in ways in which it will not be later released. This can include the production of "blue" hydrogen or the capture of CO_2 from processes or the atmosphere specifically for use in creating chemical feedstocks or fuels.



Note: In some specific sectors other strategies will contribute as well – for example, replacements for clinker, the use of alternative building materials or the relocation of plants to better utilise renewable resources.

Reduced demand and improved energy efficiency

Reducing energy and material demand and intensity of use will not in itself deliver zero emissions, but it will reduce the overall scale and cost of the challenge. A range of actions can contribute, including: energy efficiency, behavioural and process changes, relocation of supply or demand, and the application of circular economy principles which include recycling, reuse, materials substitution, more efficient materials design and the use of sustainable biomass resources.

The industry sector can benefit from the cost savings that come from improvements in energy efficiency. In the industry sector, energy efficiency would improve on average by up to 1% per year under IRENA's Transforming Energy Scenario over the 2016-2050 period compared to 0.3-0.5% per year in the Planned Energy Scenario. The annual improvements exceed 1% until 2030 and continue at 0.6-1.0% per year between 2030 and 2050. Going beyond this increase in efficiency is difficult since, at a certain point, processes will near their thermodynamic minimum energy use.[2]

In the transport sub-sectors, energy demand continues to increase year by year, despite consistent efficiency improvements in road freight, aviation and shipping. To reduce demand, further efficiency improvements, along with modal shifts, will be necessary, especially from road freight and aviation to rail. In the Transforming Energy Scenario roughly 30% of CO_2 emission reductions from the Planned Energy Scenario's 2050 levels in the shipping, aviation and road freight sub-sectors can be attributed to demand reduction measures. These are particularly important to eliminate emissions in the aviation sector, which is responsible for almost 40% of CO_2 emission reductions by 2050 according to the Transforming Energy Scenario.

Reducing demand and improving energy efficiency is not the focus of this report; a fuller discussion can be found in analysis from IRENA and the Copenhagen Centre on Energy Efficiency (IRENA, 2017a), in the International Partnership for Energy Efficiency Cooperation's reports on industry (IPEEC, 2020a) and transport (IPEEC, 2020b), in the commentary on the circular economy for the energy transition (Gielen and Saygin, 2019) and in the work of the Ellen MacArthur Foundation (EMF, 2017).

Direct use of clean electricity – predominantly produced from renewable sources

The decarbonisation of the power sector will enable increased use of renewables in the industry and transport sectors through the direct electrification of applications. Direct electrification with renewable electricity is an increasingly practical and low-cost option which should be the first energy supply option considered when scoping decarbonisation strategies.

Renewable power will make the largest contribution to the use of renewables in industrial applications. Many electricity-intensive sectors such as aluminium smelters are already linked with generation assets that offer cheap electricity from hydropower or geothermal power; that approach is likely to be used more in the future. Several large manufacturing companies are in the process of integrating renewable power generation into their existing manufacturing plants through either solar PV panels on the production facilities, wind turbines on site or other sources of renewable energy.

Electricity demand is expected to grow in the manufacturing industry, due to increasing electrification of production processes and expansion of production in electricity-intensive sectors, such as non-ferrous metals. Consumption of electricity in industry will grow

2 Thermodynamics imposes ultimate and inviolable limits. However, imaginative approaches can work around these limits – for example, heat pumps can provide 3-4 units of heating using just 1 unit of electricity.

from around 9 000 terawatt-hours (TWh) today to over 14 000 TWh in the Planned Energy Scenario for these reasons. In the Transforming Energy Scenario, increased electrification, both direct and indirect, will further increase electricity consumption in industry to over 16 400 TWh by 2050. Reaching zero emissions will likely require further substantial increases.

In transport, electrification with renewables also plays a large role in achieving the elimination of CO_2 emissions by 2060. According to IRENA's Deeper Decarbonisation Perspective, in order to eliminate emissions in road freight transport by 2060, around 45% of emission reductions will come from the switch to battery electric vehicles. Electrification will also play an important role in the decarbonisation of the shipping and aviation sectors, particularly in small and short-distance applications.

Electrification is discussed further in the Annex, and its use is explored in the following chapters. The synergies with the power sector, through "sector coupling", are also discussed in a range of other IRENA publications, including the *Innovation landscape for a renewable-powered future* report (IRENA, 2019a) and the upcoming update of the *Electrification with renewables: Driving the transformation of energy services* report (IRENA, forthcoming a).

Direct use of renewable heat and biomass – including solar thermal, geothermal, biofuels and bio-feedstocks

The use of biomass – either directly as feedstock or heat or through conversion to advanced biofuels – is a well-established option that could play a larger role in transport and in industry to produce low-, medium- and high-temperature heat, replacing fossil fuels. The environmentally, socially and economically sustainable supply of biomass feedstocks is a key consideration. The supply of biomass and the production of biofuels is discussed further in the Annex, and its use is explored in subsequent chapters.

In IRENA's Transforming Energy Scenario, the use of biomass as a fuel is expected to grow by three times to around 28 exajoules (EJ) by 2050, which would amount to around 19% of industrial energy use. Another 11 EJ would be used as feedstock, predominantly for bioplastics production (5.3 EJ to produce around 125 Mt of bio-based plastics). A further 2.1 EJ of biomass would be used as feedstock for ammonia and methanol alongside almost 10.6 EJ of renewable hydrogen.

In the three transport sub-sectors covered in this report, biofuels also play an important role in reducing CO_2 emissions. In IRENA's Transforming Energy Scenario, close to 15% of CO_2 emission reductions by 2050 in these three sub-sectors can be attributed to the use of biofuels. Biofuels will be particularly important to the decarbonisation of the aviation industry, where 10 EJ per year of biofuels will be needed, according to IRENA's Deeper Decarbonisation Perspective, providing an emission reduction of 25% compared to the Planned Energy Scenario.

Solar thermal systems and geothermal heat can also make a significant contribution to low- and medium-temperature heat requirements in industry, which account for nearly half of all process heat requirements. In the Transforming Energy Scenario, solar water heater use in industry is expected to grow to around 6 EJ in 2050. This could represent up to 1 500 gigawatts (GW) of installed capacity. Reaching this level represents a significant effort since current installed capacity is less than 100 megawatts (MW). A large opportunity exists for small- and medium-sized enterprises outside of the energy-intensive sectors, since the temperature of the process heat is usually lower in such plants and the scale of energy consumption is smaller (IRENA, 2014).

Indirect use of clean electricity via synthetic fuels and feedstocks – predominantly using renewable electricity

Indirect electrification with renewables (*i.e.*, the conversion of renewable electricity into other clean energy carriers such as green hydrogen and synthetic fuels) to provide energy or carbon feedstocks is not currently a widely deployed option. However, it is an option that is receiving increasing attention and is likely to expand rapidly. The production of green hydrogen and e-fuels is discussed in the Annex, and its use is explored in subsequent chapters.

The use of green hydrogen plays an important role in the decarbonisation of the iron and steel, and chemical and petrochemical, industries. Green hydrogen can be used to replace hydrogen produced from coal or natural gas in the production of direct reduced iron, while synthetic hydrocarbon feedstocks can be used to replace primary petrochemicals, which could contribute to reducing CO_2 emissions in 2050 by 30% and 20% respectively, according to IRENA's Deeper Decarbonisation Perspective.

Shipping, aviation and road freight transport can also benefit from the use of green hydrogen and other synthetic fuels. Hydrogen fuel cells provide an ideal solution for clean long-haul road freight transport, while synthetic fuels can replace the use of fossil fuels in shipping and aviation. The use of hydrogen and synthetic fuels could reduce CO_2 emissions in 2050 by 22%, 25% and 50%, in the road freight, aviation and shipping sectors respectively, according to IRENA's Deeper Decarbonisation Perspective.

Use of carbon dioxide removal measures – including carbon capture, utilisation and/or storage (CCUS)

Given the challenges in eliminating CO_2 emissions in several of the heavy industry sectors, carbon capture, utilisation and/or storage (CCUS) has an important role to play. A good example is the cement industry, where 60% of the CO_2 emissions are process emissions and cannot be directly mitigated through the use of renewable-based solutions.

The role of CCUS technologies will include directly capturing CO_2 from industrial processes or from the production of fuels – in particular the production of blue hydrogen. CCUS might also be used as a transitional solution. Crucially, in the context of the zero-emission objective, the captured CO_2 must be either permanently stored or used in ways in which it is not eventually released.

CCUS is not the focus of this report, but for completeness it is briefly explored where relevant in the discussions of each sector.

2.

INDUSTRY

2 Industry

The industrial production of key materials is an essential enabler of modern economies. As countries develop, demand for such material continues to grow. However, that production currently comes with high CO_2 emissions. Industry accounts for around 28% of total global CO_2 emissions, but four industrial sectors in particular – iron and steel, chemicals and petrochemicals, cement and lime, and aluminium – account for around three-quarters of total industrial emissions.

Reducing emissions and eventually reaching zero will require radical shifts in how such materials are produced, consumed and disposed of. To date, however, the need to drive long-term emission reductions in these four industrial sectors has not received the necessary policy attention. A review of national policy strategies as set out in the Nationally Determined Contributions mandated under the Paris Agreement shows that as of 2017, out of a total of 2 326 measures proposed by countries, only 31 measures addressed specific industrial sectors.

A number of reasons account for this lack of action. Two in particular are key. Firstly, only a few economically viable CO_2 emission reduction solutions are currently available for these industrial sectors, and there is a lack of consensus and stakeholder acceptance among the sectors on which of the options are most suitable (Ahman *et al*., 2017). Secondly, carbon leakage – that is, the transfer of production to other locations where emission reduction requirements are lower – is also a deterrent in promoting decarbonising efforts. Although some earlier studies have considered this to be a less important issue (Gielen, 2000; Gielen and Yagita, 2002), newer reviews argue that for some regions this may be a barrier given that decarbonisation technologies are expensive and can impact competitiveness.

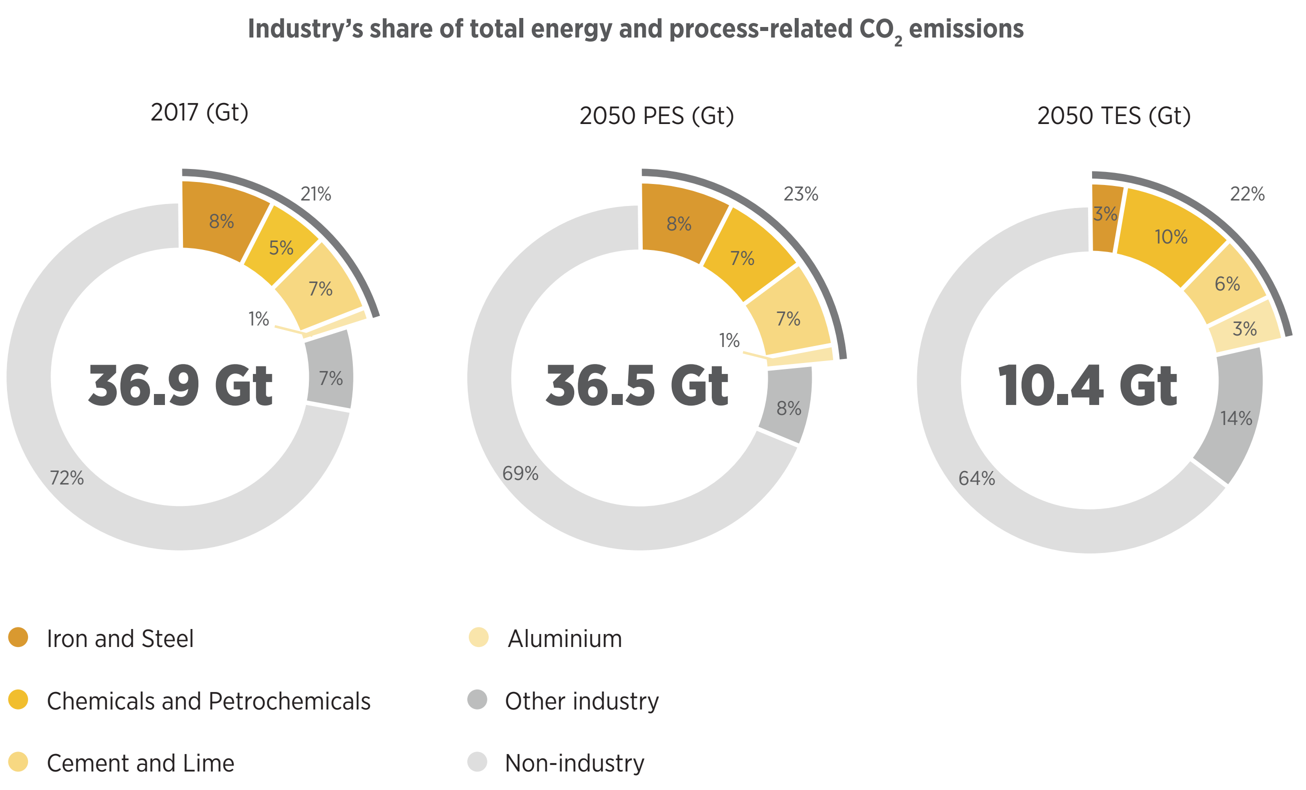
2.1 Industrial emissions and energy use

The majority of energy used in industry is currently sourced from fossil fuels. The total final energy and non-energy use in industry in 2017 amounted to nearly 160 EJ. Nearly one-third of that amount is coal, while oil, natural gas and electricity account for one-fifth each. Nearly a third of the energy and non-energy use is accounted for by the chemical and petrochemical industry alone (IRENA calculations based on IEA, 2017). But energy use is not the only source of emissions in the industrial sector. There are four main sources of industrial sector CO_2 emissions, all of which must be addressed to reach a zero-emission goal:

- **direct energy-related emissions** from fossil fuel combustion to generate process heat in the form of hot water, steam and direct heat;
- **indirect energy-related emissions** from the generation of electricity and district heat for some industrial processes, for motors and for auxiliary uses;
- **process emissions** as a result of the industrial processes themselves, for example CO_2 released from the consumption of anodes in aluminium production; and
- **product life-cycle emissions** such as fugitive emissions produced during the use of solvents, lubricants and other compounds, and end-of-life plastic waste incineration.

Figure 5 shows how industry's share of total energy and process-related CO_2 emissions will need to change over time. In 2017, industry accounted for over a quarter of total energy and process-related CO_2 emissions. Under current planned policies and programmes laid out by governments and companies, industrial emissions can be expected to increase slightly overall by 2050 (from 10.4 Gt in 2017 to 11.4 Gt in 2050), while CO_2 emissions from other sectors decrease, meaning that industry's share of total energy and process-related CO_2 emissions will grow to one-third, up from one-quarter. In the Transforming Energy Scenario, industry's energy and process CO_2 emissions fall to 3.7 Gt, but they represent 36% of remaining CO_2 emissions. Achieving the reductions set out in the Transforming Energy Scenario will be challenging, but even more so if the goal is to go further to reach zero emissions.

FIGURE 5: Industry's share of total energy and process-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



Source: IRENA, 2020a; IEA, 2017

2.2 Renewables-based emission reductions

IRENA's Transforming Energy Scenario (see Box 2 and Chapter 1) describes a pathway, across all sectors, for a 70% reduction in energy-related CO_2 emissions by 2050. This scenario does not result in zero emissions, but it does illustrate how significant reductions in emissions could be achieved and where further effort will be needed to reduce emissions to zero by around 2060.

Table 2 compares the energy demand and emission levels in these four industry sectors for the baseline year of 2017 and for the 2050 Planned and Transforming Energy Scenarios, and what would remain to be addressed by 2060.

In the Transforming Energy Scenario for 2050, a combination of energy efficiency, renewable energy, carbon capture and storage (CCS) and other measures (recycling/reuse, new materials and products, among others) reduces the industrial sector's energy and process-related CO_2 emissions from 10.4 Gt per year in 2017 to 3.7 Gt per year in 2050. This leaves the industry sector as the single-largest emitting sector, making up over half of remaining emissions in 2050.

TABLE 2: INDUSTRY SECTOR ENERGY DEMAND, EMISSIONS AND RENEWABLE ENERGY SHARE

Sectors	Metric	2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Industry total	Energy (EJ/year)	157	246	190	6.7 Gt/yr reduction (64% of 2017 total)	3.7 Gt/yr reduction (36% of 2017 total)
	CO_2 emissions (Gt/year)[1]	10.4	11.4	3.7		
	Renewable energy share[2] (%)	11%	20%	52%		
Iron and steel	Energy (EJ/year)[3]	32	27	36	2.8 Gt/yr reduction (90% of 2017 total)	0.3 Gt/yr reduction (10% of 2017 total)
	CO_2 emissions (Gt/year)[1]	3.1	2.9	0.3		
	Renewable energy share[2] (%)	4%	12%	55%		
Chemicals and petro-chemicals	Energy (EJ/year)	46.8	79.8	53.4	0.7 Gt/yr reduction (41% of 2017 total)	1.0 Gt/yr reduction (59% of 2017 total)
	CO_2 emissions (Gt/year)[1]	1.7	2.5	1.0		
	Renewable energy share[2] (%)	3%	2%	29%		
Cement and lime	Energy (EJ/year)	15.6	13.3	10.3	1.9 Gt/yr reduction (75% of 2017 total)	0.6 Gt/yr reduction (25% of 2017 total)
	CO_2 emissions (Gt/year)[1]	2.5	2.6	0.6		
	Renewable energy share[2] (%)	6%	20%	56%		
Aluminium	Energy (EJ/year)	4.5	5.8	4.0	0.01 Gt/yr reduction (2% of 2017 total)	0.4 Gt/yr reduction (98% of 2017 total)
	CO_2 emissions (Gt/year)[1]	0.4	0.6	0.4		
	Renewable energy share[2] (%)	16%	38%	60%		

Notes:
1. Emissions include direct energy and process emissions.
2. Including electricity and district heating.
3. Energy demand for iron and steel includes blast furnaces and coke ovens. Demand increases under the Transforming Energy Scenario due to the addition of 500 Mt of steel based on direct reduced iron (DRI). This leads to increased steel production overall as it is now green steel.
Source: IRENA, 2020a; IEA, 2017

Table 2 also shows how the share of renewable energy in total industrial energy use could increase from just 11% in 2017 to 52% in 2050 under the Transforming Energy Scenario – two-and-a-half times larger than in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario renewable energy would contribute around 98 EJ to industry's total demand of 190 EJ for energy and feedstock by 2050. Almost 50% of that would be sourced from renewable electricity, around 35% from biomass as fuel and feedstock, and 8% from solar thermal. Renewable hydrogen, direct geothermal applications and renewable district heat would comprise the remaining 8%.

If emissions are to be driven to zero in these sectors, then a further substantial increase in renewables share will be needed. Determining the more detailed energy and renewable implications of eliminating those remaining emissions will be the subject of further analysis by IRENA in 2021.

The options that could in principle assist in bridging that 11.4 Gt per year gap in 2050 between planned energy scenarios and the zero-emission goal are relatively clear. The most promising options make use of abundant, and increasingly low-cost, renewable resources. This chapter focuses on the small number of options in each sector that currently look consistent with a pathway to zero emissions by around 2060.

2.3 Iron and steel

Key statistics

- The iron and steel sector is a major energy user and a major emitter of CO_2. In 2017, the sector accounted for 32 EJ of total global final energy use, and in 2018 it produced 7-9% of total global CO_2 emissions. In 2018, 1 810 Mt of steel was produced globally with 1.85 tonnes of CO_2 emitted for each tonne of steel produced.
- In 2018, 74% of the energy feedstocks used in global iron and steelmaking processes were coal, coke and other coal products (IEA, 2020). Around 71% of global steel is produced via the blast furnace / basic oxygen furnace (BF-BOF) route, which is highly reliant on metallurgical coal as the chemical reducing agent to make iron. Most of the remaining 29% of steel is produced via the electric arc furnace (EAF) route, mainly using steel scrap with fossil fuel-produced electricity providing the energy input.
- The four largest steel-producing countries in 2019 were China (53% of global production), India (5.9%), Japan (5.3%) and the United States (US) (4.6%) (WSA, 2020a).

Main decarbonisation options

- Depending on the raw material used, two main steel production pathways are in current use. In the first pathway (BF-BOF), a blast furnace is used for iron production, then the basic oxygen furnace is used for steel production. This pathway is mainly used for ore-based steelmaking. The second pathway (DRI-EAF) involves the direct reduction of iron followed by steelmaking in an electric arc furnace; the pathway is suitable for both ore- and scrap-based steelmaking.
- Improving the energy efficiency of processes, further improving material efficiency and applying the principles of a circular steel economy (to ensure that even higher proportions of steel scrap are recycled) can all play useful roles in reducing emissions from iron and steel production. But there is only limited scope for improvements, so these steps will not be enough on their own.
- A structural shift in iron and steelmaking is needed. There are two primary options to achieve this: switching to alternative processes that can utilise renewable energy and clean, preferably green, hydrogen; or utilising clean, preferably renewable, energy and capturing CO_2 emissions from existing processes with CCUS technologies.
- The most promising renewables-based option is to adapt the DRI-EAF route to use renewable hydrogen as the reducing agent and renewables as the energy source. Doing so would produce 80-95% fewer CO_2 emissions than conventional processes.
- An alternative approach is to apply CCUS technologies to either the BF-BOF or DRI-EAF steelmaking processes.
- Smelting reduction (an alternative process that effectively combines blast furnace and DRI techniques) may be an economically more viable route for CCUS usage.
- A range of other emission reduction routes exist, including, for example, the use of biomass, renewable-based hydrogen and waste plastics in blast furnaces to substitute coal and coke; however, they appear unlikely to be able to deliver zero or near-zero emissions.

Key insights

- The DRI-EAF route with green hydrogen has benefited greatly from research and development (R&D) efforts over the past decade. At least six plants are being piloted, mainly in Europe.
- Renewable hydrogen-based DRI can become a viable alternative to traditional blast furnaces at a carbon price of around USD 67 per tonne of CO_2, subject to the availability of low-cost renewable electricity.
- If the BF-BOF route is to continue to be used, then it will need to be combined with cost-effective CCUS technologies. Currently one operational steel plant is using CCUS (not BF-BOF, but a natural gas-based DRI-EAF steel facility equipped with CCUS, located in the United Arab Emirates).
- The priority for governments and industry should be to create, and potentially mandate, early demand for "green" steel despite higher costs early on. Demand will incentivise improvements in process efficiency and costs.
- Increased activity and public and private funding for research, development and demonstration (RD&D) into hydrogen-based DRI and new BF-BOF-based designs with CCUS (including retrofits) is urgently required, with a particular focus on full-scale demonstration plants.
- Coupling iron ore mining and green ironmaking in places with abundant and low-cost renewable resources, such as Australia, while decoupling the ironmaking and steelmaking processes in countries heavily reliant on fossil fuels, such as China, Japan and the Republic of Korea, could create new value and supply chains while also delivering emission reductions. For example, CO_2 emissions from the iron and steel industry could be reduced by nearly a third, to around 0.7 Gt of CO_2 per year, by Australia producing 400 Mt of DRI using green hydrogen.
- China's current dominance in global steelmaking, and the expected increase in production capacity in a limited number of other developing or emerging countries, means that actions taken by those countries will be crucial for reducing global CO_2 emissions in this sector.

Sector emissions and energy use

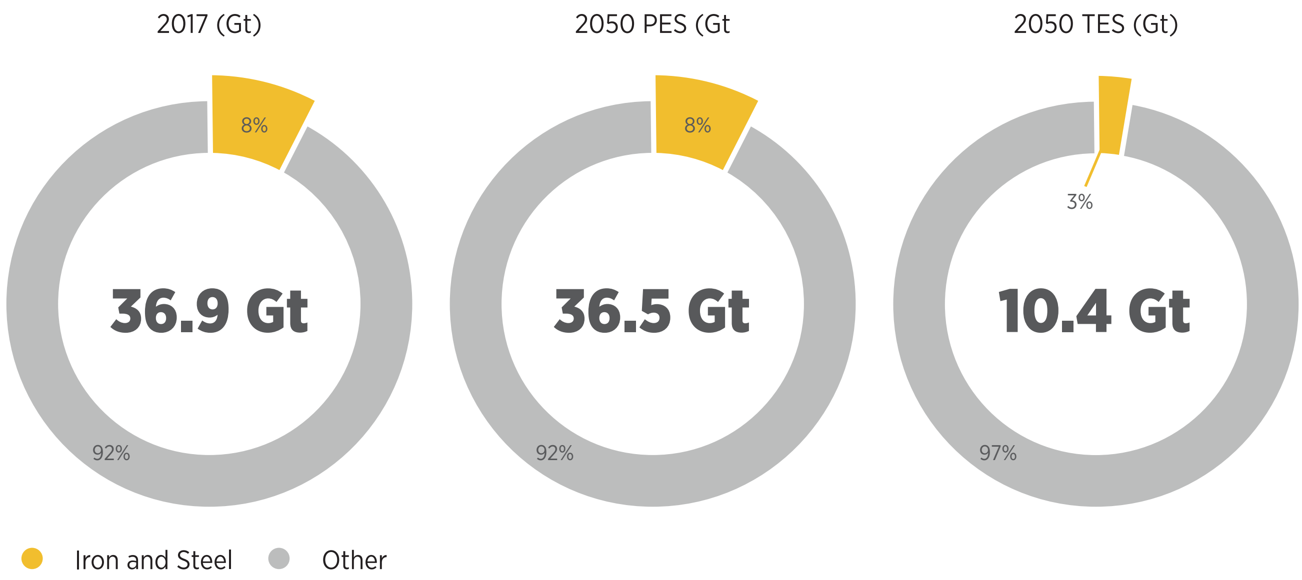
Figure 6 shows how iron and steel's share of total energy and process-related CO_2 emissions will need to change over time. In 2017, iron and steel accounted for 8% of total energy and process-related CO_2 emissions. With current planned policies and programmes, iron and steel's share of emissions can be expected to remain flat by 2050. In the Transforming Energy Scenario, however, the sector's share of emissions would shrink to 3%, leaving 0.3 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 3 shows how the share of renewable energy in total iron and steel energy use could increase nearly 10-fold from just 4% in 2017 to 55% in 2050 under the Transforming Energy Scenario – more than four times larger than in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 20 EJ of iron and steel's total demand of 36 EJ for energy and feedstock by 2050. This would be sourced mainly from renewable electricity and from indirect electrification with green hydrogen and synfuels, with some biomass used as fuel and feedstock as well.

Delivering zero emissions will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 7, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes. Figure 8 shows the estimated range of abatement potential for each measure plotted against estimates of the range of the cost of abatement.

FIGURE 6: Iron and steel share of total energy and process-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)

Iron and steel's share of total energy and process-related CO_2 emissions



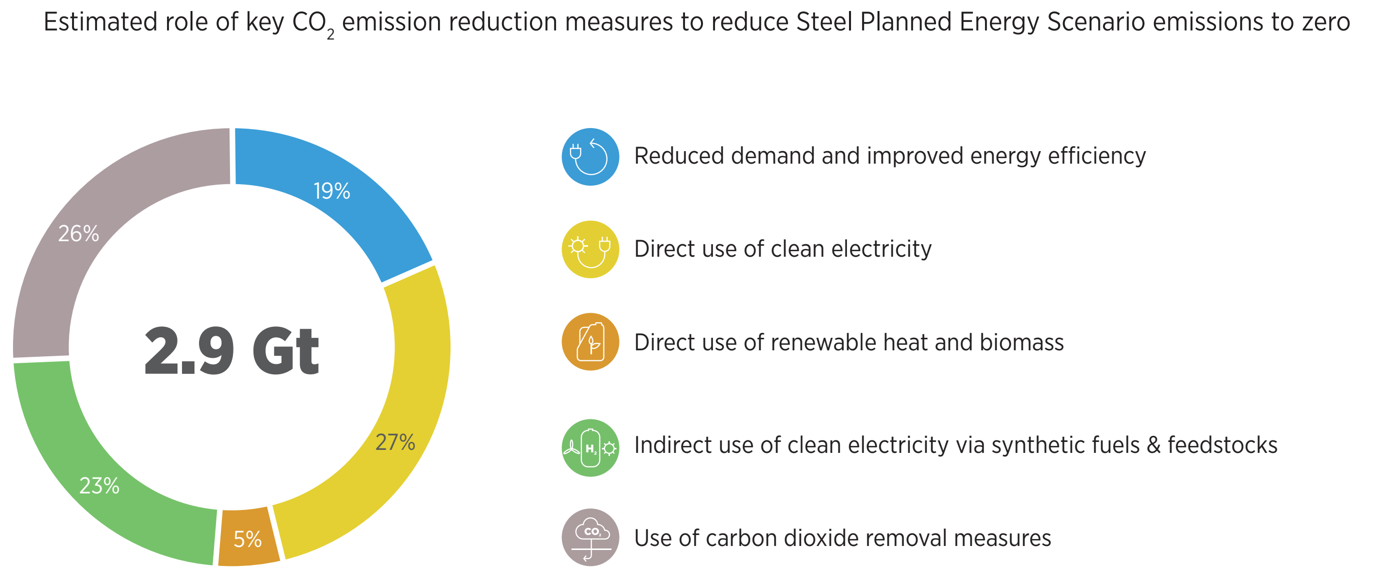
Source: IRENA, 2020a; IEA, 2017

TABLE 3: IRON AND STEEL ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Iron and steel (energy and process)	Energy (EJ/year)[1]	32	27	36***	2.8 Gt/yr reduction (90% of 2017 total)	0.3 Gt/yr reduction (10% of 2017 total)
	CO_2 emissions (Gt/year)[2]	3.1	2.9	0.3		
	Renewable energy share[3] (%)	4%	12%	55%		

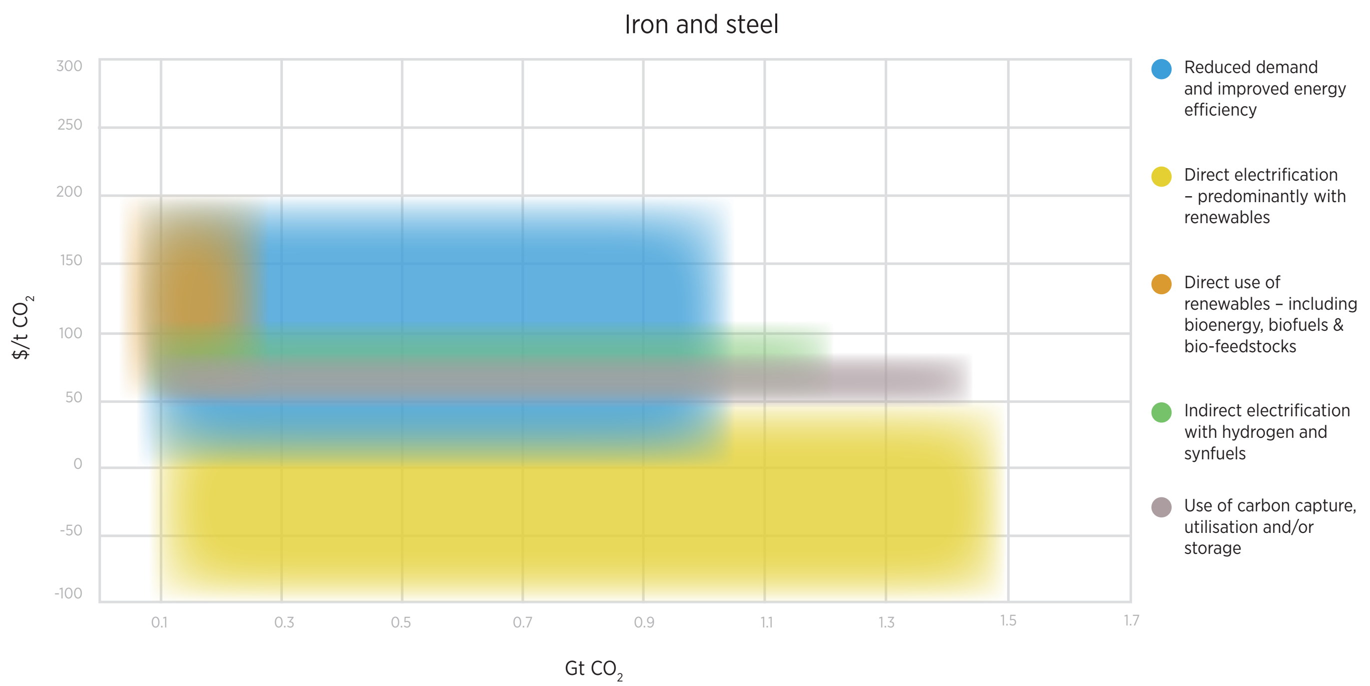
Notes:
1. Energy demand includes: a) electricity and district heat; b) blast furnaces and coke ovens.
2. Emissions include direct energy and process emissions.
3. Renewable energy share includes electricity and district heat.
Source: IRENA, 2020a; IEA, 2017

FIGURE 7: Emission reduction measures to reach zero emissions in the iron and steel sector, from Planned Energy Scenario to zero



Source: IRENA analysis

FIGURE 8: Estimated abatement potential of measures to reach zero energy emissions in the iron and steel sector plotted against estimates of the cost of abatement



Source: IRENA analysis

Sector overview and the emission reduction challenge

Steel is an alloy of iron and carbon that is widely used as an engineering and construction material. Although many combinations are possible, depending on the type of raw material used (*i.e.*, iron ore or scrap), the two main steelmaking processes are: the blast furnace / basic oxygen furnace (BF-BOF) route and the direct reduced iron / electric arc furnace (DRI-EAF) route, discussed in Table 4.

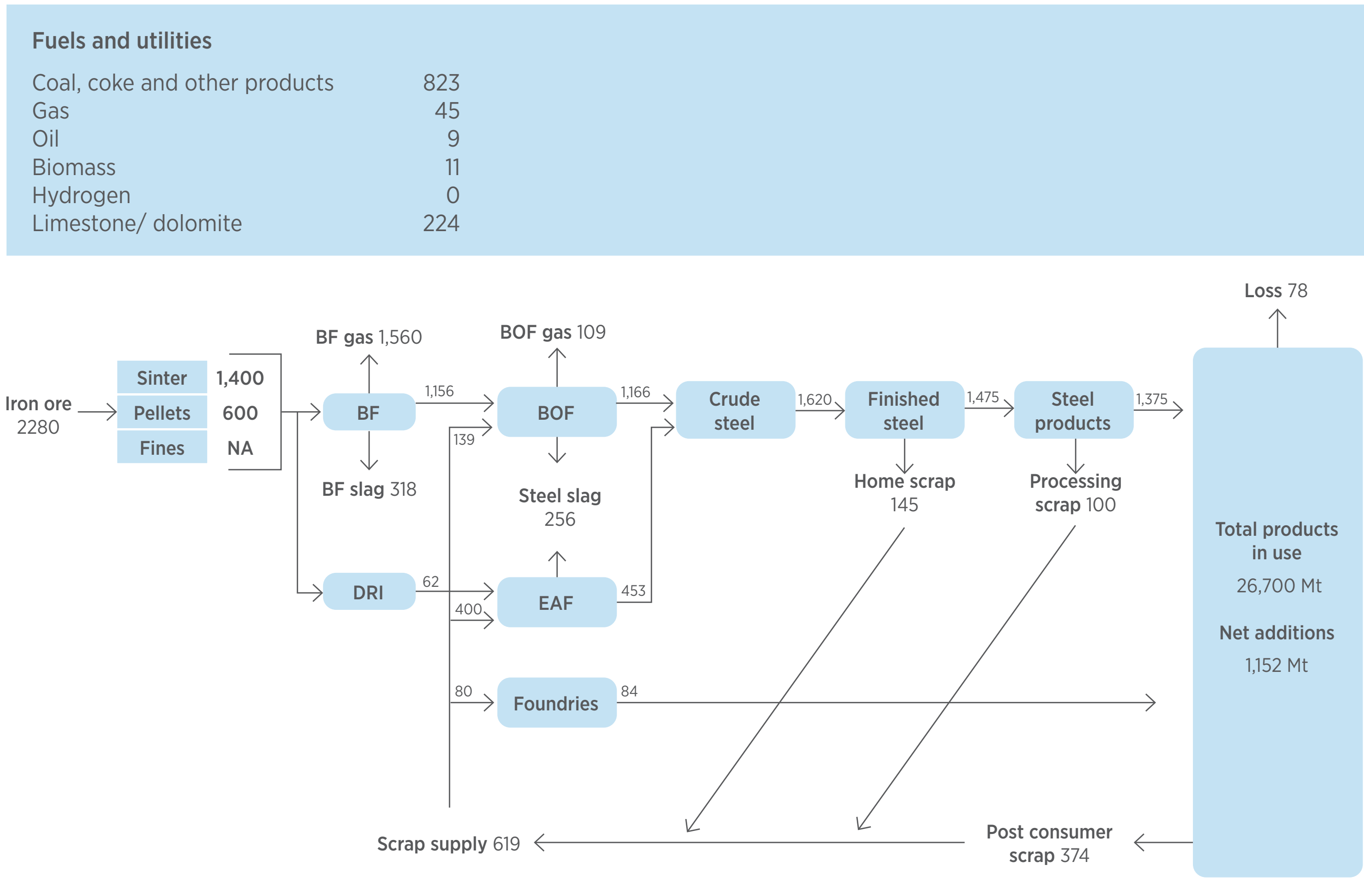
TABLE 4: COMPARISON OF THE TWO STEELMAKING TECHNOLOGY PATHWAYS

Steelmaking process	Blast furnace / basic oxygen furnace (BF-BOF) route	Direct reduced iron / electric arc furnace (DRI-EAF) route
Ironmaking process	Before it is converted into steel, iron ore is reduced to iron (also called hot metal or pig iron) in the blast furnace or via smelting reduction: **Hot metal / pig iron from blast furnace (BF):** To reduce iron ore to iron (or to smelt iron from iron ore), metallurgical coal is turned into coke, an almost pure form of carbon, and used as the main fuel and as chemical reducing agents in blast furnaces. **Molten pig iron from smelting reduction (SR):** This process is a combination of the direct reduction and smelting processes. For this, the iron ore is reduced to sponge iron, then melted with coal and oxygen. Instead of coked coal, the reducing agents are provided by natural gas (or gasified coal).	If steel scrap is available, it can be used as a source of iron in the steelmaking process. Overall, depending on plant design and availability of resources, a variety of iron sources can be used in the EAF route, such as: ➔ **Pig iron from blast furnaces** ➔ **Steel scrap to be recycled** ➔ **Sponge iron or direct reduced iron (DRI):** Direct reduction is defined as the group of processes for making iron from iron ore in solid state without exceeding the melting temperature of iron using carbon monoxide and hydrogen derived from natural gas or coal, so no blast furnace is needed. ➔ **Direct electrolytic iron ore reduction** ("electrowinning"): This is an immature technology being researched; the concept is that iron is reduced from iron ore through direct electrolysis in an electrolytic bath similar to primary aluminium smelting.
Steelmaking process	Hot metal is further refined in a basic oxygen furnace. The BOF process always uses up to 15-20% additional cold iron units, usually scrap, but DRI and pig iron can also be used. Alloys and fluxes are added to purify the steel and to adjust its final composition.	Steel is produced by melting steel scrap, or potentially iron produced by one of the above routes, with the heat generated by an electric arc, with additives used to adjust the chemical composition of the steel. Alloys and fluxes are added to purify the steel and to adjust its final composition.
Global share	71% of steel is produced using this route. Of this, the blast furnace is by far the predominant route, with smelt reduction playing a very minor role.	29% of steel is produced using this route.

Source: IRENA, based on WSA, 2020b

Globally, more than two-thirds (71%) of steel is produced through the BF-BOF route. Figure 9 shows the material flows in the global iron and steel industry in 2015, indicating the various fuels used in the iron and steelmaking process. That year, 74% of the feedstock was coal, coke and other coal products (823 Mt/year).

FIGURE 9: Material flows in the global iron and steel sector in 2015 (Mt/year)



Source: Gielen et al., 2020

In addition to the large amount of fossil fuels needed as raw material, iron and steel production is energy intensive. As Table 5 shows, in 2015 the iron and steel sector consumed 34 EJ of the total global final energy use of around 274 EJ per year. This process relies heavily on the use of coal and coke.

The heavy use of fossil fuels results in high CO_2 emissions. In 2018, the steel industry accounted for 7-9% of total global direct CO_2 emissions, making it one of the largest sources of industrial emissions worldwide. Energy use and processes in this sector produced 3.63 Gt of direct and indirect CO_2 emissions. In 2019, 1 869 Mt of steel was produced globally, with the production of 1 tonne of steel emitting 1.85 tonnes of CO_2 on average, the majority of which is released during the chemical reduction of iron ore to metallic iron during the ironmaking process (WSA, 2020a; WSA, 2019a).

TABLE 5: GLOBAL ENERGY USE FOR IRON AND STEELMAKING, 2017

	Energy use (EJ/year)	Share (%)
Coking coal and coke	24.0	69.9
Other coal	5.6	16.2
Blast furnace gas and coke oven gas	-2.8	-8.3
Natural gas	2.3	6.8
Oil	0.4	1.1
Biomass	0.2	0.5
Electricity	4.1	12.0
Heat	0.6	1.7
Total	**34.3**	**100**

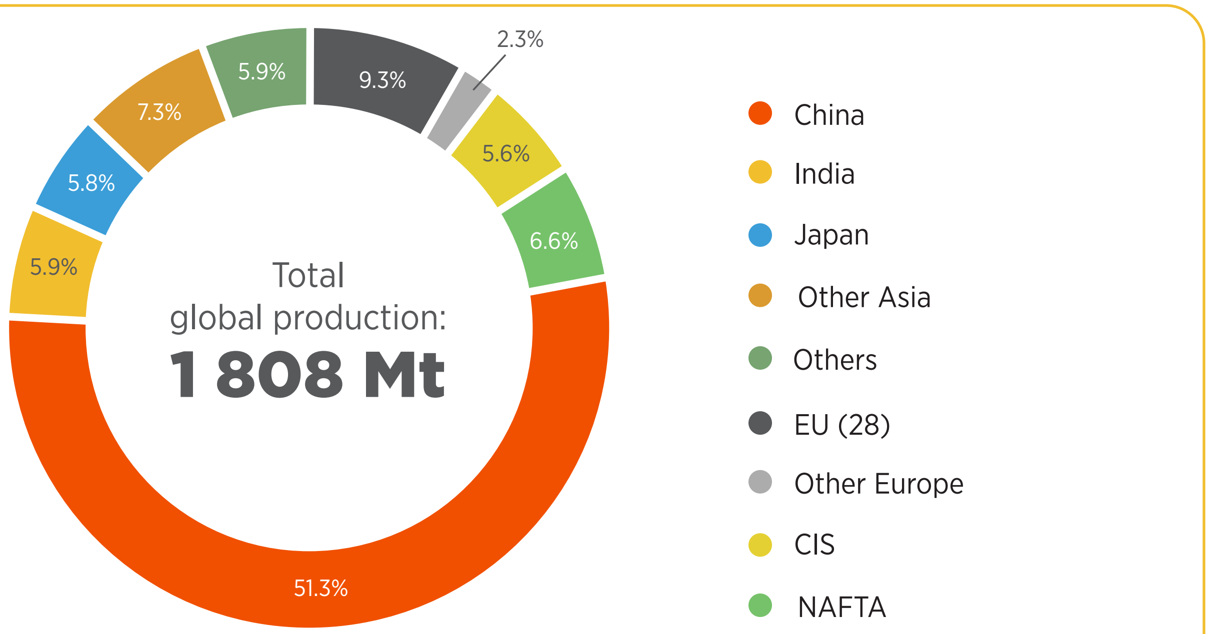
Note: Includes the energy content of blast furnace and coke oven gases as by-products.
Source: IRENA calculations based on IEA, 2017

Electric arc furnaces can be used to recycle steel, but steel scrap availability is typically limited by the long life span of steel products, such as steel used in the automotive and construction industries. In 2017, an estimated 750 Mt of steel scrap was available globally, out of which 630 Mt (84%) was recycled by the steel and foundry casting industry (WSA, 2019a). By 2050, global steel scrap is expected to reach 1.3 billion tonnes, much of that from developing and emerging economies, such as China (around 400 Mt). Over the next 15 years, India and the Association of Southeast Asian Nations (ASEAN) region are expected to double their availability of steel scrap (WSA, 2018), opening up the possibility for greater use of the EAF route.

The DRI-EAF route is less energy intensive than the BF-BOF process and has the advantage that it can be powered by renewable electricity. The amount of DRI produced in 2018 increased to around 100 Mt from 77 Mt in 2011, but remains small compared to the 1 247 Mt of pig iron produced in 2018 (WSA, 2019b).

China's steel production accounts for 51.3% of total global production (Figure 10). China's production has been expanding for three decades now, from 32 Mt in the 1980s to 928 Mt in 2018, mostly using the BF-BOF route (WSA, 2019b). As China's economy diversifies, its role in steel production is anticipated to decrease while production in other emerging economies is expected to increase. This highlights the co-dependency of policy actions in this sector. Actions taken in China to shift the low-emission production processes will be crucial for reducing global CO_2 emissions in this sector, but they will need to be complemented by actions across many other countries as new production capacity is installed.

FIGURE 10: Share of global steel production, 2018



Note: CIS = Commonwealth of Independent States. NAFTA = North American Free Trade Agreement.

The iron and steel sector is a highly competitive global sector. Energy costs are a large part of the total cost of the iron and steelmaking processes, so emission reduction measures that impact energy costs or add other complexities can have far-reaching impacts on the total costs and on competitiveness. The steel industry is characterised by complex value chains, high capital investment costs (CAPEX), mature technology and low margins, leading to relatively low investments in RD&D. A more systematic policy approach, complemented by clear market incentives, would support the industry in its drive to decarbonise.

Options for reaching zero

Improving the energy efficiency of processes, further improving material efficiency, and applying the principles of a circular steel economy to ensure that a high proportion of steel scrap is recycled can all play a role in reducing emissions from iron and steel production. However, these measures alone will be insufficient to bring CO_2 emissions down to zero in an industry that is heavily reliant on fossil fuels both as fuel and feedstock. A structural shift in iron and steelmaking is needed. There are two primary options to achieve this: by switching to alternative and more innovative processes that can utilise renewable energy; and, in circumstances where that option is not viable, by capturing CO_2 emissions from existing processes with CCUS technologies.

The principal renewables-based decarbonisation option is to shift most steelmaking to the DRI-EAF route. Currently DRI production uses carbon monoxide and "grey" hydrogen sourced from either natural gas or coal. Using "green" hydrogen, produced from renewable power, to provide both the high-temperature heat and the reducing agents needed for DRI-EAF steel production, alongside the use of renewable electricity, could make this process a close-to-zero emissions option, with an 80-95% reduction in CO_2 emissions compared to the BF-BOF route.

In the BF-BOF route, decarbonisation strategies could initially expand the use of natural gas, biomass, waste plastics, hydrogen or electricity as a partial substitute for coal and coke in the blast furnace. These options alone will not deliver sufficiently deep decarbonisation. Reducing the BF-BOF emissions to low levels will require the deployment of CCUS technologies. CCUS applied to iron and steelmaking is still in its early stages of development, with significant uncertainties in its costs and widespread applicability.

In the longer term, an alternative to conventional iron and steel making technologies is the electrolysis of iron ore in a molten oxide electrolyte. In theory, iron can be reduced from iron ore through direct electrolysis, therefore making use of renewable power without the need to produce renewable-based hydrogen in the ironmaking process. This technology has not yet been demonstrated at scale but is being investigated by researchers and may be developed further.

The technology shift required to decarbonise the iron and steel industry could have geopolitical and global economic implications. The shift from BF-BOF to the green hydrogen DRI-EAF route could enable a wider relocation of the iron and steel sector to places where relatively low-cost and abundant renewable electricity sources are available (Gielen *et al*., 2020).

A wider application of either of these emission reduction options will require large-scale infrastructure changes and investments. The widespread adoption of CCUS technologies will depend on the wide availability of CO_2 capture facilities, transport pipelines and storage options, whereas hydrogen-based DRI will depend on the deployment of new infrastructure for hydrogen production and distribution. The prospect of wider relocation, as mentioned above, could help crowd-in these investments and trigger the creation of markets for greener steel, if supported through wider, systemic policy at the global level aimed to incentivise shifts in the sector towards a circular steel economy. Such new infrastructure will need to be deployed rapidly over the next 10-15 years to allow for a pathway to zero emissions by 2060.

REACHING ZERO – OPTION 1: Renewable-based hydrogen DRI-EAF route

Fossil fuel-based DRI production uses a syngas of carbon monoxide and hydrogen as the reduction agent, with the syngas produced from either natural gas or coal. The fossil fuel-based DRI process is in commercial use and accounted for 6% of total global iron production in 2019. The choice of the fuel for the DRI process is typically driven by local cost and supply considerations. India, for example, which was the world's largest producer in 2019 with 34% of total DRI production worldwide, is mainly using coal-based DRI (WSA, 2020a). The US, where natural gas prices dropped thanks to the boom in shale gas production, recently saw an increase in gas-based DRI capacity.

Fossil fuel-based DRI production is today dominated by two technologies: the low-pressure MIDREX process and the high-pressure HYL/Energiron process. Whereas MIDREX uses around 55% hydrogen in its gas mix, HYL/Energiron uses 70% and has been shown to operate effectively at over 90% hydrogen.

Fully hydrogen-based DRI production has received growing attention as an enabler both for renewable energy use and for CO_2 emission reductions. In this process, the DRI-EAF route using hydrogen generated from renewable power could achieve a reduction in CO_2 emissions of 80-95% compared to the BF-BOF route (Otto *et al*., 2017; Prammer, 2018).

Renewable hydrogen-based DRI could become a viable alternative to traditional blast furnaces at a CO_2 price of around USD 67 per tonne, subject to the availability of low-cost renewable electricity (Gielen *et al.*, 2020). In this context, countries with the potential to generate very-low-cost renewable power (Box 4) could have a competitive advantage in the production of renewable hydrogen-based iron. The steel industry has already begun to see the location of electric arc furnaces in areas with abundant and relatively low-cost renewable power.

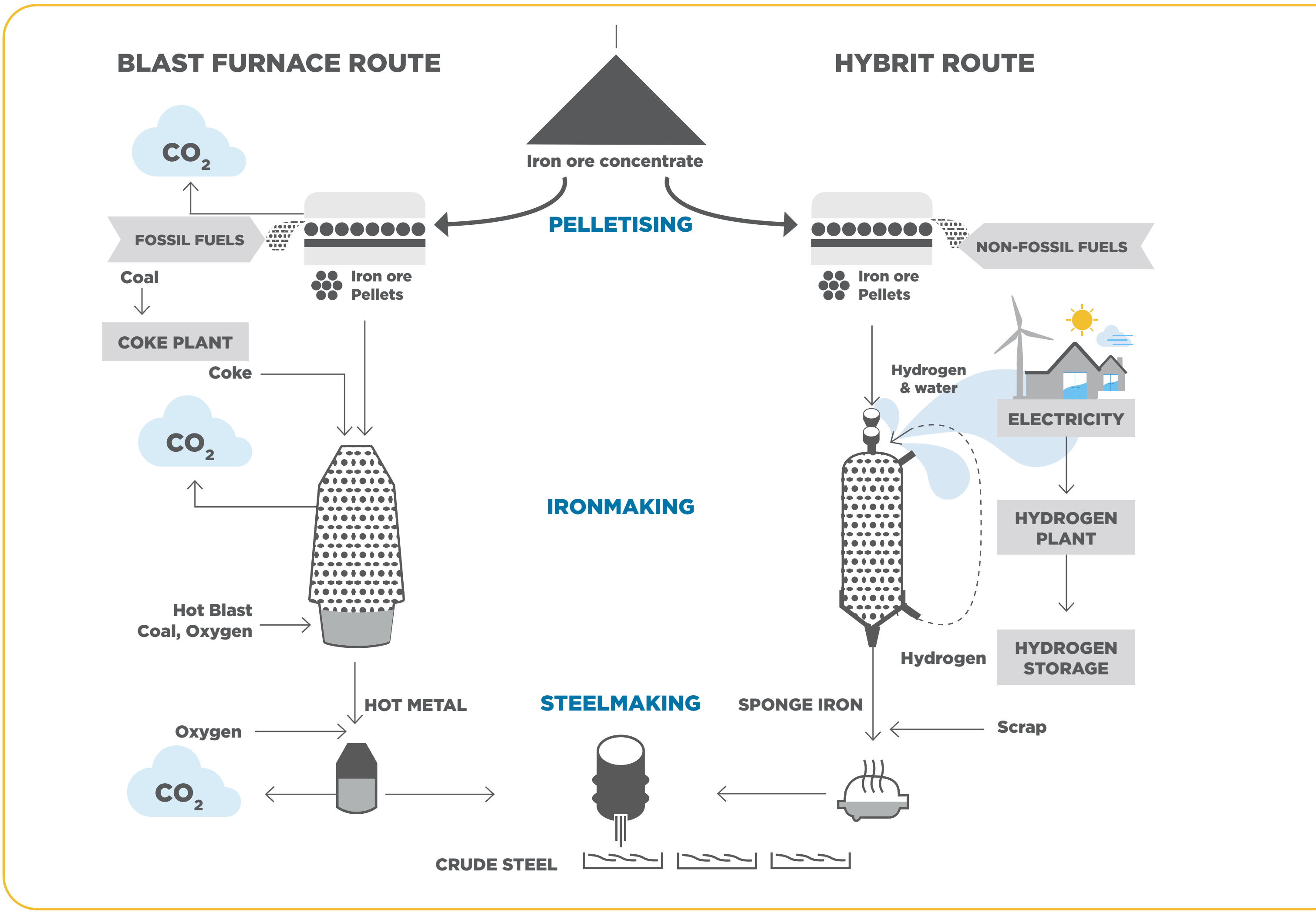
As shown in Table 6, renewable hydrogen-based DRI pilot projects are also being conducted in Austria (Zauner, 2018; Prammer, 2018) and in Sweden (HYBRIT, 2019). To illustrate the differences, Figure 11 compares the conventional BF-BOF route with this novel route tested in Sweden, illustrating where coal is substituted with renewable hydrogen and highlighting that CO_2 emissions can be avoided throughout the entire process.

TABLE 6: EXAMPLES OF SMALL- AND LARGE-SCALE RESEARCH AND PILOT PROJECTS EXPLORING RENEWABLE HYDROGEN-BASED DIRECT REDUCED IRON

Country	Project name	Key stakeholders	Project status
Austria	Sustainable Steelmaking (SuSteel), part of H2Future project	Voestalpine, Montanuniversität, K1-MET	Ongoing
Germany	H_2 Hamburg	ArcelorMittal, Midrex	Ongoing
Germany	Salzgitter Low CO_2 Steelmaking (SALCOS)	Salzgitter, Fraunhofer Institute, Avacon, Linde, Tenova	Ongoing
Sweden	Hydrogen Breakthrough Ironmaking Technology (HYBRIT)	SSAB, LKAB, Vattenfall	Ongoing (began test operations in September 2020)
US	Novel Flash Ironmaking	American Iron and Steel Institute, University of Utah, Berry Metal Company, ArcelorMittal, the Timken Company, United States Steel Corporation	Research completed
15 European countries	European Union (EU)-funded ULCOS (Ultra-Low Carbon dioxide Steelmaking) programme	47 partners including all major stakeholders from the steel industry, research institutes and universities, European Commission, led by ArcelorMittal	Research completed (phase 1)

Source: Voestalpine, 2018; ArcelorMittal, 2020; Salcos, 2019; HYBRIT, n.d.; US DOE, 2019; EC, 2010

FIGURE 11: Renewable hydrogen-based DRI-EAF route piloted in Sweden compared to the conventional BF-BOF route



Source: HYBRIT, n.d.

Another planned pilot project is a facility in Hamburg, Germany which aims to produce 100 000 tonnes of steel per year using green hydrogen. The project, which is being developed by Midrex, a DRI technology provider, and ArcelorMittal, the world's largest steelmaker, aims to use 100% hydrogen as a reductant in this process. Initially, the hydrogen will be "grey", but the project promoters aim to switch to "green" hydrogen as low-cost renewable power becomes available.

These pilot projects are important demonstrations of what can be achieved, but the scale is currently very small, and far larger changes are needed. Based on forecasts for steel production and considering a concomitant increase of 15-29% in the DRI route, while production from BF is halved for primary iron production, Gielen *et al*. (2020) estimate that 350 Mt of new DRI capacity is needed until 2050 – a six-fold increase from current capacities.

The scale of hydrogen production needed is very large and would have very significant implications for infrastructure, trade and the scale of national power systems, which will require careful consideration.

BOX 4: NEW GLOBAL TRADE OPPORTUNITIES FOR AUSTRALIA, A COUNTRY WITH RICH IRON ORE AND RENEWABLE RESOURCES

Australia is the world's largest exporter of iron ore, accounting for USD 49.3 billion of exports in 2017, or 51.9% of the global total. The country produced around 883 Mt of iron ore that year, of which 99% was exported. By comparison, its production of iron and steel is negligible. With the average export value less than USD 50 per tonne of iron ore, there is a significant opportunity to develop a production chain that includes the final steel product, thereby increasing the value-added in Australia.

At the same time, China, the largest iron ore importer with 68% of global imports, has significant air pollution problems, caused in large part by the iron and steel sector, the largest coal-consuming industry (Yang *et al*., 2018). Moving the most-polluting ironmaking process away from urban areas, where clean processes based on renewables are available, could help reduce local air pollution in China. Australia has a unique low-cost renewable electricity generation potential based on abundant solar and wind resources. If these renewable energy resources can be leveraged to produce iron with green hydrogen via the DRI route, it provides an opportunity for Australia to export higher-value-added "green" iron that was produced with very low CO_2 emissions.

CO_2 emissions from the iron and steel industry can be reduced by nearly a third, to around 0.7 Gt of CO_2 per year, by producing 400 Mt of DRI using green hydrogen in Australia. To achieve this, the renewable power generation capacity needed in Australia would need to increase 10-fold compared to the total current installed renewable capacity. At the same time, USD 0.9 trillion, or 0.7% of the total energy sector investment needs, would be required. Further, global DRI production would have to increase seven-fold from today's level, while the hydrogen energy used would equal 1% of the global primary energy supply.

By coupling the iron ore mining and ironmaking processes (*e.g*., in Australia), but decoupling ironmaking from the steelmaking process (*e.g*., in China, Japan and the Republic of Korea), countries that have integrated industries today could maintain their steelmaking industries intact while reducing CO_2 emissions. With supportive enabling policy frameworks in place, such a shift could develop from 2025 onwards at scale. Because this approach is replicable, it could be expanded to other parts of the world and to other energy-intensive industry sectors (Gielen *et al*., 2020).

REACHING ZERO – OPTION 2: Iron and steelmaking with CCUS

Where decarbonisation via the DRI-EAF route is not a viable option, the use of CCUS must play a role in emission reduction for the iron and steelmaking sector. In principle, CCUS can be used with either the BF-BOF process or the DRI-EAF route, as well as with the smelting reduction route, as explained below:

- BF-BOF route with CCUS: Much of the focus to date has been on how to retrofit CCUS onto existing blast furnace designs. For example, a pilot (called the DMXTM Demonstration in Dunkirk), designed by French provider Axens, is expected to be installed at the ArcelorMittal steelworks site in Dunkirk, France to capture 0.5 tonnes of CO_2 an hour (0.004 Mt of CO_2 per year), starting in 2020. After the first phase, further CCUS units are planned in Dunkirk and in other locations on the North Sea. The quantities of CO_2 capture envisaged by this pilot are currently very small.

- DRI-EAF route with CCUS: The world's first DRI plant with CCUS started operation in Abu Dhabi (United Arab Emirates) in 2016, operated by Emirates Steel Industries. The Al Reyadah project, a gas-based DRI plant, is supported by the Abu Dhabi Government, Abu Dhabi National Oil Company and Masdar. It has a capacity to capture 0.8 Mt of CO_2 per year, which is transported via a 43-kilometre pipeline to the nearby oilfields to be used for enhanced oil recovery (EOR) (McAuley, 2016; Element Energy, 2018).

- Smelting reduction with CCUS: This process is a combination of the direct reduction and smelting processes where the iron ore is reduced to sponge iron, then melted with coal and oxygen. Several configurations and technologies are available for the smelting reduction process, such as the HIsarna process, developed through the partly EU-funded ULCOS project, currently being tested by Tata Steel in the Netherlands (Junjie, 2018). Smelting reduction has the twin advantage that it eliminates the need for coke ovens and reduces the need for iron ore preparation. Instead, coal is gasified and used to reduce iron ore. Moreover, CO_2 emissions from smelting reduction processes can be captured more easily as the CO_2 concentration in the flue gas is higher (Kuramochi et al., 2012).

Other emission reduction routes

Although their potential and practicality are currently unproven, a range of other emission reduction routes are being explored in the iron and steel sector which might play a role in the future. These options are not fully consistent with the goal of reaching zero emissions, but they may assist in the transition. Some examples include:

- Biomass can be used as a substitute for coal and coke in the BF-BOF route. Countries with large biomass availability, such as Brazil, are already using charcoal in small-scale blast furnaces, although elsewhere it is much costlier than coke and cost reductions would be necessary. Using biomass instead of coal and coke more widely could cut emissions by an estimated nearly 50%, but this remains a costly option and its use on a larger scale is only in the research stage. Two noteworthy initiatives are ongoing: a consortium in Australia is exploring the use of sustainable forms of charcoal, while a consortium in Germany is exploring hydrothermal carbonisation to cook biomass into a bio-coal slurry (CSIRO, 2018).

- Hydrogen is being explored in Germany as an alternative to coke in a project led by ThyssenKrupp and Air Liquide (ThyssenKrupp Steel, 2019). The project was announced at the end of 2019 as a first-of-its kind pilot that aims to inject hydrogen in the conventional BF-BOF steelmaking route. The initial phase of the project aims to test the technology on one blast furnace, after which it is expected to be extended to three others in 2022. If the hydrogen will be produced via electrolysis from renewable power, ThyssenKrupp estimates that it could reduce CO_2 emissions by up to 20%.

- Plastics that are not suitable for recycling could theoretically be used in blast furnaces with a reduction of around 30% of the CO_2 emissions in the iron and steel industry, according to a study published in 2019. Waste plastics could provide an alternative to coal, while also helping to reduce the temperature needed via the BF-BOF route, which could enhance the energy efficiency of this process (Devasahayam et al., 2019). Plastic waste separation will, however, be critical to avoid chemicals such as chlorine from polyvinyl chloride (PVC) affecting the steel quality.
- Hydrogen plasma smelting reduction (HPSR) is a process in which hydrogen plasma is used to reduce fine iron ore powders. Hydrogen is used as the reduction agent for the iron ore, while its plasma state offers the thermal energy for melting the metallurgical iron. By using hydrogen as a reduction agent, the only by-product is water, and therefore the CO_2 emissions are avoided. The SuSteel project, piloting this technology, is led by Austrian companies K1-MET and Voestalpine. The first lab-scale process with a capability of 100 grams of melt was successfully operated and is now being scaled into a 90-kilogram reactor (K1-MET, 2020).

More information on this topic can be found in the following publications and platforms:

Renewables-based decarbonisation and relocation of iron and steel making: A case study **(https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12997)**

Steel, hydrogen and renewables: Strange bedfellows? Maybe not… **(www.forbes.com/sites/thebakersinstitute/2020/05/15/steel-hydrogen-and-renewables-strange-bedfellows-maybe-not)**

Global industrial carbon dioxide emissions mitigation: Investigation of the role of renewable energy and other technologies until 2060 **(https://payneinstitute.mines.edu/global-industrial-carbon-dioxide-emissions-mitigation-investigation-of-the-role-of-renewable-energy-and-other-technologies-until-2060)**

World Steel Association reports **(www.worldsteel.org/publications)**

LeadIT Leadership Group for Industry Transition **(www.industrytransition.org)**

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, with an appendix on steel **(www.energy-transitions.org/mission-possible)**

Net Zero Steel Initiative **(www.energy-transitions.org/sites/default/files/ETC sectoral focus – Steel_final.pdf)**

2.4 Chemicals and petrochemicals

Key statistics

- Globally around 644 Mt of petrochemicals was produced in 2018, and the sector continues to grow rapidly.

- A few chemicals dominate production, particularly steam cracking products (ethylene, propylene, butadiene, aromatics), ammonia and methanol.

- A limited number of commodities – ethylene, propylene, butadiene, aromatics (benzene, toluene, xylenes), ammonia, methanol, carbon black, and chlorine and sodium hydroxide) – accounts for 75% of the sector's energy and non-energy use.

- Plastics account for the majority of product in volume terms. Plastics production grew 20-fold in the past five decades to reach 360 Mt by end of 2018 and could grow 3-fold globally by 2050 in a scenario of unrestricted use.

- The CO_2 emissions of petrochemical products come from different sources, including: direct energy and process emissions from production processes (around 1.7 Gt/yr); product use phase emissions (0.2 Gt/yr); and emissions from decomposition/incineration processes (around 0.24 Gt/yr). Additionally another 1 Gt per year is stored in hydrocarbon products which could be released if these are eventually consumed. IRENA's Planned Energy Scenario estimates that emissions, unchecked, would grow to 2.5 Gt per year by 2050.

- The bulk of the feedstocks in the sector are derived from oil and natural gas, and the sector consumes 10-15% of global production of these fuels. A significant amount of coal is also used as feedstock, particularly in China. China accounts for 54% of global methanol production and for around 45% of ammonia production.

- The share of renewable energy in the chemical and petrochemical industry's total energy use could increase nearly 10-fold from just 3% in 2017 to 29% in 2050 under the Transforming Energy Scenario – more than 14 times larger in 2050 than in the Planned Energy Scenario – contributing around 15 EJ of the chemical industry's total demand of 53 EJ for energy and feedstock by 2050. Achieving zero emissions would require far higher renewable shares, approaching 100%.

Main decarbonisation options

- Emission reductions can be achieved by: reducing demand for petrochemicals, reducing emissions from the energy used in the production processes, adopting alternatives to fossil fuel feedstocks and permanently storing the carbon embedded in the products at the end of their life.

- Adopting the principles of the circular economy is an essential starting point that will assist the implementation of other approaches by reducing the scale of the challenge; it is also critical to managing other environmental concerns such as the impact of plastic waste on local ecologies.

- One renewables-based option is the use of biomass feedstocks, with the process energy sourced from renewables. This involves either replacing primary petrochemicals with bio-based chemicals (which can then be used to produce products that are chemically identical to petrochemical-derived products) or replacing fossil fuel-derived polymers (particularly plastics) with alternatives produced from biomass (these may have different chemical compositions and different properties than fossil fuel-based alternatives).

- A potential alternative option is the use of synthetic hydrocarbon feedstocks, with the process energy sourced from renewables. The key challenge here is the cost of sourcing clean CO_2 (i.e., not captured from fossil fuels). Currently, sourcing clean CO_2 from biomass or from direct air capture (DAC) is very expensive and substantially increases the overall production costs.

- The combination of CCUS for process emission and renewables for energy could greatly reduce emissions while allowing the continued use of fossil fuels for feedstocks. However, the carbon stored in chemicals or products could be emitted at the end of those products' life cycles and so requires the permanent storage of the carbon in those products through either a highly efficient circular economy, the long-term storage of waste products or CCUS applied to end-of-life combustion.

Key insights

- In the petrochemical sector fossil fuel feedstocks are used to produce a range of "primary petrochemicals" which are the "building blocks" for a wide range of materials – for example plastics, synthetic organic fibres such as nylon, and other polymers, which have many uses.

- There are several reasons why the sector has made limited progress in reducing CO_2 emissions. These include: that much of the energy efficiency potential has been already realised; multiple conversion processes are integrated in large ageing industrial complexes, which limits the remaining energy efficiency potential; petrochemical production is increasingly integrated with refinery operations; and the high cost of low-carbon alternatives, such as bioplastics, acts as a major barrier to their uptake.

- Reducing greenhouse gas emissions from the chemical industry will require electrification of many processes. As a result, the (already significant) energy demand of the chemical industry will likely increase.

- Stronger collaboration between the chemical industry and the energy sector is needed to ensure complementary strategies for managing high shares of variable renewable energy in power systems. Access to renewable energy will influence decisions on the future locations of chemical production.

- Bioplastics currently constitute less than 1% of total plastics production.

- The circular economy is not well developed in this sector and its products. The majority of post-consumer plastic and textiles is incinerated or landfilled. Low recycling rates and low energy recovery rates add to energy use and CO_2 emissions.

- Persistent issues remain in the way carbon emissions are controlled for. A key problem is that feedstock carbon and the "storage" of carbon in materials or products is not being counted in the sector's carbon footprint. Emissions resulting from waste incineration of these products are also not specifically allocated. These gaps in measuring and accountability reduce the incentives for action in these areas.

- A zero-carbon chemical and petrochemical industry is feasible by the mid-21st century. But this will incur additional cost and therefore will not happen by itself. Governments must create the enabling framework for such a transition.

- This is a complex transition that could follow several different pathways. A life-cycle approach is needed to capture the full greenhouse gas emission impact and all mitigation opportunities.

- The implication for the global energy system can be significant, as well as the effects on material flow and location choice. Significant uncertainty remains regarding the speed of this transition and the direction it will take.

- Front runners – consumers, governments, and chemical and petrochemical clusters and companies – will need to force this change. This will require attention to competitiveness issues and carbon leakage. For example, certification of green supply chains may be required, and market niches must be created, for example a mandatory share of green product supply.

- Governments must create the right enabling environment to allow transition experiments and to create the necessary growth to achieve economies of scale and technology learning.

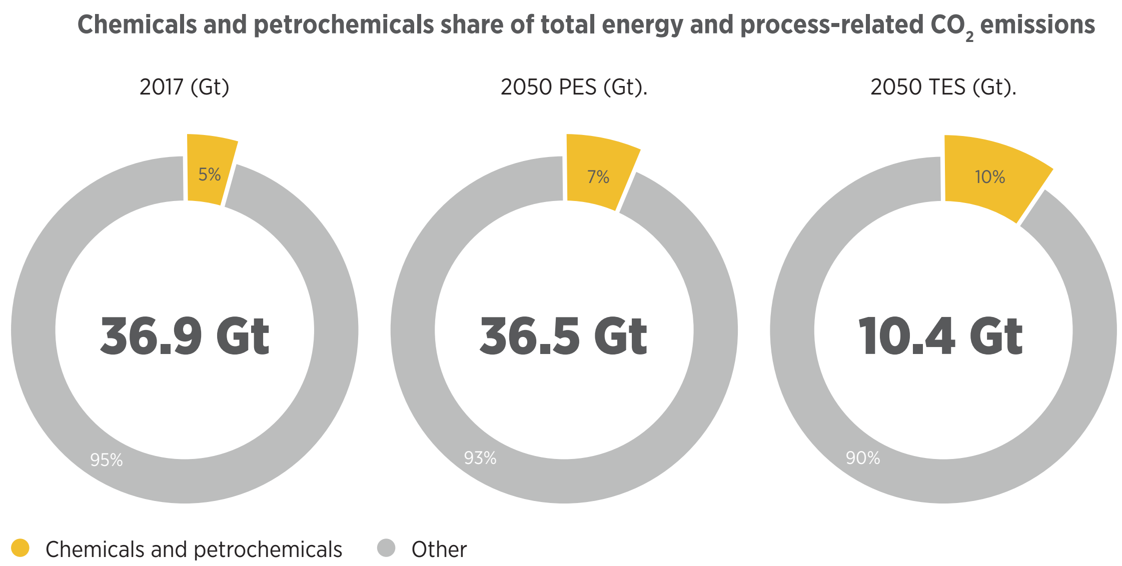
Sector emissions and energy use

Figure 12 shows how the chemical and petrochemical industry's share of total energy and process-related CO_2 emissions will need to change over time. In 2017, the chemical and petrochemical industry accounted for nearly 5% of total energy and process-related CO_2 emissions. With current planned policies and programmes, the share of emissions from the chemical and petrochemical industry can be expected to increase to 7% of total energy and process CO_2 emissions by 2050. In the Transforming Energy Scenario, the sector's share of emissions would grow further to 10% (as other sectors decarbonise more quickly), leaving 1.4 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 7 shows how the share of renewable energy in the chemical and petrochemical industry's total energy use could increase nearly 10-fold from just 3% in 2017 to 29% in 2050 under the Transforming Energy Scenario – more than 14 times larger in 2050 than in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 15 EJ of the chemical industry's total demand of 53 EJ for energy and feedstock by 2050. This would be sourced mainly from the use of biofuels, green hydrogen and synfuels as both fuel and feedstock.

Delivering zero emissions will require 100% of the energy and non-energy demand to be met by clean, predominantly renewable, sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 13 summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes. Figure 14 shows the estimated range of abatement potential for each measure plotted against estimates of the range of the cost of abatement.

FIGURE 12: Chemical and petrochemicals' share of total energy and process-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



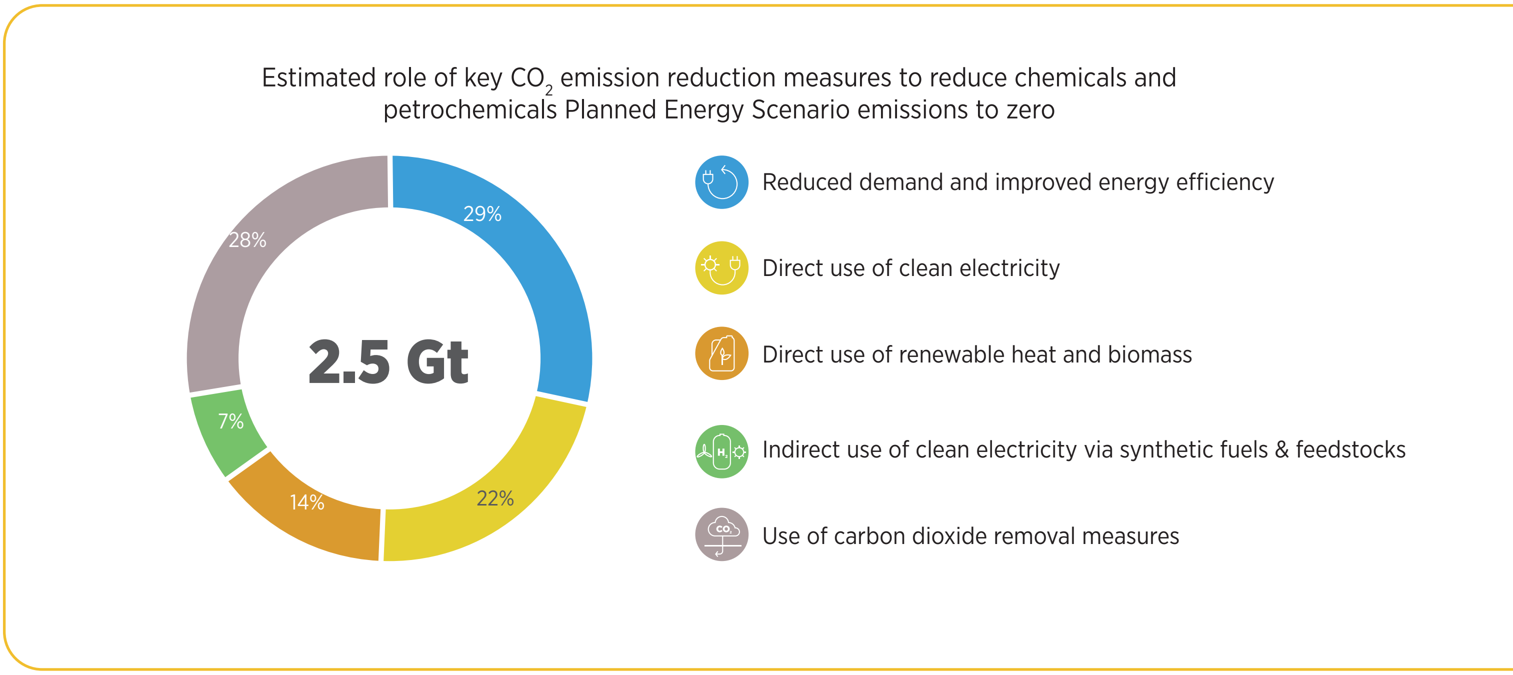
Source: IRENA, 2020a; IEA, 2017

TABLE 7: CHEMICALS AND PETROCHEMICALS ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Chemicals and petro-chemicals (energy, process, non-energy use)	Energy (EJ/year)	46.8	79.8	53.4	0.7 Gt/yr reduction (41% of 2017 total)	1.0 Gt/yr reduction (59% of 2017 total)
	CO_2 emissions (Gt/year)[1]	1.7	2.5	1		
	Renewable energy share[2] (%)	3%	2%	29%		

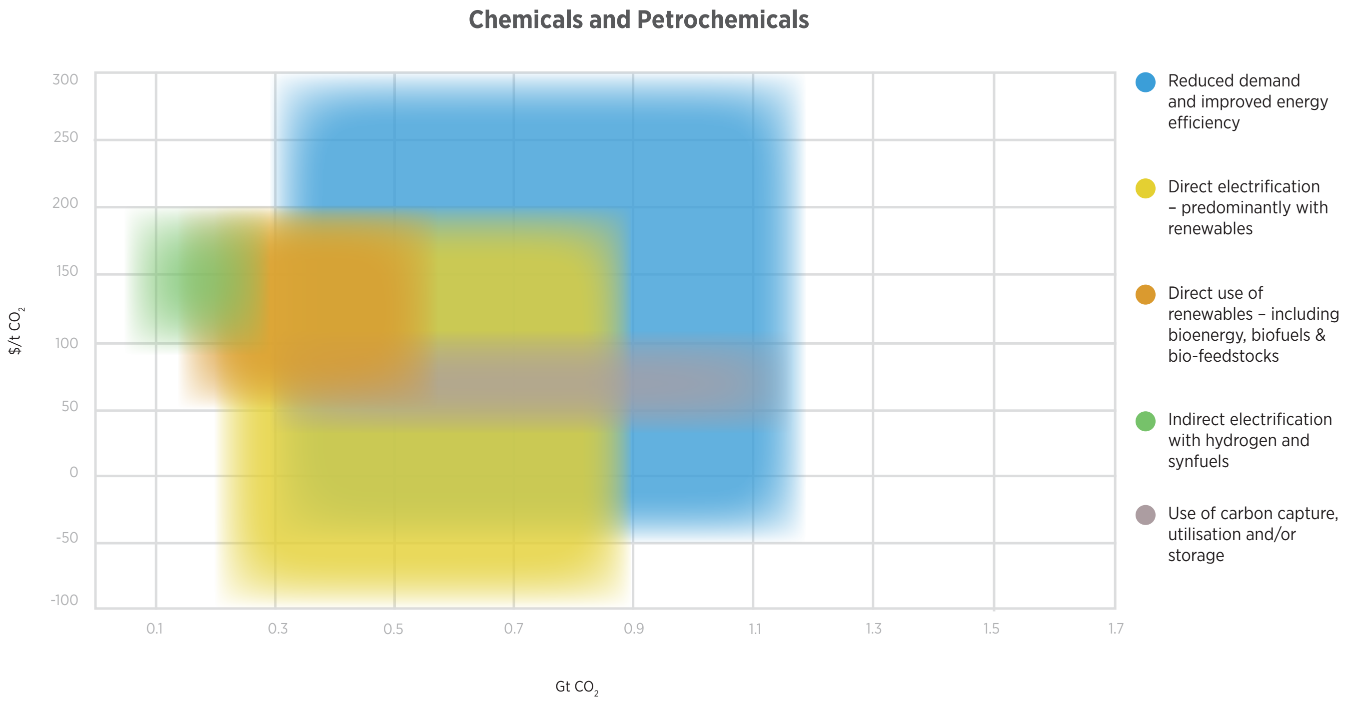
Notes:
1. Emissions include direct energy and process emissions;
2.Including electricity and district heat.
Source: *IRENA, 2020a;* IEA, 2017

FIGURE 13: Emission reduction measures to reach zero emissions in the chemical and petrochemical sector, from Planned Energy Scenario to zero



Source: IRENA analysis

FIGURE 14: Estimated abatement potential of measures to reach zero energy emissions in the chemical and petrochemical sector plotted against estimates of the cost of abatement



Source: IRENA analysis

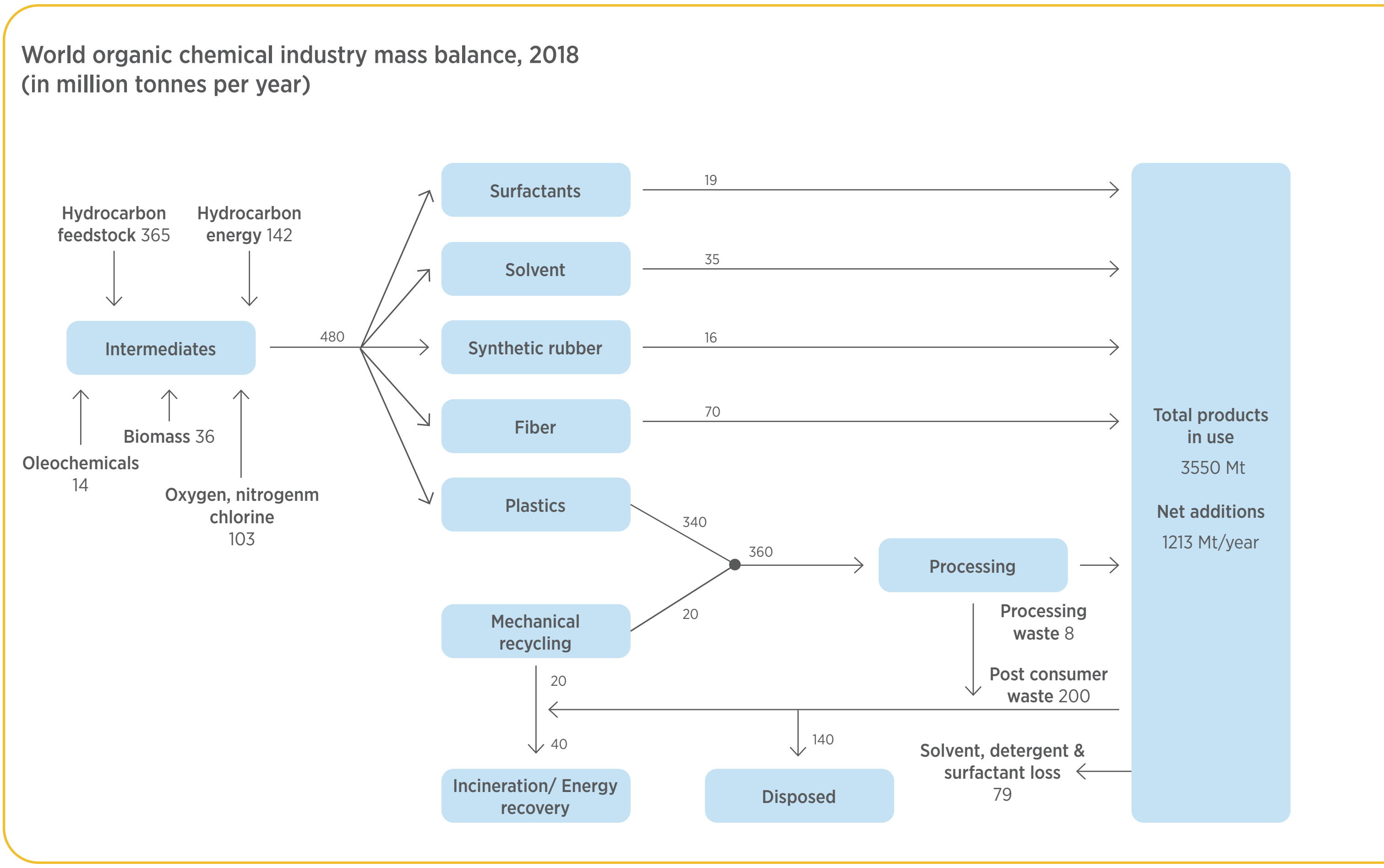
Sector overview and the emission reduction challenge

In the petrochemical sector fossil fuel feedstocks are used to produce a range of "primary petrochemicals" which are the "building blocks" for a wide range of chemicals and products – for example, plastics, fibres, solvents, inorganic chemicals and hundreds of other types of products.

The chemical and petrochemical sector is of significant economic importance. Global production amounted to USD 5.7 trillion in 2017 including pharmaceuticals. Production is projected to quadruple by 2060 (UNEP, 2019).

Globally around 644 Mt of petrochemicals was produced in 2018 (IFA, 2018), and the sector continues to grow rapidly. A few chemicals dominate production, particularly steam cracking products (ethylene, propylene, butadiene, aromatics), ammonia and methanol. Plastics account for the majority of product in volume terms, and plastics production grew 20-fold in the past five decades to reach 360 Mt by the end of 2018 (Plastics Europe, 2019). Various grades of polyethylene account for around 30% of all plastics production worldwide, while polypropylene and polyamide production account for 17% and 15% of the total, respectively. Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) account for another 19% (Grau, 2019).
Projections for the future average annual growth in plastics production vary from as low as 1% to a more ambitious high of 3% per year (Bourguignon, 2017; Hundertmark et al., 2018; Saygin et al., 2014; WEF, 2016).

FIGURE 15: World petrochemicals production, processing and recycling



Source: Saygin and Gielen, submitted for publication

Sources of emissions

The chemical and petrochemical sector is a major contributor to global industry's CO_2 emissions, ranking third behind the iron and steel and cement sectors. Decarbonising the chemical and petrochemical industry is particularly challenging because it is currently both a large user of fossil fuel energy and a large user of fossil fuel-derived raw materials for non-energy use.

The life cycle of petrochemical products involves different CO_2 emission streams:

- direct energy emissions from production processes (around 1.2 Gt per year),
- direct process emissions from production processes (around 0.5 Gt per year)
- emissions from product use, decomposition and waste (around 0.4 Gt per year) and
- CO_2 stored in a growing stock of products (around 1 Gt per year).

The hydrocarbon stocks, as a result, are contained both in products in use and those that make their way to controlled and uncontrolled waste disposal systems globally.

The sector has roughly equal amounts of emissions from energy used in production processes and from feedstock use. Both of these need to be eliminated if the sector's emissions are to be reduced to zero.

A limited number of commodities accounts for the majority of energy use and related CO_2 emissions in this industry (see Table 8): ethylene, propylene, butadiene, aromatics (benzene, toluene, xylenes) (produced from the steam cracking process), ammonia, methanol, carbon black, and chlorine and sodium hydroxide. The production of this limited set of nine products accounts for 75% of the sector energy and non-energy use. The remainder is accounted for by subsequent conversion process where these "building blocks" are used to produce plastics, fibres, solvents, etc. The energy use for the processing of the building blocks is generally small compared to the production of the building blocks. Chemical and petrochemical production sites can be large with a high level of heat integration, which complicates energy and CO_2 intensity analysis for individual products.

TABLE 8: ENERGY USE AND FEEDSTOCK USE PER TYPE OF PRODUCT, 2017

	[EJ/yr]
Ammonia	6.1
Methanol	2.8
Ethylene	9.6
Propylene	5.8
Aromatics	8.9
Carbon black	0.7
Chlorine	0.6
Total	**34.5**

Source: IRENA analysis

Table 9 provides an overview of the sources of the energy use for petrochemical production. The bulk of the feedstocks in the sector are derived from oil and natural gas, and the sector consumes 10-15% of global production of these fuels.

TABLE 9: ENERGY AND FEEDSTOCKS FOR PETROCHEMICAL PRODUCTION, 2017

	[EJ/yr]
Coal	5.1
Natural gas	15.6
Oil	20.7
Biomass and waste	1.3
Heat	2.4
Electricity	4.5
Total	**45.1**

Source: IEA, 2018a and IRENA analysis

A significant amount of coal is used, principally for the production of ammonia and methanol, and particularly in production in China, where a coal-based petrochemical industry has been gradually emerging. China accounts for 54% of global methanol production, for around 45% of ammonia production and for around 20% of synthetic resin production.

More than a quarter of all methanol demand currently is related to olefins production, produced predominantly using coal feedstock in China. These developments matter from a global perspective as projections suggest that the demand for synthetic resin and (coal-based) ethylene production in China is expected to increase from 16% in 2015 to 36% in 2050 (Ke, 2019), thus making the elimination of coal an important challenge.

Barriers to progress

There are several reasons why the sector has made limited progress in reducing CO_2 emissions. These include:

- Energy efficiency has been high on the agenda for decades and the remaining potential is limited.
- Multiple conversion processes are integrated in large ageing industrial complexes that result in high systems efficiency but that also limits the remaining energy efficiency potential (Saygin et al., 2011).
- Around half of the sector's heat demand is for high-temperature processes that cannot be easily supplied by renewable energy resources (Saygin et al., 2014).
- Petrochemical production is increasingly integrated with refinery operations, with modern refinery designs allowing 50% petrochemicals in the product mix. Such plant design concepts lock in fossil energy use.
- The high cost of low-carbon alternatives, such as bioplastics, acts as a major barrier to their uptake. Bioplastics currently constitute less than 1% of the total plastics production (Chen and Patel, 2012; Karan et al., 2019; Saygin et al., 2014).
- The circular economy is not well developed in this sector and its products. The majority of post-consumer plastic and textiles is incinerated or landfilled (Kümmerer et al., 2020). Low recycling rates and low energy recovery rates add to energy use and CO_2 emissions (Hatti-Kaul et al., 2020).

BOX 5: ZERO-EMISSION PATHWAY FOR THE GLOBAL CHEMICAL AND PETROCHEMICAL SECTOR

The chemical and petrochemical sector relies mainly on fossil fuels and fossil feedstocks; therefore it will need to undergo a substantial transformation in the coming years to achieve its complete decarbonisation. Saygin and Gielen (forthcoming) have conducted an in-depth assessment exploring the techno-economic potential of 20 technology options that fall within five different pathways for decarbonising the sector's direct CO_2 emissions from the production, materials use and waste handling, and that can put the sector on a path to net-zero emissions by the mid-21st century. The impact of each option was assessed through its potential under IRENA's Transforming Energy Scenario. The five pathways are: 1) demand reduction through energy efficiency improvements; 2) demand reduction through the application of circular economy concepts; 3) direct electrification with renewables; 4) direct use of renewable energy, such as biomass; and 5) decarbonising industrial processes with CCUS technologies.

According to the authors, the realisation of this potential pathway would require an investment of USD 9.6 trillion by 2050, an amount equivalent to 8% of all energy sector investments needed to reach the Paris Agreement's climate goals. The transformation of the chemical and petrochemical industry could also increase the sector's energy and feedstock costs by roughly 35%, averaging a CO_2 abatement cost in 2050 of USD 57 per tonne of CO_2. This process would also have considerable implications and would require a substantial scale-up of renewable power capacity and feedstocks. The study predicts biomass energy use to increase to 1.2 billion tonnes per year, green hydrogen production capacity to increase to 1 000 GW, and the overall chemical and petrochemical sector to shift to renewable power (3 000 – 6 000 GW).

In terms of emission reductions, the authors foresee that around 29% of the necessary CO_2 emission reductions in the Transforming Energy Scenario will come from demand reduction, energy efficiency improvements, and reuse and recycling through circular economy concepts. Direct use of renewables (14%), direct electrification (15%) and indirect electrification through green hydrogen and synthetic fuels (7%) also have an important role to play in decarbonising the sector. Finally, the remaining 28% of emissions would be abated through the use of CCUS technologies, including bioenergy with carbon capture and storage (BECCS).

While the Transforming Energy Scenario only achieves a 50% reduction in the sector's CO_2 emissions, the authors argue that the remaining emissions could be abated through different solutions, including a change in carbon accounting methodologies that would consider the inclusion of biomass carbon storage in synthetic organic products, the replacement of urea-based fertilisers with others such as ammonia nitrate, the uptake of direct air capture in industrial processes, the replacement of natural gas with biomethane and hydrogen, and the uptake of seasonal electricity storage solutions. The analysis also shows a need for a fundamental change in the sector's material flows. Production plants are commonly situated close to the source of their feedstocks; therefore this transformation may trigger a change in the location of production facilities, a topic that warrants further analysis.

Overall, the authors conclude that a transition to zero carbon for the chemical and petrochemical sector is complex but feasible by mid-century; however, there will be a cost, and therefore the transformation will need to be facilitated by an enabling framework supported by governments. A premium will likely have to be paid for green chemical products, and in order for them to be competitive, the negative environmental effects of non-green products should also be factored into their price.

Production patterns

The diversity of production routes and end products is very large and beyond the scope of this report. From an energy use and emission reduction perspective, however, there are some key processes and products which warrant the most attention.

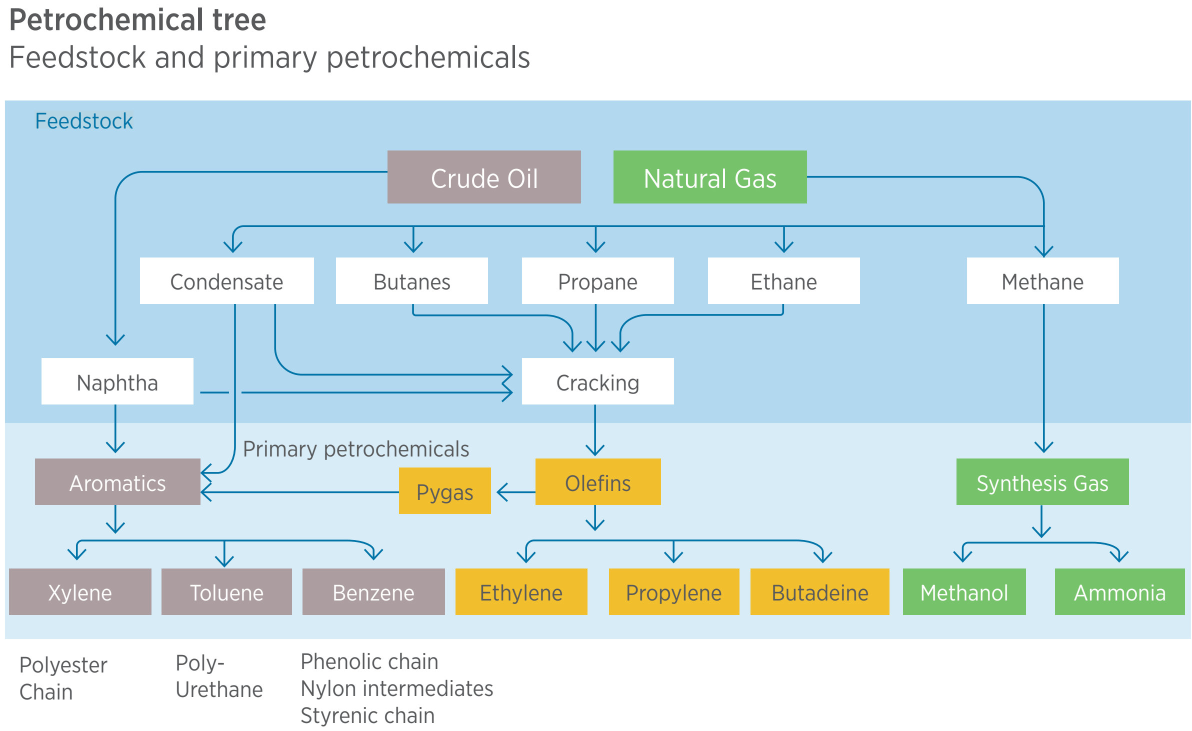
Two groups of primary petrochemicals are particularly important:

- **Olefins,** principally ethylene, propylene and butadiene. Ethylene and propylene are the precursors of many industrial chemicals and plastics products. Butadiene is used in particular for making synthetic rubber. Around 150 Mt of ethylene and 110 Mt of propylene are produced and consumed annually.
- **Aromatics** include benzene, toluene and xylenes. Benzene is used in the manufacture of dyes and synthetic detergents, toluene is used in making explosives, and xylenes are used in making PET and synthetic fibres. Around 155 Mt of aromatics are produced and consumed annually.

Ammonia and methanol are also particular important. Both can be produced from syngas (a mixture of carbon monoxide and hydrogen) derived from natural gas or from coal gasification. Ammonia is primarily used in making fertilisers but could have a much wider role as discussed later in the section. Similarly, methanol has a role as a building block for other chemicals, including as part of an alternative production route for olefins, but could also have a wider role as discussed in the Annex of this report.

The production of some of these building blocks is discussed below, and the production of ammonia is discussed in a focus sub-section later in this section.

FIGURE 16: Feedstock and primary petrochemicals



Source: ABB, 2020

Aromatics production and use

Aromatics include benzene, toluene and the xylenes (*i.e.*, ortho-xylene, meta-xylene and para-xylene). These chemicals can be extracted or distilled from gasoline manufacturing streams. They are valuable since they are used as building blocks to produce a large range of products. Benzene's largest derivate is polystyrene, but it is used across a number of industrial sectors in the production of clothing, packaging plastics, paints, adhesives, agrochemicals and pharmaceuticals, among others. Toluene is produced in different grades which can be used in the production of polyurethane, as a solvent, or as a feedstock for the production of benzene and xylene. Xylene is used as a feedstock in the production of PET and to produce other products such as medicines, dyes and solvents.

Olefins production and use

Olefins include ethylene, propylene and butadiene, and they are used to produce plastics such as polyethylene. Polyolefins account for nearly half of all plastics production.

Together the energy use and feedstock (in energy equivalent terms) use for their production accounts for a third of total final energy use in the chemical and petrochemical sector. Within this, the feedstock component is the dominant source of emissions from this sub-sector.

The principal production route of olefins is steam cracking of crude oil-derived feedstocks. The costs of producing olefins from a renewable-hydrogen route are currently twice as expensive as the conventional naphtha-based route of producing ethylene and propylene.

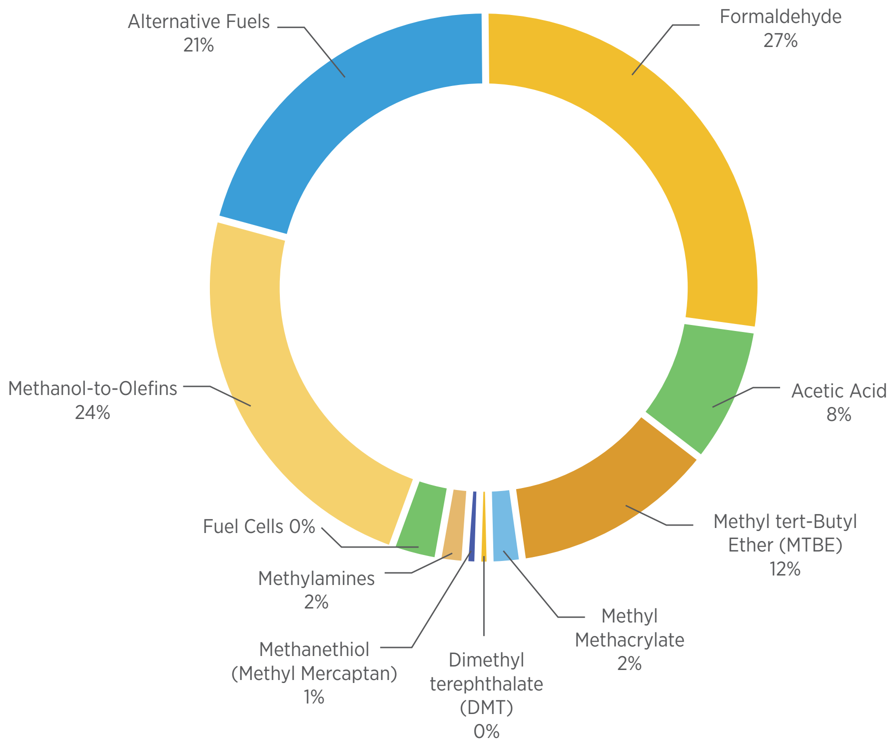
Methanol production and use

Methanol is an essential building block for other chemicals. There are two conventional routes to produce methanol: from coal (which dominates in China) and from natural gas (which dominates in most other locations) (see the Annex for a fuller discussion of methanol production). "Grey" methanol produced through these processes, however, could be replaced with "green" methanol either produced from biomass or synthesised from hydrogen and CO_2 (as discussed in the Annex).

Methanol holds a key position in the chemicals sector where it is used extensively in the production of formaldehyde, acetic acid, di-methyl terephthalate (DMT) and other solvents. It is used extensively as a denaturing and anti-freezing agent, as an industrial solvent for resins and inks, as an adhesive for wood items and as a dye. Methanol is also used in a broad range of applications in various industry sectors discussed in this report. It can also be used solely as a vehicle fuel or blended with petrol to produce a fuel that is more efficient, compared to conventional petrol. Figure 17 shows the application breakdown in 2018.

The global methanol market reached a total volume of around 92 Mt in 2018 and is expected to grow beyond 100 Mt by 2024. As the world's largest methanol producer and consumer, China accounted for half of total global demand in 2018 followed by the rest of Asia, Europe, North America and Latin America.

FIGURE 17: Global methanol applications, 2018



Source: Methanol Institute, 2019a

BOX 6: MAKING THE SECTOR ACCOUNTABLE FOR EMISSIONS

Chemical and petrochemical production sites can be very large and complex with a high level of integration, which complicates energy and CO_2 intensity analysis for individual products.

Although emission reduction options are emerging in the sector, persistent issues remain in the way carbon emissions are controlled for. A key problem is that feedstock carbon and the "storage" of carbon in materials or products is not being counted in the sector's carbon footprint. Based on the products identified in Table 8, and assuming an 80% storage rate, the storage amounts to 1.13 Gt of CO_2 and the net emissions amount to 2.75 Gt of CO_2. This implies that 29% of all carbon from the sector's energy and non-energy supply is stored in products.

The emissions resulting from waste incineration of these products are also not specifically allocated, leaving another large set of emissions unaccounted for. Emissions resulting from waste incineration must therefore be included in calculations of the full life-cycle emissions. Estimates vary from 75 Mt to 200 Mt of emissions from incineration of synthetic organic materials (Khaza *et al*., 2018; Hundertmark *et al.*, 2018), and further analysis is needed to determine the precise amounts. As a result of these gaps in measuring and accountability there have been few incentives for action; this urgently needs to be addressed.

Options for reaching zero

Emission reductions can be achieved by: reducing demand for petrochemicals, reducing emissions from the energy used in the production processes, adopting alternatives to fossil fuel feedstocks and permanently storing the carbon embedded in the products at the end of their life. Some of these emission reduction trajectories are less promising than others for a goal of reaching zero. Realistically the sector will need a combination of approaches.

Reducing demand through efficiencies and adopting the principles of the circular economy is an essential starting point that will assist the implementation of other approaches by reducing the scale of the challenge (Box 7). The circular economy is also critical to managing other environmental impacts such as the impact of plastic waste on local ecologies.

In addition to these approaches, however, reaching very low or zero emissions will require a combination of three options:

1. the use of biomass for feedstocks, with the process energy sourced from renewables,
2. the use of synthetic hydrocarbons for feedstocks, with the process energy sourced from renewables, and
3. the use of fossil-fuel feedstocks with process and waste emissions captured and permanently stored and with the process energy sourced from renewables.

The following sections discuss these three approaches. All three require the use of energy from zero-carbon, preferably renewable, sources. In practice that means the use of either renewable electricity, green hydrogen or biomass (see the Annex for further discussion of these energy carriers). Integrating those energy sources into chemical production processes will be challenging but is achievable. The following sub-section discusses ways in which renewables can help decarbonise the sector's energy use. The Options sections that follow therefore focus mainly on the ways in which emissions from feedstocks can be avoided.

Decarbonising process heat: Energy efficiency and renewable energy potentials

The chemical and petrochemical sector's energy intensity has been steadily declining at an average annual rate of 0.5-1%. This improvement has been achieved through energy efficiency technology retrofits, system-wide efficiency measures such as motor systems and process heat cascading as well as the implementation of new energy-efficient process technologies (Saygin et al., 2013, 2012). Despite the efficiency gains, however, the sector's energy demand has grown by around 3% per year over the past decade. A further 15% reduction in final energy use could still be achieved if the sector were to implement best practice technologies widely (Saygin et al., 2011a, 2011b).

The share of direct renewable energy use in the sector's total final energy consumption and non-energy use is currently less than 1%. Biomass is the main renewable energy source, but its potential for both process energy and feedstock is much higher than its current share (Saygin et al., 2014).

A shift to renewable electricity could also increase the total renewable energy share. Electricity is traditionally used for the chlor-alkali electrolysis process and for the operation of fans, pumps and compressors. However, a large proportion of the fossil fuel use for steam and process heat generation could technically be replaced with electricity (Philibert, 2019). For low and medium temperature, highly efficient heat pumps could be deployed. The largest potential for heat pump integration is found in distillation, evaporation, drying and heating processes, which often take place at temperatures between 100 °C and 500 °C. Electrically driven heat pumps can be deployed at temperatures of up to 280 °C, while higher temperatures might be reached depending on the availability of suitable heat sources (Zühlsdorf et al., 2019).

Integrated sites use steam networks at different pressures to cascade the heat down. Overall heat demand is generally defined by the highest-temperature heat required. The resulting waste heat still contains so much energy that lower-temperature heat requirements can in general be easily fulfilled. Today's heat pumps do not achieve the required temperature level or the volume of heat required for basic chemical processes, and further innovations will be needed.

Other approaches are beginning to emerge: for example, electricity-based alternatives to the traditional steam cracker process are also under development, and the potential to green the gas supply using either green hydrogen (from renewable power) or biomethane is being explored in several countries.

BOX 7: REDUCING DEMAND BY EXPANDING THE CIRCULAR ECONOMY

The circular economy includes recycling, reuse, materials substitution, more efficient materials design and the use of sustainable biomass resources. Circular flows are better from an environmental perspective because they reduce the need to extract primary resources, they increase process efficiencies, and they reduce the need for waste disposal. Circular flows can also reduce energy needs. For example, recycling of materials is often more energy efficient than production of primary materials from natural resources. Recent estimates suggest that a reduction of 50% or more of energy and resource use can be achieved for many sectors and products in this manner (see, for example, Gielen and Saygin, 2018). There is often also a sound economic reason for recycling that can create additional revenue streams for businesses.

The market for recycling, however, remains small. One reason is the price dynamics and low profit margins. Virgin plastic prices depend on the developments in crude oil prices. Recycled plastic prices depend on the cost of collection, sorting and processing. Falling oil process negatively affect the competitiveness of recycling. Production of primary packaging materials also has become very efficient and cost-effective over the years, which makes it challenging to find alternatives.

A circular economy requires detailed insights into how materials are used and where waste materials arise. One aspect is that materials are stored in products that have varying life spans. Whereas food packaging or delivery service packaging may have a life span of a few days, use of materials in buildings and infrastructure may last decades or even hundreds of years. There is a clear trend for plastics towards shorter life spans. Notably the growth of the internet delivery economy in recent years has vastly increased the amount of packaging waste.

In China (which accounted for 50% of global e-commerce in 2017), parcel packaging waste contributed 40% of municipal solid waste in 2017. Due to the rapid increase in express parcel garbage, the proportion of plastic and paper waste in domestic garbage has increased greatly. Over 90% of the parcel plastic packaging waste is not recycled and will be thrown away directly as household garbage. Consequently, the share of plastic waste in China increased from 12% to 20%, and the share of paper waste increased from 9% to 14%. Total plastic waste recycling was 17-18 Mt in 2018 (the year plastic waste imports were banned) (1421 Consulting Group, 2019).

Worldwide in 2010, more than 250 Mt of plastic waste was generated per year (including processing waste) (Geyer *et al*., 2017). Another source estimates an even larger amount of 275 Mt of plastic waste (Jambeck *et al*., 2015).

[For fuller discussion, see Saygin and Gielen, forthcoming.]

REACHING ZERO – OPTION 1:
Using biomass for feedstocks and renewables for energy

The use of sustainably sourced biomass to replace fossil fuel use as both fuels and feedstock is a leading option for decarbonising the chemical production sector.

Crucially if, through a fully effective circular economy approach and/or the safe disposal of biomass-derived products at the end of their life, the carbon captured in the products produced is not released to the atmosphere, then negative emissions may be achieved.

As with the use of fossil fuels, a large number of potential production routes and end products exist. For ease of discussion these can be summarised under two strategies:

4. Replacing primary petrochemicals with bio-based chemicals – these chemicals can then be used to produce products that are chemically identical to petrochemical-derived products. These products have the same advantages and disadvantages as their fossil fuel-derived equivalents but are currently more expensive.
5. Replacing fossil fuel-derived polymers (particularly plastics) with alternatives produced from biomass. The products produced may have different chemical composition and different properties to fossil fuel-based alternatives. Some such products may have properties that are beneficial (such as being biodegradable) but may face complexities in replacing conventional products.

A full discussion of the multiple possibilities is beyond the scope of this report. To illustrate some of the options, the following sub-sections discuss the production of some of the bio-based alternatives to primary petrochemicals (bio-methanol, bioethanol, and bio-ethylene and bio-aromatics) as well as the growing role of bioplastics. A more in-depth discussion of some options is referenced in Box 5.

Bio-methanol

Biomass-based production of methanol is very low, below 200 kilotonnes per year , but is expected to gradually ramp up (IRENA, forthcoming c). Several bio-based methanol production plants are in operation in Canada, the Netherlands and Sweden.

There are several pathways to produce bio-methanol. One option is steam reforming of raw glycerine, a residue from vegetable oil and animal fat processing. In 2010, BioMCN (BioMethanol Chemie Nederland) launched a commercial plant with a production capacity of 200 kilotonnes per year to produce methanol through this process, but production was terminated in 2013 for both technical and economic reasons.

A second option is to produce methanol through gasification of biomass. Värmlands-methanol, a Swedish company, is preparing to build a plant in Hagfors, Sweden that will gasify forestry residues and convert the syngas into fuel-grade methanol for a capacity up to 100 tonnes per year (IRENA, forthcoming c). A biochemical company, Enerkem, is building a plant in Rotterdam, the Netherlands that plans to turn 350 kilotonnes of waste, including un-recyclable plastic, into 270 million litres of bio-methanol every year. The company also operates a commercial-scale waste-to-biofuels facility in Alberta, Canada which began producing methanol in 2015, using the city's non-recyclable and non-compostable waste. The plant is designed to process into methanol over 100 000 metric tonnes per year of unrecoverable waste otherwise destined for landfill (Methanol Institute, 2019b). In 2017, BioMCN formed a consortium to build a large-scale biomass refinery to convert 800 kilotonnes of waste wood per year into 200 kilotonnes of bio-methanol. However, the project failed to progress because it was not possible to mobilise sufficient financing despite support from the European Commission.

A third alternative is to produce methanol through an anaerobic digestion route. Anaerobic digestion is a series of biological processes in which micro-organisms break down biodegradable material in the absence of oxygen. Currently, 15% of BioMCN's bio-methanol is produced from biomass (67 kilotonnes per year out of a total of 450 kilotonnes) using this route, while the remainder is produced from natural gas. In this plant, biomass waste is broken down by anaerobic digestion and the resulting biogas is separated into methane and CO_2, and the methane fraction is fed into the gas system together with natural gas and later processed into methanol. Another example can be found in the US state of Texas, where the OCI Beaumont methanol plant with a production capacity of 912 kilotonnes is growing the production of bio-methanol from biogas sourced from a range of waste digestion plants and other renewable sources (OCI, 2019; OCI Partners LP, 2019).

Another option is to produce methanol from the pulping cycle in pulp mills. When pulp wood is converted into pulp for further processing to various qualities of paper, methanol is formed in the digester where the wood chips react with the cooking chemicals (mostly sodium hydroxide and sodium sulphide). In 2020, a large pulp mill in Sweden, Södra, started producing methanol with 5 kilotonnes per year of production capacity (Södra, 2020), becoming the world's first unit to produce methanol from this type of source.

Bio-methanol is currently more expensive to produce than conventional methanol. A 2017 techno-economic study suggested a cost differential of USD 1-2 per gallon for bio-methanol and natural gas methanol (Biofuels Digest, 2017).

Bioethanol and bio-ethylene

There are three well-established methods for producing ethanol from renewable sources: the direct fermentation of starch/sugar-rich biomass (*e.g.*, maize starch, sugar beet or sugar cane); hydrolysis of lignocellulosic biomass (*e.g.*, wheat, wood or agricultural waste, and subsequent fermentation to ethanol); and lignocellulosic biomass gasification with microbial fermentation or chemical conversion with a catalyst (Griffin *et al*., 2018).

Ethylene can be readily produced from bioethanol, and the production of bio-based ethylene has been carried out on a commercial scale in Brazil and India for some years now, although volumes are relatively small (less than 0.5% of total global ethylene production). Costs at these current small scales are higher than for fossil fuel ethylene, which calls for increased efforts to scale production and drive down costs.

Bio-aromatics (bio-BTX)

Aromatics, principally benzene, toluene and xylenes (BTX), have a total production volume of around 150Mt per year. Aromatics are an important component of transport fuels and are used as solvents as well as chemical building blocks. Demand for p-xylene in particular has grown in recent years since it is a building block for PET products (bottles, etc.).

Conventionally, the majority of aromatics are recovered from refinery cuts, and some are a by-product of steam cracking. In recent years, increasing effort has focused on developing biomass alternatives. Given the differences in composition between oil and biomass, the same production techniques cannot be used interchangeably. However, the chemical composition of biomass is much closer to the functional aromatics, so there is a focus on developing catalytic direct conversion routes.

Lignin, a high-volume resin by-product of pulp production, has long been viewed as a promising feedstock because it contains aromatic structures. A number of lignin modifications are being developed, but in general most bio-aromatics production processes are in the pre-commercial development stage with commercial scale a few years away (EC, 2019). Higher production capacities for bio-BTX of 150 kilotonnes may be achieved by 2025 or after, with a few middle-scale industrial plants becoming active worldwide. Reducing uncertainty regarding supply, technological improvements and higher fossil energy or carbon prices may lead to an increase by 2030 in the range of 450 kilotonnes, a 0.2% bio-share (EC, 2019).

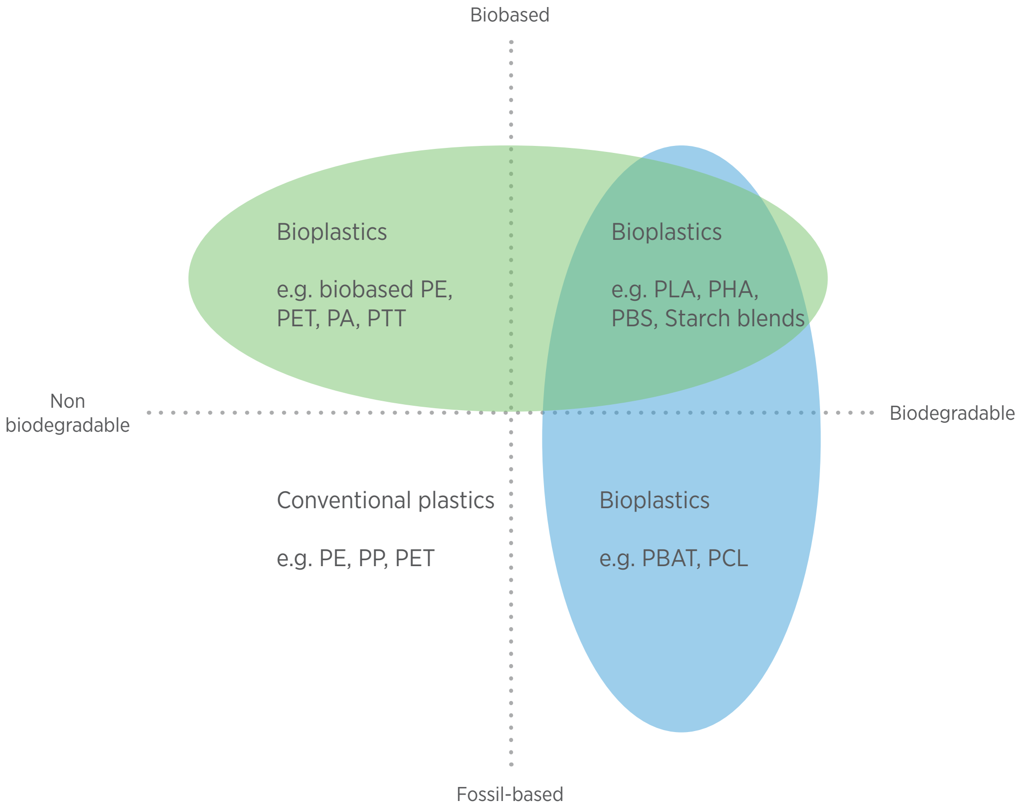
Biomass-based plastics

The term bioplastics is used to cover a wide range of different products and process techniques, only some of which are consistent with a zero-emission objective. According to European Bioplastics, bioplastics are defined as either bio-based, meaning that the material or product is at least partly derived from biomass, such as corn/maize, sugar cane and cellulose; or biodegradable; or both. Fully bio-based plastics may be non-biodegradable, and fully fossil fuel-based plastics can be entirely biodegradable (Figure 18). While this distinction is important for environmental and waste management considerations, the discussion here focuses on the CO_2 implications of the use of biomass to produce bioplastics. Bioplastics can be clustered into two main categories:

- **Bio-based or partly bio-based, non-biodegradable plastics** such as bio-based polyethylene, polypropylene, or polyethylene terephthalate (PET)[3] and bio-based technical performance polymers such as polytrimethylene terephthalate (PTT) or

3 Partially bio-based polyester PET is also called "drop-in" bioplastic, because properties remain like fossil fuel-based plastics and production requires only adaption of the process at the beginning of the value chain.

FIGURE 18: Categories of bioplastics according to feedstock and biodegradability

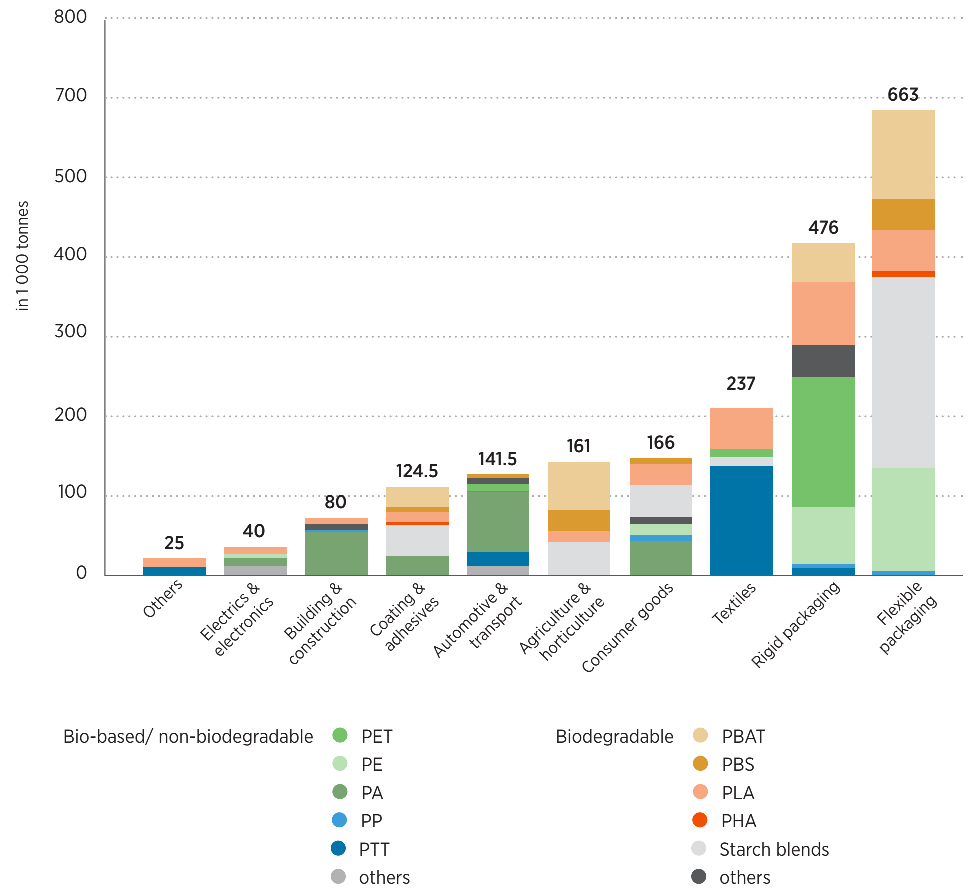


Note: PA (polyamide), PBS (polybutylene succinate), PBAT (polybutylene adipate terephthalate), PCL (polycaprolactone), PE (polyethylene), PET (polyethylene terephthalate), PHA (polyhydroxyalkanoate), PLA (polylactic acid), PP (polypropylene), PTT (polytrimethylene terephthalate).
Source: European Bioplastics, 2018

thermoplastic polyester elastomers (TPC-ET). Bio-polyethylene is already produced at scale by Braskem in Brazil with 200 kilotonnes per year, and further projects are planned by Dow Chemicals. Bio-polypropylene and bio-polyvinyl chloride (bio-PVC) are expected to be produced at scale soon. The bio-based technical performance polymers are usually used to produce textile fibres, foams and cables, among others.

- **Plastics that are both bio-based and biodegradable,** such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) or polybutylene succinate (PBS), which include starch blends made of thermo-plastically modified starch and other biodegradable polymers and polyesters. These plastics have been available at industrial scale only for the past few years, but more innovations are emerging, for example through the introduction of new bio-based monomers, such as succinic acid, butanediol, propane diol or fatty acid derivatives. In 2019, according to European Bioplastics, the global production capacity of bioplastics reached 2.11 Mt, concentrated in Asia (45%), followed by Europe (25%), North America (18%) and South America (12%). Between 2019 and 2024, bioplastics demand is expected to increase to 2.43 Mt. Bioplastics are mainly used in packaging, which accounted for 53% of total bioplastics use in 2019. Despite the potential for wider use, bioplastics production currently represents only 1% of the 359 Mt of annual plastics production. Both supply and demand would need to increase significantly to replace fossil fuel-based plastics in a zero-carbon scenario. Large consumer brands with global presence that rely on single-use plastics could play a major role in driving early demand.

FIGURE 19: Global production of bioplastics in 2019 by market segment



Note: PA (polyamide), PBS (polybutylene succinate), PBAT (polybutylene adipate terephthalate), PCL (polycaprolactone), PE (polyethylene), PET (polyethylene terephthalate), PHA (polyhydroxyalkanoate), PLA (polylactic acid), PP (polypropylene), PTT (polytrimethylene terephthalate).
Source: European Bioplastics, 2020a

Emissions could be greatly reduced in the plastics sector if fossil fuel-based plastics are substituted with bio-based plastics, using especially third-generation non-food feedstocks, combined with renewable energy. For example, in Europe, substituting fossil fuel-based polyethylene with bio-based polyethylene could reduce emissions by 24 Mt of CO_2 per year (European Bioplastics, 2020b). Further technology innovation and pilot deployments are needed to build knowledge, confidence and economies of scale. Certification schemes, international standards and regulatory instruments will be key for a massive scale-up while ensuring availability of sustainably sourced feedstock.

REACHING ZERO – OPTION 2: Using synthetic hydrocarbons for feedstocks and renewables for energy

The falling costs of renewable electricity have expanded opportunities for the production and use of green hydrogen across different end-use sectors. Hydrogen can be produced from renewables-powered electrolysis and synthesised with a carbon source in the presence of a catalyst to produce synthetic hydrocarbon feedstocks which could substitute for primary petrochemicals. These hydrocarbons can then be further refined into different chemicals. As with the production of primary chemicals from biomass, the key advantage is the identical processes and products which should make substituting for fossil fuels simple.

Several different processes can be employed to produce synthetic hydrocarbons, including thermo-chemical and electro-chemical processes. The Fischer-Tropsch and methanol syntheses, discussed in the Annex, are prime examples. Different processes have their own advantages and disadvantages, and at this early stage in their development it is unclear what will be optimum routes so all warrant consideration. For example, thermo-chemical processes can be advantageous if there is surplus hydrogen from another chemical process, electro-chemical processes can be advantageous when electricity costs are low, and photo-chemical processes can be a good option for isolated applications that require rapid deployment (Chen *et al*., 2018).

Electro-chemical conversion of CO_2 into hydrocarbons, which is not yet deployed at a commercial scale, is an option that is of particular interest to the RD&D community, given that it only requires CO_2, water and electricity (Hazarika and Manna, 2019). Single-step electro-chemical conversion, which involves the electrolysis of water and CO_2, could offer advantages over thermo-chemical processes such as the avoidance of losses related to hydrogen compression and product separation. It can also be applied at lower pressures and temperatures, but there can be issues related to system stability and feedstock impurities (Chen *et al*., 2018). This process can in principle be used to produce a wide array of products including carbon monoxide, methane, ethylene, methanol, formic acid and ethanol. Research into electrocatalytic materials for CO_2 reduction has intensified in recent years, with advances in selectivity, efficiency and reaction rate progressing towards practical implementation. Several companies have made significant advances towards the commercial electro-chemical conversion of CO_2 to carbon monoxide. However, there is still an objective to develop catalysts for CO_2 reduction with improved activity, selectivity and stability for liquid products such as methanol. Even with the development of better catalysts, there is a significant gap between laboratory-scale research and industrial processes; the viability of electro-chemical processes at scale is not yet clear (Schiffer and Manthiram, 2017).

The science of electrocatalytic CO_2 reduction continues to progress, with an emphasis on identifying the targets for practical application, improving the economics of chemical products and reducing barriers to market entry. Moving ahead, it will be important to scale CO_2 electrolysers and increase the stability of catalysts to reach thousands of hours of continuous operation. Product separation and efficient recycling of CO_2 and electrolyte also need to be managed.

The main barrier for the widespread use of all synthetic hydrocarbon conversion processes is the cost-effective sourcing of clean CO_2. As discussed in the Annex, reaching zero emissions requires sourcing "clean" CO_2, not CO_2 captured from fossil fuels. If CO_2 is captured from fossil fuel combustion flue gases, the one-time use of this CO_2 at best halves emissions compared to the reference case. This is a significant reduction, but it is not compatible with the long-term objective of eliminating emissions. Currently, sourcing clean CO_2 from biomass or from direct air capture (DAC) or bioenergy flue gas capture tends to be higher than for fossil fuel combustion flue gases – typically USD 100-200 per tonne by 2030 or today even USD 500-600 per tonne for DAC – and so substantially increases the overall production costs for synthetic hydrocarbons. Costs will need to fall substantially before this option becomes a credible alternative to the use of biomass.

REACHING ZERO – OPTION 3: Capturing and storing process and waste emissions and using renewables for energy.

CCUS technologies can in principle be applied to some conventional petrochemical production processes to capture process emissions arising from the use of fossil fuel feedstocks. If the energy required for the processes were also sourced from renewables, then CO_2 emissions from the production stages would be greatly reduced.

The combination of CCUS and renewables would greatly reduce emissions while still allowing the use of fossil fuel feedstocks, by storing the carbon from those feedstocks in chemicals or other products. However, to ensure that the carbon is permanently stored, instead of re-emitted at the end of the product lifetime, it will be necessary to have:

- a highly efficient circular economy that keeps recycling hydrocarbon products,
- long-term storage of waste hydrocarbon products, or
- end-of-life combustion with CCUS.

The processes, standards and regulation to ensure that these options are correctly applied and that emissions are not eventually released will be complex and need to be robustly applied, monitored and enforced.

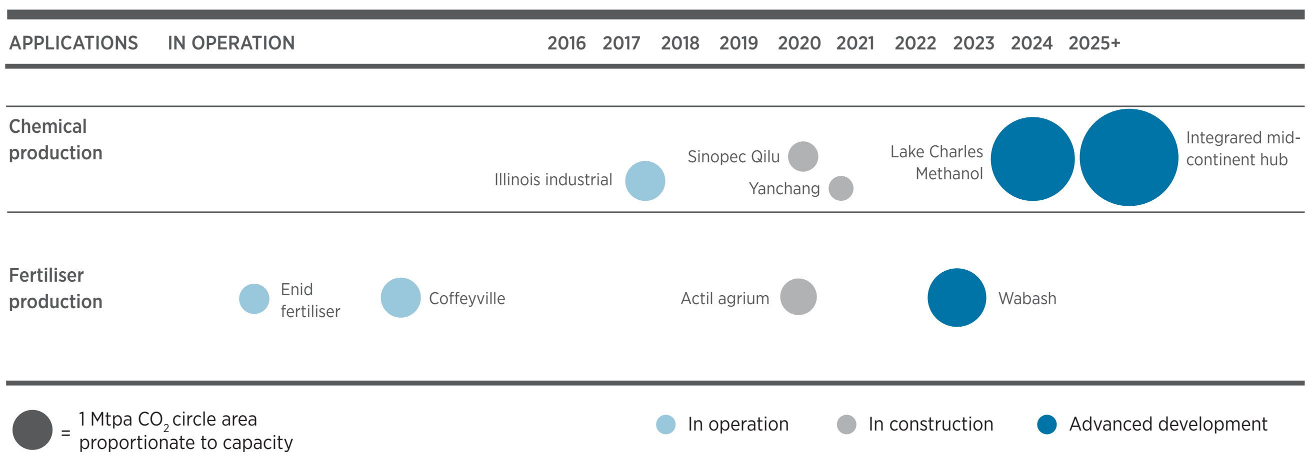
CCS is close to being an economically viable option to capture CO_2 from high-concentration flue gas streams. This includes ammonia, ethylene oxide and hydrogen production as well as steam crackers. CO_2 capture is already applied in ammonia and hydrogen production plants, on the order of 200-400 plants worldwide. However, the bulk of the CO_2 that is captured is vented or used for short-term applications, for example for the production of urea nitrogen fertiliser or in the beverage industry for fizzy drinks. Only a small fraction of the CO_2 that is captured is used for enhanced oil recovery (EOR, where part of the CO_2 stays underground) or it is stored underground in empty oil and gas reservoirs or in aquifers.

In the chemical and petrochemical industry or related industries 21 facilities with CCS are completed or operating worldwide (Saygin and Gielen, forthcoming; Global CCS Institute, 2020). Eight are ammonia fertiliser production units, five are ethanol plants, three are hydrogen production units, and three are for various other chemicals. There is also one facility integrated with methanol production. Some examples of current and planned facilities are shown in Figure 20 including:

- For ammonia derived from coal or natural gas, two large-scale plants operational in the US capture CO_2 and use it for EOR. One has been operational since 1982 (Enid Fertiliser) and the other since 2013 (Coffeyville).

- Two other large-scale ammonia plants with CCUS are planned in Canada and the US, with the captured CO_2 to be used for EOR and to be stored in dedicated geological sites, respectively.
- A plant in the US (Illinois Industrial), operational since 2017, stores CO_2 captured from an ethylene plant in a large saline reservoir.
- Four other ethylene plants with CCS are being developed in China and the US with plans to mainly use the captured CO_2 for EOR.

FIGURE 20: Large-scale CCUS facilities in operation, construction and development for chemical or fertiliser production



Source: Global CCS Institute, 2019b

Where capture occurs routinely the additional costs are limited to the pressurisation, transport and injection, as well as monitoring systems to ensure that the CO_2 remains underground. The cost of these steps varies on the distance to the storage and the electricity cost for pressurisation. Under favourable conditions these costs can be below USD 20 per tonne of CO_2. In less-favourable conditions they can rise to more than USD 75 per tonne of CO_2. The vast amount of CCUS is at this moment related to EOR. The oil revenues are sufficient to create a net benefit even in an environment without a CO_2 price. However, very few EOR operations monitor what happens to the CO_2 underground, and long-term storage over thousands of years is not a given. Industrial co-generation units could be equipped with CCS, albeit at a higher cost. These depend on the specific operation and the local energy cost, but the capture part can add USD 25-50 per tonne of CO_2, to which the transport and storage cost must be added.

Considering CO_2 capture and use, Hepburn *et al.* (2019) claim a 300-600 Mt per year carbon capture and utilisation (CCU) potential in chemicals by 2050, with an associated cost of USD 80-320. They state that only a few of the technologies are economically viable and scalable. Some are commercialised, such as the production of urea and polycarbonate polyols. Some are technically possible but are not widely adopted, such as the production of CO_2-derived methanol in the absence of carbon monoxide. Breakeven costs per tonne of CO_2, calculated from the scoping review, for urea (around USD 100) and for polyols (around USD 2 600) reflect that these markets are currently profitable.

A critical question relates to the CO_2 benefits of CCU. From an emitter perspective, the elimination of emissions via CCU may suggest 100% emission reduction. However, that is only the case in some applications. An extreme example is the use of urea fertiliser: the CO_2 is stored but released soon after fertiliser application. Fehrenbach *et al*. (2019) conclude a 35% reduction of CO_2 emissions in a scheme where coal power plant CO_2 emissions are captured and used for methanol production, with use of clean energy for the conversion. Such approaches are therefore not compatible with a zero-emission objective.

Focus: Plastics recycling and pyrolysis

Despite much discussion on the benefits of recycling and reuse, there has not been a strong trend in recent years towards a less resource-intensive, circular economy. Rather, increasing global demand is straining primary resources and leading to greater plastic waste. The topic is, however, increasingly recognised as important at the national and international level.

Policy making on the topic is complex and requires a nuanced approach to deliver the wide-ranging and interconnected behavioural and process changes needed. There is high risk of ineffective approaches with unintended consequences.

An example of the latter is plastics recycling, which has proven challenging for technical and economic reasons. Germany's experience illustrates the difficulties even with pro-active government policies and a supportive public. Extensive recycling requirements and systems were put in place in Germany over two decades ago. Germany's waste volume, however, continues to be the highest in Europe, at 626 kilograms per capita in 2016 (Bünder, 2018)[4]. Other estimates suggest that this amount increased by 11% between 2005 and 2016, and although 66% of the waste is collected for recycling, the recycling rate remains much higher for paper and board and glass than for plastics. The critical bottleneck remains plastic recycling, where less than 50% of plastic packaging waste is recycled or exported, and the other half is incinerated in Germany (Wecker, 2018).

Plastic waste recycling processes can be divided into:

- mechanical recycling (melting of thermoplastics),
- back-to-monomer chemical recycling (e.g., splitting PET into its monomer components) and
- back-to-feedstock thermal or chemical recycling (e.g., pyrolysis).

At present around 10% of plastic waste worldwide is recycled mechanically. Mechanical recycling is limited to pure or well-separated waste streams and does not work when, as is often the case, waste streams consist of mixed plastic waste. Collection and separation can add greatly to the total processing cost, and often only a small share of collected materials can be recycled mechanically.

To tackle the problem more effectively, studies have suggested materials use efficiency and chemical recycling as the two core components of the circular economy, and globally, technology developers are now focusing on providing chemical rather than mechanical recycling solutions.

Although it is inherently restricted in its application to condensation-type polymers such as PET and polyamide, back-to-monomer recycling has the potential to generate some of the highest plastics recycling profitability levels. Monomer recycling can avoid the capital investments needed for steam crackers and aromatics plants, as well as the high-capital-cost plants required to make PET and polyamide intermediates (Hundertmark *et al.*, 2018). However, back-to-monomer and back-to-feedstock processes require energy to break down larger molecules to smaller building blocks, plus additional energy for

4 This includes 222 kilograms of packaging waste and 38 kilograms of plastic packaging waste.

separation and conversion of these building blocks back to plastics. This results in significant energy use and, if fossil fuels are used, higher CO_2 emissions.

Pyrolysis is expected to be a key process to enable chemical recycling, although significant uncertainties remain. Recent reviews suggest that it presents several advantages for treating plastic waste – particularly solid plastics originating from the municipal sector (see, for example, Hundertmark *et al.* (2018)).

Pyrolysis involves the degradation of the constituting polymers of the plastic material waste by heating them in inert (non-reactive) atmospheres. The process is typically conducted at temperatures between 350 °C and 900 °C and produces carbonised solid char, condensable hydrocarbon oil and a high calorific value gas. The product's selectivity and yields of product fractions depend on the plastic type along with process conditions. It is divided into two main types, thermal (without the presence of catalysts) and catalytic pyrolysis. Thermal pyrolysis produces liquids with low octane value and higher residue contents at moderate temperatures. The gaseous products obtained by thermal pyrolysis typically require upgrading to be used as a fuel. Pyrolysis can also be conducted catalytically, reducing the temperature and reaction time required for the process and allowing the production of hydrocarbons with a higher calorific value such as fuel oil (Antelava *et al.*, 2019).

The wider use of pyrolysis needs to be considered with some caution. The process relies on pure waste streams and does not work for mixed plastic waste. Among the different kinds of plastics that can be used in pyrolysis, PET typically produces a very low yield of liquid oil in comparison with other plastic types with 50-90% gaseous product. PVC pyrolysis results in significant amounts of harmful hydrochloric acid and very low yield of liquid oil. Additionally, pyrolysis oil contains chlorinated compounds that can degrade the oil quality.

In Europe and the US several companies are using pyrolysis to produce fuel from plastics. These plants typically are small scale, operating at a capacity of 10-25 kilotonnes per year with typical yields of around 850 litres of oil product per tonne of waste (Haig *et al.*, 2017).

The potential of pyrolysis as a solution to plastics recycling therefore faces three key challenges:

- Pyrolysis will only work for part of the waste flows. Notably, for packaging waste and multilayer films it is not the preferred technology.
- Whereas the yield of pyrolysis can be high for pure plastic waste streams, the product is a liquid that needs to be further processed before being used to produce new plastics. The overall cycle efficiency is on the order of 75% at best.
- The economics of chemical recycling are not yet established, and impurities or expensive sorting requirements may make the process uneconomical.

For these reasons, the assumptions of very high (70%) plastic waste recycling rates in some studies may be overly optimistic. In IRENA's Transforming Energy Scenario, a more modest, but still very challenging, recycling rate of 50% is assumed (25% mechanical and 25% chemical/feedstock recycling), with the remainder going to incineration with energy recovery. To achieve higher rates of recycling in the future a mix of advanced sorting technologies, avoidance of complex multilayer materials and a combination of recycling technologies will be needed.

Focus: Renewable power-to-ammonia

With an annual production of 200 Mt per year, ammonia is the second most-produced synthetic inorganic commodity worldwide, and a prominent example of a chemical product with a high dependency on fossil fuels for both energy and feedstocks. With 95% of its hydrogen feedstock derived from fossil fuels, ammonia is responsible for 420 Mt per year of CO_2 emissions, or

1.3% of global emissions (Nayak-Luke, 2018). Ammonia production is energy-intensive, consuming around 2% of the world's energy demand (Kyriakou *et al*., 2020).

Production of green ammonia

Currently, 90% of ammonia (NH_3) is produced via the Haber-Bosch process, which uses elemental nitrogen (N) and hydrogen (H_2) under high pressure and temperatures and is derived mainly from steam-reformed natural gas. This process route has the advantage that it could be fed with green hydrogen produced from biomass gasification or water electrolysis using renewable power (wind, solar, hydropower). Notably, although the Haber-Bosch process has been optimised for mass production, it can operate at 20-30% minimum load if needed, when combined with renewable power sources (Tang and Qiao, 2019).

The renewable power-to-ammonia process opens the possibility of decarbonising ammonia production and enables the use of ammonia as an energy vector to help decarbonise different end-use sectors. A number of innovative ammonia production projects are ongoing (Box 8) to explore the process.

The estimated cost of green ammonia production is USD 500-600 per tonne. This cost is mainly affected by the cost of the green hydrogen and the electricity used and is expected to decrease to the USD 350-400 per tonne range by 2050 (IRENA, 2019d). Current costs for conventionally produced ammonia are on the order of USD 200 per tonne. This cost difference is the major barrier to wider use of ammonia. Efforts to reduce green hydrogen costs, as discussed elsewhere in this report, will be key to reducing the green ammonia cost. Among others, the following factors will also be crucial for successful project development:

- access to renewable power-to-hydrogen supply chains;
- creating an international market for a new exportable energy commodity (*i.e.*, "green ammonia");
- market frameworks recognising the flexibility value provided by electrolysers;
- regulatory frameworks allowing revenue stacking from multiple services, *i.e.*, power grid flexibility, selling ammonia, electricity, etc.; and
- affordable transmission and distribution infrastructure costs.

Applications of green ammonia

The fertiliser industry uses 80-85% of ammonia produced globally[5] (Nayak-Luke, 2018). However, ammonia, and in particular green ammonia, has several potential applications across different sectors. In expanding the use of hydrogen, a key challenge is the transmission, distribution and high-pressure storage of this low-density gas. Compared to hydrogen, green ammonia, which is an energy-dense carbon-free liquid fuel, has several advantages for the decarbonisation of end-use sectors.

Potential applications of green ammonia and ammonia-derived chemicals include:

- **As a synthetic fuel:** ammonia can be used in fuel cells, or combusted in engines and gas turbines[6];
- **As a renewable feedstock**: for the fertiliser industry;
- **As energy storage:** liquid ammonia, at atmospheric pressure cooled to -33 °C, or pressurised at 9 bar at room temperature, can be transported in carbon-steel pipelines, rail cars, trucks and ships;
- **Ammonia-derived chemicals** can provide potential ammonia storage, indirect hydrogen storage or be a source of alternate fuels such as hydrazine, ammonia borane, ammonia carbonate and urea.

5 Ammonia is also used for nitric acid production via the Oswald process and as a refrigerant.

6 The study estimates the efficiency of ammonia used in open- and combined-cycle gas turbines, *i.e.*, cracking of ammonia into its elements in high temperature and combusting the hydrogen at 53%.

BOX 8: INNOVATIVE RENEWABLE POWER-TO-AMMONIA PROJECTS

1. Australia: Yara and Engie partnered to test the renewable power-to-ammonia technology in fertiliser production, with a 2.5 MW solar power plant, investing USD 200 million, aiming to create a bankable prototype for a larger project pipeline in the future. A feasibility study started in 2019 for the design of a 100 MW green hydrogen plant integrated with Yara's existing ammonia* plant in Pilbara, Western Australia (Yara, 2019). According to the project promoters, Pilbara's ammonia tanks can hold 80 000 tonnes of ammonia, which would be the equivalent to renewable hydrogen for 250 000 megawatt-hours of electricity or fuelling 60 000 fuel cell electric vehicles with a driving range of 20 000 kilometres. For every 1 kilogram of green hydrogen, 5.6 kilograms of ammonia would be produced and 5.5 kilograms of CO_2 would be offset (Yara, n.d.).

2. Australia: H2U, a specialist green hydrogen infrastructure company is developing two large-scale P2A projects in South Australia, based on integration of 100% renewable energy through a high-capacity factor (>70%) virtual power plant scheme. The Eyre Peninsula Gateway project was first unveiled in February 2018 as part of an announcement for AU$12.2m (USD 8.9 million) in funding support under the South Australian Government's Renewable Technology Fund. A total of 250 million AUD (USD 182.1 million) is to be invested in the initial demonstration stage, with a capacity of 80 MW of electrolysis and 120 tonnes per day of ammonia. This stage will integrate a 30 MW hydrogen-fired gas turbine plant and produce up to 10,000 tonnes per year of hydrogen and 40,000 tonnes per year of ammonia. Further expansions are expected from late 2025. In February 2020, H2U announced plans for a second export-class green ammonia development in Gladstone, Queensland. Operations are expected to begin in 2025, with a planned capacity of 3 GW of electrolysis and 4,800 tonnes per day of ammonia when completed (Queensland Government, 2020).

3. Denmark: Haldor Topsoe, a technology provider for ammonia plants, is demonstrating efficiency improvements in the renewable power-to-ammonia technology by incorporating waste heat to reduce power consumption (and costs). The company also works on reducing the CAPEX by removing the air separation unit from the Haber-Bosch process. With a budget of DKK 26.8 million (USD 4.3 million), the project is funded by the Danish Energy Agency and run in collaboration with the Danish transmission system operator and Vestas (Brown, 2019).

4. Iceland: The start-up Atmonia plans to build a USD 2 million prototype for an electro-chemical catalyst process for generating aqueous ammonia directly from air and water, using renewable power (Cleantech, 2019).

5. Saudi Arabia: Air Products, ACWA Power and NEOM announced a USD 5 billion investment for the construction of a green ammonia plant, which will be powered by 4 GW of solar, wind and storage. The plant will be able to produce 650 tonnes per day of hydrogen by electrolysis using ThyssenKrupp technology; nitrogen by air separation using Air Products technology; and 1.2 million tonnes per year of green ammonia using Haldor Topsoe technology. The project is scheduled to be operational in 2025 (NEOM, 2020).

6. US: Starfire Energy's power-to-ammonia production process involves hydrogen production by proton exchange membrane electrolyser, nitrogen production by pressure swing adsorption, ammonia synthesis and liquid ammonia storage. It has built a 10 kilogram per day ammonia synthesis system in Colorado using its low-pressure Rapid Ramp ammonia process and had plans to expand the plant to 100 kilograms per day in 2020 (Beach, 2019).

* To decarbonise the entire ammonia sector of 2.5 million tonnes in Australia, 20 GW of electrolysers is needed.

More information on this topic can be found in the following publications and platforms:

IRENA's Technology briefs including on bio-methanol, production of bioethlyene and on renewable-methanol (upcoming) (www.irena.org/publications/2013/Jan/Production-of-Bio-methanol)

IEA Bioenergy Technology Collaboration Programme: Bio-based chemicals (www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf)

European Bioplastics (www.european-bioplastics.org)

Bio-based Industries Joint Undertaking – partnership between the EU and the Bio-based Industries Consortium (www.bbi-europe.eu)

Ammonia Industry Association (https://ammoniaindustry.com)

Ammonia Energy Association (www.ammoniaenergy.org)

Methanol Institute (www.methanol.org/about-methanol)

LeadIT Leadership Group for Industry Transition (www.industrytransition.org)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, with an appendix on plastics (www.energy-transitions.org/mission-possible)

Collaborative Innovation for Low-Carbon Emitting Technologies in the Chemical Industry (www.weforum.org/projects/collaborative-innovation-for-low-carbon-emitting-technologies-in-the-chemical-industry)

2.5 Cement and lime

Key statistics

- Global cement production has grown by a factor of 3.5 between 1990 and 2019, reaching 4.1 Gt in 2019. In 2019, China accounted for 54% of global cement production.

- Cement and lime production accounts for around 2.5 Gt of CO_2 emissions, or just under 7% of total global energy and process-related CO_2 emissions in 2017. This share is expected to remain flat in the coming decades, as other sectors decarbonise more quickly.

- A variety of cement types exist, but the most common is "Portland cement", which is produced by mixing clinker with smaller quantities of other additives such as gypsum and ground limestone. Production of Portland cement releases on average 866 kilograms of CO_2 per tonne of cement produced.

- Clinker production is responsible for the bulk of the sector's emissions, including both energy and process emissions. Around 50-60% of total emissions are directly emitted from the thermal process of heating limestone (calcination) to produce clinker, with the remaining emissions coming from fuel combustion in rotary kilns, and other indirect emissions.

Main decarbonisation options

- No single option in this sector can reduce emissions to near zero. Full decarbonisation will require a consideration of the full life cycle of cement with several strategies pursued in parallel.

- These will include reducing demand for conventional cement (through lower amounts of cement in concrete and the lower use of concrete in construction), eliminating energy emission (through a fuel switch to renewables), reducing process emissions from cement production (through lower amounts of clinker in the cement) and eliminating or offsetting the remaining process emissions (through CCUS and BECCS).

- Several supplementary cementitious materials are being researched that could reduce the amount of clinker needed. These include the use of by-products from other industries, such as blast furnace slag (ironmaking) or fly ash (coal power plants), but their availability is limited and is likely far less than the amounts needed, especially if the processes that supply these materials are phased out over time.

- Several alternative cement formulations are being explored that could reduce the amount of cement needed. Alkali-activated formulations, for example, use materials that can be recycled from other industrial by-products, such as blast furnace slag, fly ash, steel slag (steelmaking) and red mud (aluminium production), among others. However, just as with clinker substitutes, the availability of these materials is limited.

- If wood is used instead of concrete in construction then emissions in materials production will be reduced, carbon can be stored in products, and the cascading of waste wood after use enables further energy savings and emission reductions. The amount of wood needed, however, to replace a significant proportion of concrete use may be prohibitively large.

- To eliminate energy emissions, the above approaches need to use renewable energy sources to replace fossil fuels. Alternate fuels that could be used in cement kilns include biomass but also waste products such as used tyres, municipal solid waste and industrial residues. Renewable electrification of some heat production may have a role.

- The above approaches will reduce emissions but will not in themselves be sufficient to eliminate emissions. CCUS will therefore be needed in the cement sector for some plants. CCS could also be used in combination with bioenergy (BECCS) to produce negative emissions.

- A conceptual strategy for zero emissions therefore could look like:

1. Reduce demand for conventional cement (through a combination of material efficiency, alternative construction techniques, alternative cement types and alternative building materials).

2. Eliminate energy emissions for all cement (through fuel switching to renewables).

3. Reduce process emissions from conventional cement (through reduction in clinker use – *i.e.*, by lowering ratios of clinker-filler and/or the use of alternative binders).

4. For the remaining emissions:

    a. Apply CCS to a proportion of plants.

    b. Offset emissions from the remaining unabated plants through negative emission technologies – for example, BECCS, concrete reabsorption or CO_2 stored in wood used for construction.

Key insights

- The cost of zero-carbon cement production is currently around double that of standard cement.

- Renewable energy sources have been underutilised in the cement sector. Renewables could eliminate the 40% of emissions that are energy related. The remaining process emissions will need to be addressed via material efficiency, material replacement and CCS.

- Reducing overall demand, reducing clinker use and offsetting some process emissions through other in-sector negative-emissions approaches (BECCS, concrete reabsorption, use of wood in construction) will reduce the amount of CCS needed.

- Research into substitutes for clinker and cement is not translating into innovation in operational plants. More development and demonstration projects are needed.

- Scaling up CCUS will be an important component of delivering zero emissions, but it is not a mature technology in this application. Demonstration projects are needed.

- Decarbonising cement will require large-scale investments in technological and operational innovation. Technology and enabling policy frameworks are needed to overcome the economic barriers and prevent carbon leakage.

- Creating early sources of demand for green cement or alternatives (through public procurement, corporate sourcing and minimum percent requirements or maximum emission requirements per construction project) will build scale and reduce costs.

- China's role is currently crucial, and a number of developing countries are likely to grow in significance. Production in those countries must start on the right (zero-carbon-compatible) track. Major developed economies can set an example and assist by showing leadership on projects as well as on demand, regulations, carbon border taxes, etc.

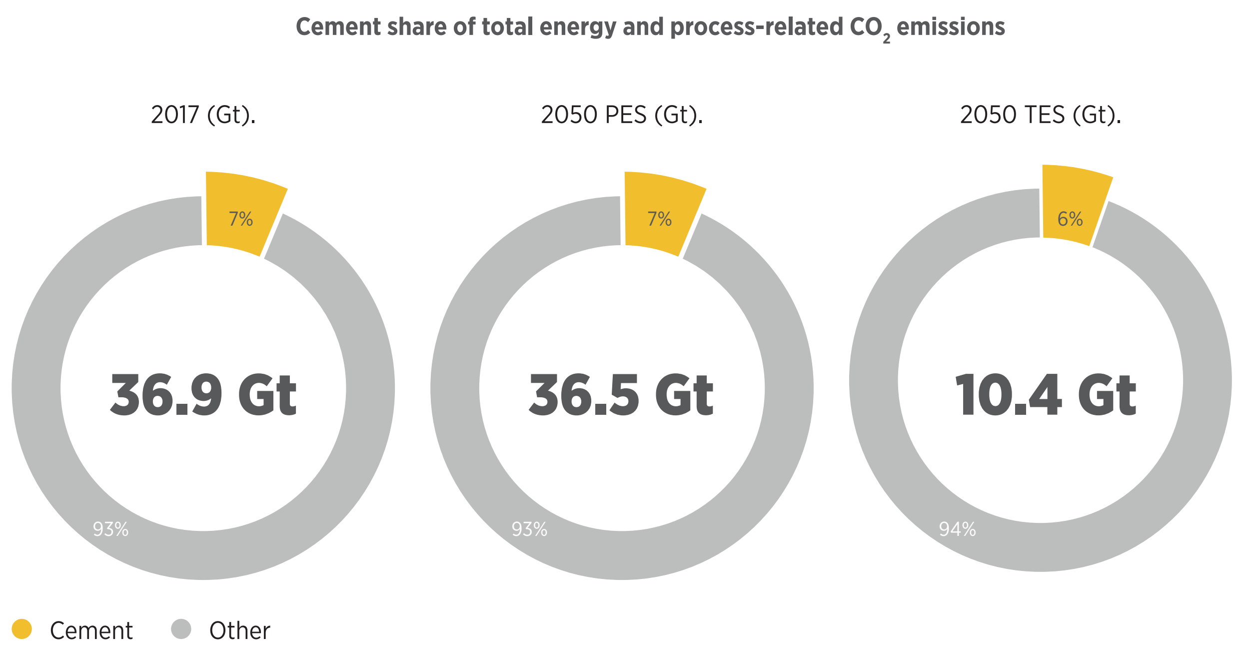
Sector emissions and energy use

Figure 21 shows how cement's share of total energy and process-related CO_2 emissions will need to change over time. In 2017, cement accounted for almost 7% of total energy and process-related CO_2 emissions. With current planned policies and programmes, the share of cement's emissions can be expected to remain largely unchanged by 2050. In the Transforming Energy Scenario, the sector's share of emissions would shrink slightly to 6%, leaving 0.6 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 10 shows how the share of renewable energy in cement's total energy use could increase nearly 10-fold from just 6% in 2017 to 56% in 2050 under the Transforming Energy Scenario – more than double the share in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 5.7 EJ of cement's total demand of 10.3 EJ for energy and feedstock by 2050. This would be sourced mainly from biomass and waste as well as a small amount from renewable electricity.

Delivering zero energy emissions will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 22, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes. Figure 23 shows the estimated range of abatement potential for each measure plotted against estimates of the range of the cost of abatement.

FIGURE 21: Cement and lime's share of total energy and process-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



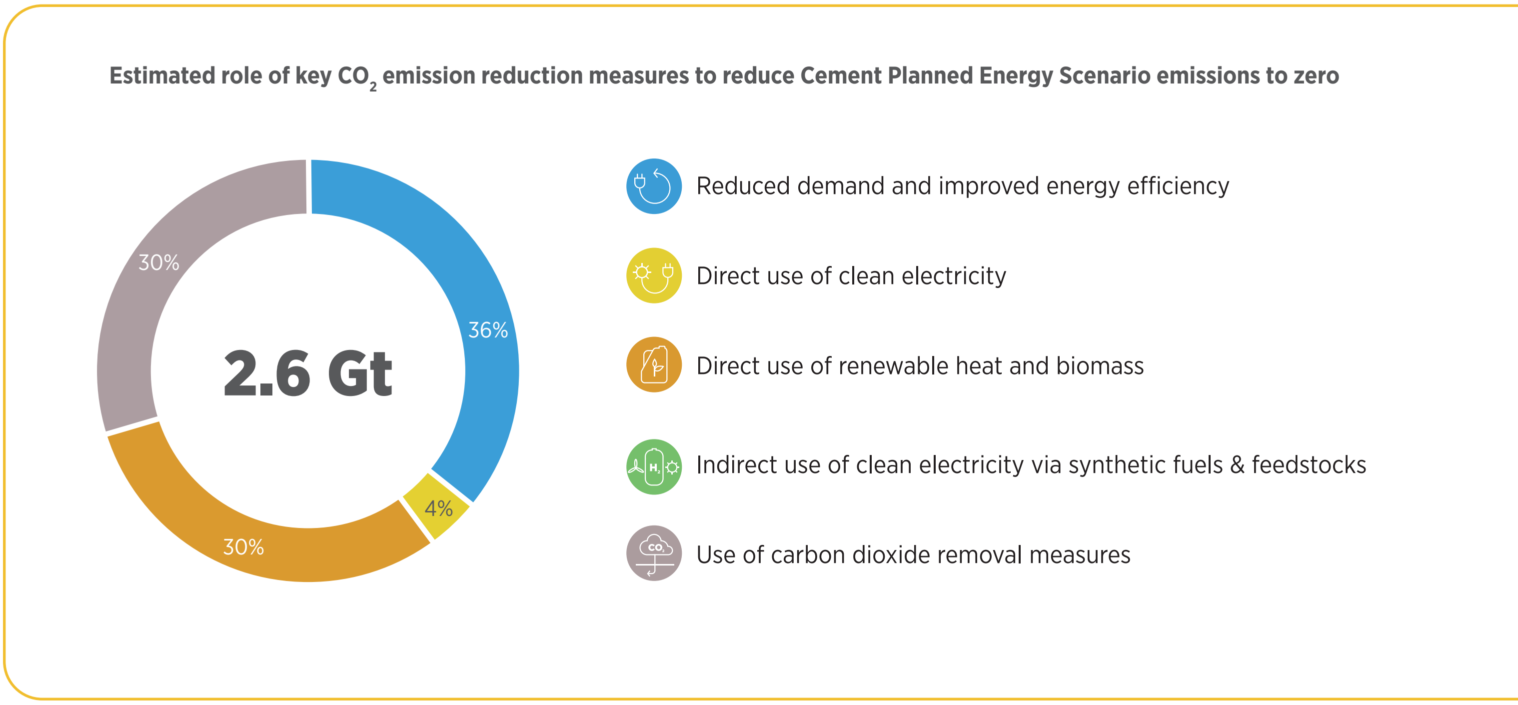
Source: IRENA, 2020a; IEA, 2017

TABLE 10: CEMENT AND LIME SECTOR ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Cement and lime (energy and process)	Energy (EJ/year)	15.6	13.3	10.3	1.9 Gt/yr reduction (75% of 2017 total)	0.6 Gt/yr reduction (25% of 2017 total)
	CO2 emissions (Gt/year)[1]	2.5	2.6	0.6		
	Renewable energy share[2] (%)	6%	20%	56%		

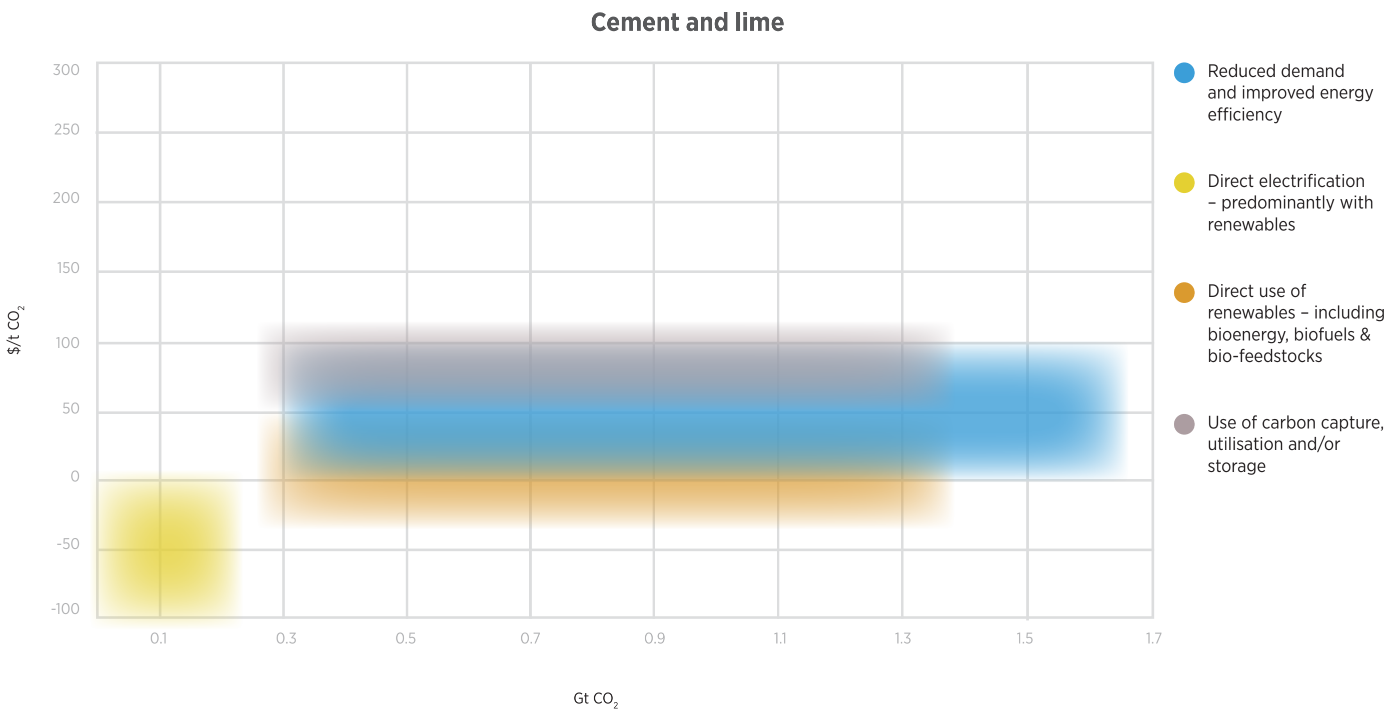
Notes:
1. Emissions include direct energy and process emissions;
2.Including electricity and district heat.
Source: IRENA, 2020a; IEA, 2017

FIGURE 22: Emission reduction measures to reach zero energy emissions in the cement and lime sector. Other measures are needed to address process emissions.



Source: IRENA analysis

FIGURE 23: Estimated abatement potential of measures to reach zero energy emissions in the cement and lime sector plotted against estimates of the cost of abatement



Source: IRENA analysis

Sector overview and the emission reduction challenge

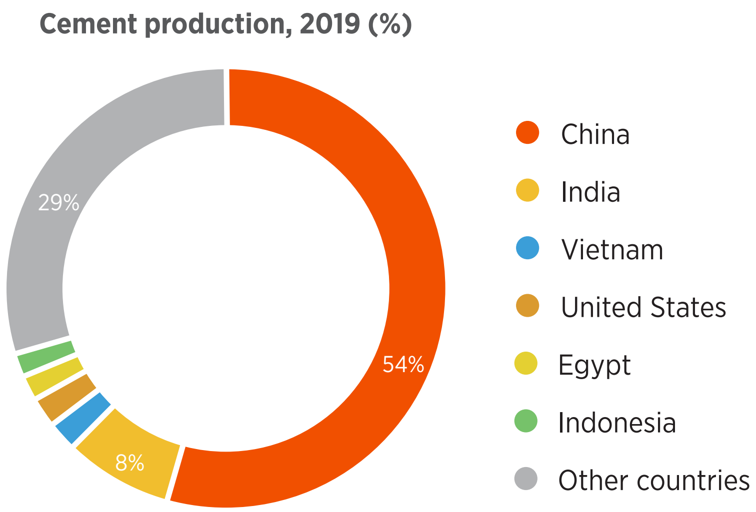
Cement is a fine, soft, powdery-type substance, used mainly to bind fine sand and coarse aggregates together in concrete. Cement is a glue, acting as a hydraulic binder – that is, it hardens when water is added. The vast majority of cement is used for concrete where it is mixed with water, sand and gravel forms.

The cement-making process can be divided into two basic steps:

- Clinker (the main constituent of cement) is first made in a kiln, which heats raw materials such as limestone (calcium carbonate) with small quantities of other materials (e.g., clay) to 1 450 °C. During this process, known as calcination, the calcium carbonate is transformed into calcium oxide (lime), which then reacts with the other constituents from the raw material to form new minerals, collectively called clinker.
- Clinker is then ground with gypsum and other materials to produce the grey powder known as cement. Although various types of cement exist, the most common is called "Portland cement", which is produced by mixing clinker with smaller quantities of other additives such as gypsum and ground limestone (CEMBUREAU, 2020).

Global cement production has grown from 1.2 Gt in 1990 to 4.1 Gt in 2019. A large part of that production expansion has taken place in China, which produced over half of global cement in 2019 (Figure 24), amounting to 2.2 Gt. By 2030, Chinese production is projected to decline to 1.6 Gt of cement and 0.8 Gt of clinker, with a further decline to 1 Gt of cement by 2050 (CNREC, 2016). However, global production is projected to grow strongly in other emerging economies leading to an overall increase in global cement production to 4.8 Gt by 2030 (CemWeek, 2016) and to 5.9 Gt by 2050.

FIGURE 24: Share of global estimated cement production, 2019 (%)



Source: IRENA, based on USGS, 2020

Total sectoral emissions have two main sources:

- process CO_2 released by the calcination of carbonate minerals (limestones) in the kiln feed; and
- energy-derived CO_2 released by combustion of the fuels used to heat the kiln feed.

Reducing CO_2 emissions in the cement sector is particularly challenging due to high process emissions related to the production of clinker.

Cement production releases on average an estimated 866 kilograms of CO_2 per tonne of cement produced (Farfan *et al*., 2019). The manufacture of clinker is responsible for the bulk of those CO_2 emissions. Around 50-60% of CO_2 emissions are directly emitted from calcination (*i.e.*, decarbonation of limestone), which is the thermal process of heating limestone. The remaining emissions come from fuel combustion in rotary kilns, and other indirect emissions, such as electricity production for grinding, quarrying and transport (Bataille, 2019; Naqi and Jang, 2019).

The impact of cement emissions may be mitigated to some degree since Portland cement-based concretes absorb atmospheric CO_2 in service. The rate of this carbonation is challenging to determine since it is dependent on factors such as the porosity of the concrete and the cross section of the concrete members, as well as the exposure conditions. The impact of that absorption on net sectoral emissions is not yet well quantified or understood. It might be significant enough to reduce the scale of the challenge but alone will not remove the need for other options to be pursued.

Options for reaching zero

As with other sectors the starting point should be to reduce demand as far as possible. Doing so will require a consideration of the full life cycle with several strategies pursued in parallel.

Various strategies can assist including taking new approaches to design, using higher-quality concretes, substituting concrete for other materials, improving the efficiency with which it is used, and increasing reuse and recycle rates. Making progress on this front will, however, be dependent on actions by a wide range of actors beyond the cement sector (Chatham House, 2018).

Actions to reduce overall demand for cement are important and can minimise the scale of the challenge, but ensuring near-zero emissions from the remaining cement plants will require a combination of options, which can be grouped under six headings as discussed below. Unlike in some other sectors discussed in this report these options are not interchangeable. Any given cement production facility will likely need to apply several of these options in parallel. All of the options listed involve the energy used in production to be sourced from renewables rather than from fossil fuels.

A conceptual strategy for combining these approaches to deliver zero emissions could look like Figure 25.

FIGURE 25: Strategy for reaching zero in the cement sector

1. Reduce demand for conventional cement (through a combination of material efficiency, alternative construction techniques, alternative cement types and alternative building materials).

2. Eliminate energy emissions for all cement (through fuel switching to renewables).

3. Reduce process emissions from conventional cement (through reduction in clinker use, i.e., by lowering ratios of clinker-filler and/or the use of alternative binders).

4. For the remaining emissions:

   Apply CCS to a proportion of plants.

   Offset emissions from the remaining unabated plants through negative emission technologies – for example, BECCS, concrete reabsorption or CO_2 stored in wood used for construction.

REACHING ZERO – OPTION 1: Fuel switch to renewables

For the around 40-50% of CO_2 emissions that are related to energy supply, the use of renewable energy and alternative fuels can reduce or eliminate emissions.

Alternative fuels that can also help reduce the dominance of coal in cement kilns include a wide variety of waste products including: waste oil and other fossil-based waste, tyres, plastics, animal meat and bone meal, wood and saw dust, dried sewage sludge, paper and others. Increasing the share of biomass or waste fuels used in kilns looks promising; however, more research and analysis of options and more pilot deployments are needed. Kilns have already been operated with 100% alternative fuels, demonstrating the technical and economic feasibility of such substitution; however, the availability of alternative fuels remains a key constraint.

The complex nature of cement production means that switching to alternative fuels is not necessarily a simple process (Box 9). There are different requirements for alternative fuels dependent on the location of firing in the cement plant, mainly related to particle size, moisture content and heating value (Nørskov, 2012). Introducing alternative fuels in kilns may influence the cement production depending on parameters such as clinker quality, emissions, process stability and energy efficiency. For example, solid alternative fuels often have much larger particle sizes than conventional fuels. The larger particles may influence the flame shape and temperature and increase the risk of fuel spillage. Continued combustion in the clinker bed may lead to local reducing conditions with possible effects on clinker quality and increased sulphur evaporation causing material build-ups in the pyrosystem. The moisture, ash and volatile content of the alternative fuels may also influence the flame profile and heat transfer to the clinker.

Alternative fuel use is growing rapidly. The Cement Sustainability Initiative (CSI), a global effort by 24 major cement producers in over 100 countries, has been pursing efforts to increase the use of alternate fuels since the early 2000s. The initiative also established the Getting the Numbers Right (GNR) database that documents the extent of alternative fuel use in the sector (GCCA, 2019). According to that data the use of alternative fuels increased 880% between 1990 and 2017 such that 17.5% of the fuel in 2017 was provided by alternative sources (biomass at 20% and waste at 80%).

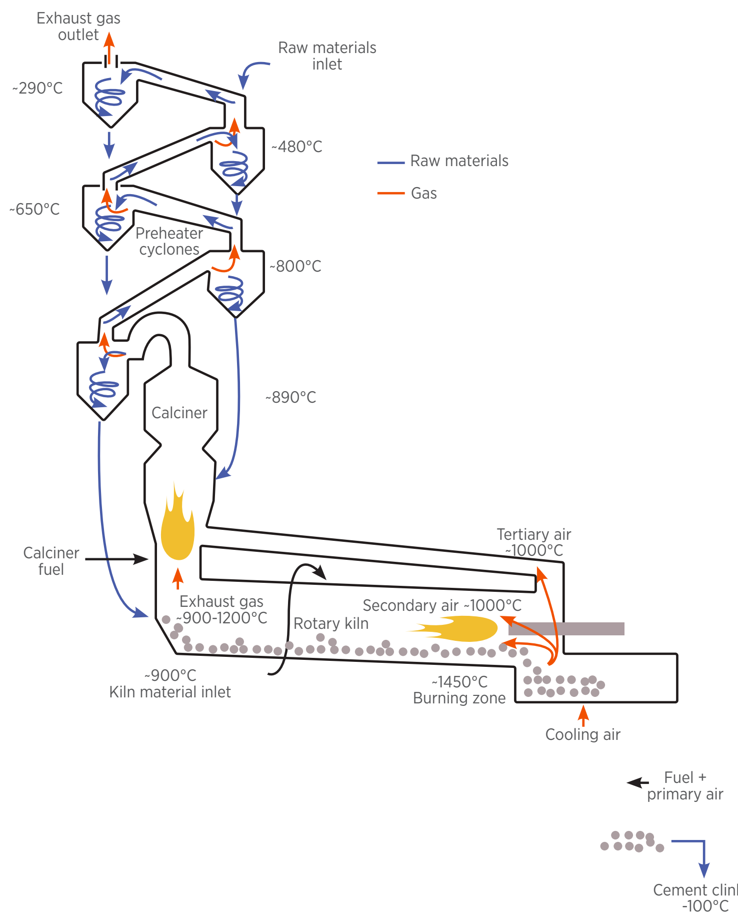
Across the large cement-producing groups the highest shares of wood and agricultural waste fuels recorded are 30-40% (IFC, 2017). In the Philippines, for example, Lafarge has achieved substitution rates of more than 30% using only rice husk. In the German cement industry, the proportion of alternative fuels (including used tyres, waste oil, pieces of commercial and residential waste as well as scrap wood and solvents) in the total thermal energy consumption increased six-fold from 1987 to 2000, and then more than doubled between 2000 and 2018. The proportion was around 68% in 2018 (VDZ, 2020a). 100% substitution is possible and has, for example, been recorded in a plant utilising liquid waste in its main burner (Zieiri and Ismail, 2019).

The electrical energy consumed in cement production is around 110 kilowatt-hours (kWh) per tonne, and around 40% of this energy is consumed for clinker grinding (VDZ, 2020b; Jankovic and Valery, 2004). There is potential to optimise conventional cement clinker grinding circuits, and in the last decade significant progress has been achieved. The increasing demand for "finer cement" products, and the need for reduction in energy consumption and greenhouse gas emissions, reinforces the need for grinding optimisation and the use of renewable electricity (Jankovic and Valery, 2004). Globally, the energy intensities of thermal energy and electricity have continued to decline gradually as dry-process kilns – including staged preheaters and precalciners (considered state-of-the-art technology) – replace wet-process kilns, and as more efficient grinding equipment is deployed (IEA, 2020).

BOX 9: FUEL FIRING IN CEMENT PRODUCTION

In cement production, two traditional positions for fuel firing exist: the calciner (around 60% of the overall thermal energy input to the pyrosystem) and the rotary kiln burner (40%). Alternative fuel firing may at some cement plants also take place at the rotary kiln material inlet end or at a mid-kiln position and/or in a separate combustion unit where large solid fuels can be injected substituting a fraction of the calciner firing (*e.g.*, complete waste tyres).

FIGURE 26: Schematic of an example cement kiln



Source: Nørskov, 2012

The temperature in the calciner is typically 850-900 °C, and the thermal energy is provided by fuel combustion in the calciner. The partly calcined raw meal with a typical calcination degree of 90-95% enters the rotary kiln where it is further heated and partly melts as it travels through the kiln while forming agglomerates of clinker nodules. The clinkers reach a maximum temperature of around 1 450 °C to 1 500 °C before entering the cooler, where they are rapidly cooled with air. The thermal energy in the rotary kiln is provided by a burner positioned in the rotary kiln at the material outlet.

In Germany, for example, electricity consumption in cement works in 2018 made up over 10% of the total energy consumption. In total, the German cement industry used 96.0 million gigajoules (GJ) of fuel in 2018, while electricity consumption was 3.78 TWh (VDZ, 2020b). Switching to renewable sources of electricity for cement production would cut 10% off of the total energy-related cement CO_2 emissions in the case of Germany.

REACHING ZERO – OPTION 2: Clinker substitutes

Reducing clinker use in cement production will minimise, but not eliminate, process emissions. The amount of clinker used varies by cement type, reaching as high as 95%, with variations in clinker content having an impact on the type of applications for which the cement can be used. Standards differ by country and region, and different cement types are favoured in different locations. In Europe, for example, cement is manufactured according to the harmonised European Standard EN 197-1, which lists 27 common cements with theoretical clinker content ranging between 5% and 95%.

In 2018, the average clinker-to-cement ratio over all cement types in the EU-27 was 73.7% (CEMBUREAU, 2018). In China, the ratio is closer to 64% on average, and globally the average clinker-to-cement ratio is around 70% (IEA, 2020).

The extent to which the clinker-to-cement ratio can be reduced will depend on the future availability of suitable clinker substitutes. IRENA's Transforming Energy Scenario expects the clinker-to-cement ratio to fall to 0.64 by 2050 (as opposed to 0.75 for the 2015-2050 period in the Planned Energy Scenario) due to the deployment of clinker substitutes (IRENA, 2017b).

Conventional clinker can be partially substituted for by alternative materials with similar properties. A variety of substitutes, called supplementary cementitious materials (SCMs), are being investigated, including both natural SCMs (either naturally occurring or artificial blending materials) and industrial SCMs, such as blast furnace slag (a by-product from ironmaking) and coal fly ash (from burning coal in power plants). However, the availability of these substitutes is limited. Around 330 Mt of blast furnace slag and 900 Mt of coal fly ash are available every year, and supply will likely decrease as coal power plants are phased out and as the DRI-EAF route expands as the prime means to manufacture iron and steel (see also section 2.3 on iron and steel).

Among the potential alternatives are red mud and calcinated clays. Clays, which are made up of silicon and aluminium oxides, are more widely available than coal fly ash and blast furnace slag (Naqi and Jang, 2019). Red mud is a waste residue from alumina production that is difficult to dispose of safely. Using red mud in cement production could be an efficient method for large-scale recycling of red mud while also reducing clinker emissions. Red mud can in principle also be used in the production of composite cements as well as alkali-activated cements (see Option 3) (Liu and Zhang, 2011).

REACHING ZERO – OPTION 3: Alternative cement formulations

Various alternate cement formulations are being explored as potential replacements for Portland cement (Naqi and Jang, 2019), but most have not yet been tested at any significant scale. One group among the formulations being looked at is alkali-activated cements[7], which use as prime materials blast furnace slag, steel slag, metakaolin, fly ash, kaolinitic clays and red mud, and on paper could compete with

7 Although a precise definition is lacking in the literature, these are sometimes known as geopolymer cements.

conventional Portland cement on emissions, costs and performance, and durability. An attraction is that they could recycle millions of tonnes of industrial by-products (*e.g.*, red mud from aluminium production). Among the various types, alkali-activated fly ash cement and alkali-activated metakaolin cement are being considered in particular.

The production cost of cement substitutes depends on the raw material used, the source location, the energy source and transport, and the availability of by-products from other industries. Some of these materials are already mixed into cement today because of their pozzolanic (*i.e.*, binding) properties, so processing them separately has limited benefits. One option that has an interesting potential is the use of red mud, a by-product of alumina production (around 2 tonnes is produced per tonne of alumina) (Naqi and Jang, 2019). Given global primary aluminium production of 64 Mt in 2017, around 132 Mt of red mud would in theory be available, equivalent to 3% of global cement production.

The various types of alternative cements could theoretically reduce CO_2 emissions by 20-100%, but their properties and feedstock requirements limit their practical use in a high CO_2 reduction scenario. To eliminate energy emissions the energy input to these processes would also need to be switched to renewables (see Option 1).

REACHING ZERO – OPTION 4: Alternative building materials and approaches

The building and construction sector is very materials intensive. Interesting opportunities exist to substitute materials and reduce CO_2 emissions. In principle the use of alternative building materials could shift some demand away from cement.

Low-cement concretes can be designed using superplasticiser and limestone filler, thereby greatly reducing CO_2 emissions in structural concretes. A significant reduction in Portland cement demand could in theory be achieved by using high-performance superplasticiser, high-strength cement and optimised particle-size distribution (Proske *et al.*, 2013). However, new concrete formulations must be subject to strict and long testing procedures before they are approved. The most potential seems to be in concrete types that have been approved for challenging environments such as high-rise buildings and bridges. Cost reduction through learning-by-doing and upscaling could lead to the use of these in less-demanding environments.

If wood is used instead of concrete, several effects occur: emissions in materials production are reduced, carbon can be stored in products, and cascading of waste wood after use enables further energy savings and emission reductions. To date, cross-laminated timber has attracted the most attention. Made by gluing wooden panels and boards together, cross-laminated timber is an adequately fire-resistant building material that can reach large dimensions. Its application has recently increased and includes projects in Canada, Japan and Sweden.

The emission reduction impact of wood replacing concrete would be amplified, since even more CO_2 is captured than avoided by reducing the cement production. Assuming a 10% replacement of concrete – and considering that the CO_2 captured in the wood has been abated – would reduce the overall cement footprint by 25%. However, the resource requirements are prohibitively large: the annual net increment required would be around 700 million cubic metres, or about 80% of the recognised supply of forest in Russia (Czigler *et al.*, 2020).

The extent to which wood can replace other construction materials varies. In the US context wood frame buildings have traditionally been widely deployed for single-family residences, and the US is also leading a trend for more wood use in high-rise buildings. The US is moving in this direction for buildings up to seven floors high in places where the codes have been relaxed (Fox, 2019). Materials such as cross-laminated timber enable even the use of wood for high-rise buildings in excess of 10 floors. However, materials supply and building standards remain barriers to rapid expansion.

REACHING ZERO – OPTION 5:
CCS for process emissions and for energy emissions

The high process emissions from clinker production will be difficult to fully eliminate by the use of cement or clinker substitutes. Applying CCUS technologies to at least some cement production is very likely needed. How much CCS is needed will depend on actions taken in material replacement and on how much can be offset by in-sector negative emissions – for example, BECCS, concrete reabsorption and CO_2 stored in wood construction materials.

Progress in the demonstration of CCS plants in general has been relatively slow to date, and costs remain high. Various studies have looked at the technology options and cost of CCS for cement kilns (Leeson *et al.*, 2017). At present, costs for full CCS are estimated to add around 70-90% to the existing price of cement. However, work on industrial carbon capture lags significantly behind that in the power sector, and much greater levels of uncertainty exist with regard to the costs of industrial CCS relative to that in the power sector.

Cement production poses particular challenges for CCS since, ideally, both energy and process emissions should be captured. The dusty nature of cement process gases also poses a big challenge to CCS. The main CCS technologies being investigated for cement plants are:

- Solvent scrubbing: A solvent scrubs CO_2 from the exhaust of the cement plant. This solvent is then regenerated after passing to a second reactor by steam from (in general) a combined heat and power (CHP) system. CHP is necessary because insufficient low-grade heat is present on the cement works to regenerate the solvent, and because direct heating using, for example, natural gas, is very inefficient.

- Calcium looping: Calcium oxide (produced from limestone) reacts with CO_2 in the exhaust gases. The calcium carbonate formed is then transferred to a second reactor (normally, both reactors are circulating fluidised beds) where the reaction is reversed by burning a fuel, usually with pure oxygen (and recycled CO_2). This reactor is also where the initial limestone feed is decarbonised. The result is a pure stream of CO_2. The reaction of CO_2 with calcium oxide is highly exothermic so heat can be removed from the carbonator and used efficiently in a steam cycle to raise power. This process has significant synergy with cement production, since the CO_2 sorbent is the main feedstock for cement production, allowing a high purge rate of exhausted material.

- Oxyfuel (full or partial): The cement kiln and the precalciner are both fired with a mixture of fuel and oxygen, rather than air. This means that pure CO_2 (and water) are produced. The system requires an air separation unit, which accounts for the majority of the electricity use (the main energy cost of this system). It has the potential to be highly efficient because the nitrogen in air is essentially being heated up in the kiln for no purpose, so that reducing the volume of gas can improve the efficiency of the process. Issues lie in sealing the (rotating) kiln against air ingress, which reduces the CO_2 percentage in the exhaust and results in potentially mild changes in the chemistry in the kiln. Since sealing the kiln is challenging, an alternative is to only oxyfuel the precalciner. Kiln CO_2 emissions would then not be captured, but 60% overall capture is possible, and at a relatively low cost.

Currently no large-scale operational cement facilities are equipped with CCS technologies. However, one large-scale demonstration project in Norway is planned to start operation in 2024. Around 400 kilotonnes of CO_2 per year are expected to be captured from the Brevik cement plant located in Telemark operated by Germany-based HeidelbergCement's subsidiary Norcem. The captured CO_2 should be transported to a multi-user storage site in the Norwegian Sea (Global CCS Institute, 2019a). The project will also co-fire the plant with up to 30% biomass (see Option 6). The total cost (investment and operating costs for five years) of the Norcem plant, which is due for final funding approval in 2020 or 2021, is estimated at USD 1 billion. Capital costs alone amount to USD 2 500 per tonne of CO_2 for this demonstration project. The project is part of a wider portfolio of CCS projects being developed in Norway, including the Northern Lights project and a waste-to-energy plant.

Some more innovative approaches are being explored. A recent EU-funded pilot lead by Calix, the LEILAC (Low Emissions Intensity Lime And Cement) project in Belgium, demonstrated that direct separation – that is, removing CO_2 from limestone during the heating process – could capture more than 95% of CO_2 process emissions (Project LEILAC, 2020; Hodgson *et al.*, 2019). This is taking place at another HeidelbergCement facility, with a capacity of 88 kilotonnes of CO_2 per year (Hill *et al.*, 2017; Edwards, 2019). The project has a budget of USD 23 million for a five-year period (around USD 55 per tonne of CO_2 capital cost only, excluding pressurisation, transport and storage cost). The CO_2 is released into the atmosphere. This direct separation process, however, would not reduce fuel emissions, meaning that only process emissions can be captured (Hill *et al.*, 2017).

As with many other options considered in this report, cost remains a major barrier. Table 11 compares the costs of different CCS technologies as found in a literature survey. None of these technologies are expected to fully capture all CO_2 emissions. Given that a modern, state-of-the-art cement plant costs on the order of USD 325 million, the addition of CCS to any system will end up greatly increasing the cost of the process (all costs for non-retrofit systems include the cost of the original cement plant). It is notable that membrane systems have been stated as having extremely low capital and operating costs (CAPEX and OPEX) by some authors, although others disagree. Very approximately, a doubling in price of cement would be necessary to account for the additional costs.

TABLE 11: COST ESTIMATES OF DIFFERENT CARBON CAPTURE TECHNOLOGIES

Author	Year	Technology	Retrofit?	Proportion of CO_2 avoided	CAPEX	OPEX		
						fixed	var	total
					USD per (Mt clinker per yr)			
ECRA	2017	Oxyfuel full	no	0.8	424	28	35	63
IEA	2013	MEA (NGCC)	yes	0.75	269	33	38	71
IEA	2013	MEA (NGCC)	no	0.75	482	33	38	71
IEA	2013	Oxyfuel full	yes	0.9	113	28	43	71
IEA	2013	Oxyfuel full	no	0.9	318	28	43	70
IEA	2013	Oxyfuel partial	yes	0.65	93	26	42	70
IEA	2013	Oxyfuel partial	no	0.65	301	26	41	67
Nwaoha	2018	MEA	yes	0.87	104	5	30	35
Nwaoha	2018	Advanced Amine (AMP-PZ-MEA)	yes	0.87	91	5	24	29
Cormos	2017	Advanced Amine (MDEA)	no	0.82	674	39	43	81
Cormos	2017	Calcium Looping	no	0.84	554	34	35	68

Note: CAPEX = capital expenditure, OPEX = operational expenditure, NGCC = natural gas combined cycle, MEA = monoethanol amine , MDEA = methyl diethanolamine.
Source: Cormos and Cormos, 2017; ECRA, 2017; IEA, ECRA, IEAGHG, 2013; Nwaoha et al., 2018

REACHING ZERO – OPTION 6: Biomass firing with CCUS

Switching to sustainably sourced biomass to supply the heat for cement kilns, and applying CCUS to that biomass-firing process (via bioenergy with carbon capture and storage/utilisation, BECCS/U) could in principle result in negative emissions. Those negative emissions could offset emissions from clinker production resulting in a net-zero or near-zero emissions process.

BECCS/U application in the cement industry is still mostly at the research stage. As discussed in Option 5 one large-scale demonstration project in Norway is planned to start operation in 2024 using post-combustion carbon capture technology and up to 30% of biomass co-firing.

Modelling studies can, however, provide some insights into the potential of CCS in combination with bioenergy use. Four different types of biomass – rice husk pellets, wood pellets, sewage sludge and municipal solid waste – were chosen to substitute 30% of the coal (on a mass basis) in a model of a European cement plant (Sanmugasekar and Arvind, 2019). With an emphasis on retrofitting, three CO_2 capture technologies – absorption using monoethanol amine (MEA), calcium looping (CaL)-based capture and oxyfuel combustion capture – were chosen for a comparative study.

The BECCS technologies studied have a lower rate of cement production as a result of co-firing biomass in existing boilers (-7% to -22%, with no modifications to the capacity of the furnace). This can be attributed to the reduced thermal energy supplied due to the low calorific value of biomass. Of the three CO_2 capture technologies, oxyfuel combustion capture is the least energy-consuming option (1.8 GJ per tonne of CO_2, with wood pellets), and the most energy use occurs in the case of MEA (8.6 GJ per tonne of CO_2, with municipal solid waste). The cement production costs increase by 42% to 89% compared to the costs without CO_2 capture. The cost of CO_2 avoided is between USD 52 per tonne of CO_2 (wood pellets with oxyfuel) to a higher range of USD 116 per tonne of CO_2 (sewage sludge with MEA). The variation in costs is significantly affected by the type of biomass used.

Calcium looping technology has a moderate performance in energy consumption and costs. The energy use for the CaL process is in the range of 4.1 GJ to 4.4 GJ per tonne of CO_2, and the cost of CO_2 avoided is in the range of USD 65 to USD 84 per tonne of CO_2. CaL also entails the highest CO_2 capture rates, in comparison with MEA and oxyfuel technologies. When the CO_2 removed from the atmosphere through the growth of biomass is included, the net CO_2 emissions are the least for CaL capture technology. Theoretically, a net negative value of CO_2 emissions is attainable in the case of CaL CCS in CO_2 combination with 30% bioenergy use (Sanmugasekar and Arvind, 2019). In contrast MEA capture only halves emissions, and oxyfuel is in between. However, MEA is currently the most likely retrofit option since there is no experience with oxyfuel or chemical looping for a commercial-scale cement plant.

The useful take-away from this study is that rates of alternative fuel use above 30% in combination with CCS would enable cement kilns to operate with negative emissions.

BOX 10: LIME PRODUCTION

Lime (calcium oxide, CaO) is produced by heating calcium carbonate ($CaCO_3$) from limestone or dolomite in small-scale vertical kilns or large-scale rotary kilns up to 900 °C, which releases CO_2. This process is carbon intensive because of both the energy-related emissions and the CO_2 released from the raw materials.

Lime is a versatile material, used for a wide range of products, with key applications in the iron and steel, pulp and paper, chemicals, agriculture and construction industries, including cement and asphalt production. Lime also plays an important role in the treatment of flue gases, the purification of water and the enhancement of soil stability, which is why decarbonisation of this sector is important for other downstream industries (Ecofys, 2014).

With an estimated total global production of lime of 430 million metric tonnes in 2019, the three leading producers were China, followed by the US and India, with annual production of 300 million metric tonnes, 18 million metric tonnes and 16 million metric tonnes, respectively (Statista, 2020).

To reduce CO_2 emissions from lime production, several options exist. For one-third of the emissions, which are energy related, fuel switching to renewable sources such as biomass would be an option. Energy efficiency measures would also provide some further emission reduction potential – for example, using vertical lime kilns to replace the more energy-intensive horizontal kilns, although this would be capital expensive.

For the remaining two-thirds of the emissions, CCUS technologies are indispensable in a close-to-zero emissions scenario. However, given the techno-economic challenges related to CCUS technologies and the lack of R&D for lime production, more public and private efforts are required.

Competitiveness of the lime industry is a concern if carbon pricing is applied in only some locations. In the EU, each carbon price increase of EUR 1 per tonne of CO_2 translates into an estimated additional EUR 1.1 per tonne of lime production cost, for a total average cost that lies between EUR 55 and EUR 70 (between USD 65 and USD 82) per tonne of lime.

BOX 11: ENERGY USE AND CO_2 EMISSION PROJECTIONS FOR THE CEMENT INDUSTRY IN CHINA

In 2019, an estimated 54% of global cement production took place in China, which is why action to decarbonise this industry in China would have a major impact on CO2 emissions from cement at the global level.

China's top 10 cement producers accounted for 56.7% of Chinese clinker capacity as of 2017, with the largest cement producers being China National Building Material (CNBM) with total cement and clinker capacity reaching 525 Mt annually, followed by Conch Cement, which aims to achieve a total cement capacity of 400 Mt annually by 2022 driven by mergers and acquisitions, as well as overseas projects. Both firms control 65% of clinker production capacity in 10 Chinese provinces, which highlights that corporate action by these actors to reduce CO2 could have important benefits at a global level.

Wei et al. (2019a) have assessed China's cement demand forecasts for 2030 which varies from 1 Gt to 2.5 Gt per year depending on the scenario. During this period, cement consumption in railway, highway and rural infrastructure is expected to increase initially but decrease thereafter, whereas cement consumption in buildings remains stable at first and then begins to decrease as we move towards 2050. Wei et al. (2019b) have also developed cement CO2 emissions projections based on business-as-usual (BAU) and best practice (BP) scenarios. Both the BAU and the BP scenarios consider technological innovations, such as the saturation of NSP (new suspension preheater) kilns, the equipping of NSP kilns with waste heat recovery technology or the implementation of more efficient grinding technology, which would improve overall energy efficiency. The BP scenario also includes the use of alternative raw materials (ARMs) and alternatives for fossil fuels (AFFs). Depending on the scenario analysis, China's cement-related CO2 emission factors in 2030 could be reduced by 59-69% compared to 2005.

Wang et al. (2014) have assessed emission reduction potentials for 2050 under different scenarios and found that in the cement sector, alternative fuels and especially CCUS constitute the main opportunities to reduce emissions, whereas the potential for additional clinker substitution is limited. The assumptions for alternative fuels and clinker substitution are similar to those in Wei et al. (2019a) – that is, the reduction of cement production by up to 50% in combination with CCUS technologies makes the key difference and could potentially lead to a scenario of close-to-zero emissions by 2050.

More information on this topic can be found in the following publications and platforms:

Global industrial carbon de emissions mitigation: Investigation of the role of renewable energy and other technologies until 2060 (https://payneinstitute.mines.edu/global-industrial-carbon-dioxide-emissions-mitigation-investigation-of-the-role-of-renewable-energy-and-other-technologies-until-2060)

European Cement Association studies (https://cembureau.eu/library)

LeadIT Leadership Group for Industry Transition (www.industrytransition.org)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, with an appendix on cement (www.energy-transitions.org/mission-possible)

Global Cement and Concrete Association (https://gccassociation.org)

2.6 Aluminium

Key statistics

- In 2017, this sector accounted for more than 863 TWh of electricity consumption and 1.2 EJ of fossil fuels to produce alumina feedstock, for primary aluminium production and for aluminium recycling. While recycling is relatively energy efficient, primary aluminium production is 20 times more energy intensive.
- Primary aluminium is produced using the bauxite calcination method for alumina production (i.e., the Bayer process) and the aluminium smelting method (i.e., Hall-Héroult processes) in two sequential steps. In total, 4-7 tonnes of bauxite are used to produce 2 tonnes of alumina, which then yields 1 tonne of aluminium.
- Direct emissions from aluminium production accounts for around 1% of global energy and process CO2 emissions with demand for aluminium projected to rise 44% by 2050, with potential associated rise in emissions to over 3%.
- Indirect emissions, related to the production of electricity, account for over 90% of current total CO_2 emissions from aluminium production. The remaining 10% are direct process emissions.
- Two-thirds of those direct CO_2 emissions from the aluminium production processes are related to the use of carbon anodes in the Hall-Héroult process.
- The level of indirect CO_2 emissions depends largely on the CO_2 intensity of the electricity production, which can range from zero for renewable energy sources to 15 tonnes of CO_2 per tonne of aluminium produced with electricity generated from coal.

Main decarbonisation options

- Decarbonising aluminium production requires decarbonising the energy used in the alumina and aluminium production stages by switching to renewable sources; and eliminating the use of carbon anodes. Options to eliminate the use of carbon anodes are not full developed or proven.
- A variety of renewable energy sources could provide the heat needed in the various stages of alumina production, such as using heat pumps and solar water heaters in the first stage and heat from biomass, geothermal or concentrating solar power (CSP) in later stages.
- The electricity needed for aluminium production could be sourced from dedicated renewable power production or from power grids with high renewable shares.
- Switching electricity supply to renewable energy sources has an additional benefit for the power sector. Aluminium smelters, with slight modifications to current designs, can provide demand-side flexibility that can facilitate the integration of variable renewable energy (VRE) sources like solar and wind into power systems.

Key insights

- There is currently no zero-carbon solution that is mature enough to be deployed at a large scale in this sector.
- Public and private sector efforts should be directed towards the accelerated adoption of renewable power and the development, piloting and commercial use of inert anodes.

- There is potential for aluminium smelters to provide demand-side flexibility which can support the integration of VRE into power systems. Exploiting that will require changes in the operations and business models of smelter operators.
- Closer collaboration between aluminium and power industries is needed to ensure that plans are compatible, particularly around flexibility in demand to help manage VRE.
- China and Germany are conducting pilots to unlock the demand-side flexibility potential of aluminium smelters for the integration of VRE into power systems. As some of these technologies are proven, wide deployment at commercial scale should be incentivised.
- RD&D efforts on inert anodes and demonstration projects are critical.
- If promising designs emerge then measures to create demand, show leadership and implement supportive regulations will become key.
- In the interim creating early sources of demand for aluminium produced using renewable energy will help reduce emissions (but will not eliminate them). Public and private sector efforts should be directed towards the accelerated adoption of renewable power and the development, piloting and commercial use of inert anodes.
- China and Germany are conducting pilots to unlock the demand-side flexibility potential of aluminium smelters for the integration of VRE into power systems. As some of these technologies are proven, wide deployment at commercial scale should be incentivised.

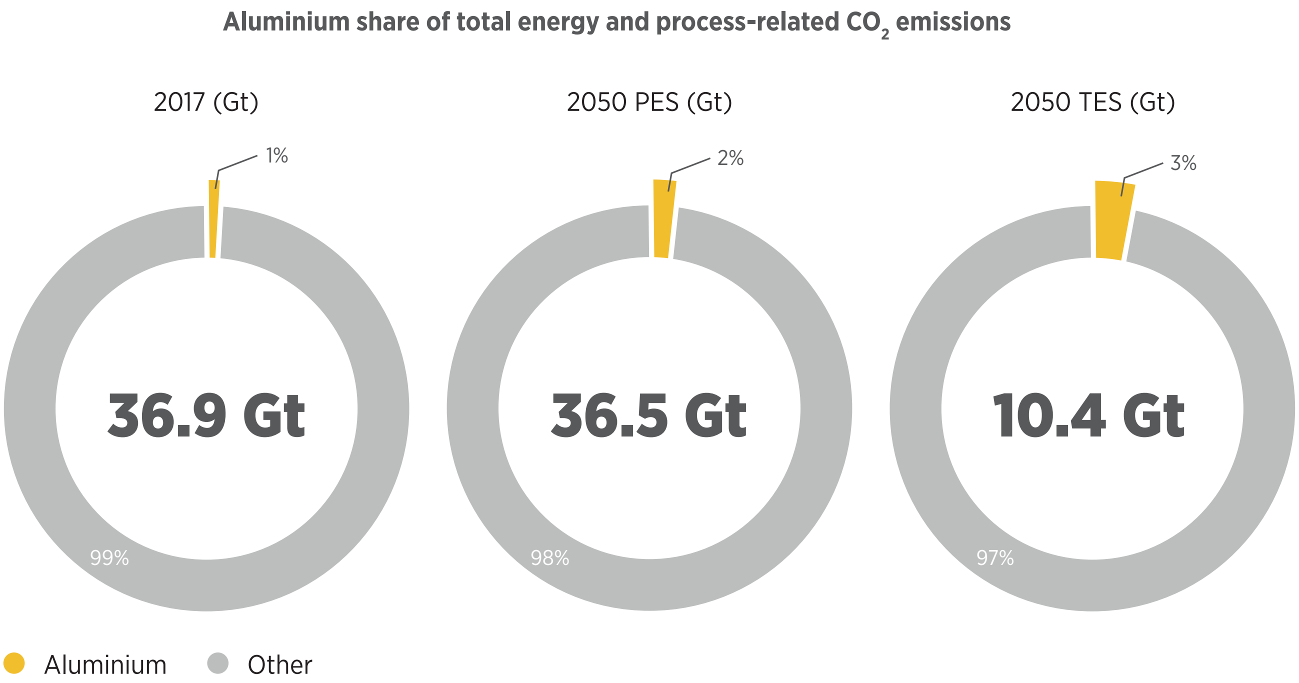
Sector emissions and energy use

Figure 27 shows how aluminium's share of total energy and process-related CO_2 emissions will need to change over time. In 2017, direct emission from aluminium production accounted for 1% of total energy and process-related CO_2 emissions. With current planned policies and programmes, aluminium's direct share of emissions can be expected to slightly increase by 2050 (to 1.5% of total energy and process CO_2 emissions). In the Transforming Energy Scenario, the sector's share of emissions would grow further to almost 3% (as other sectors decarbonise more quickly), leaving 0.4 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 12 shows how the share of renewable energy in total aluminium energy use could nearly quadruple from 16% in 2017 to 60% in 2050 under the Transforming Energy Scenario – more than 50% larger than in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 2.4 EJ of aluminium's total energy demand of 4 EJ by 2050. This would be sourced mainly from renewable electricity and from direct electrification and the direct use of other renewables such as biofuels.

Delivering zero emissions will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 28, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes. Figure 29 shows the estimated range of abatement potential for each measure plotted against estimates of the range of the cost of abatement.

FIGURE 27: Aluminium's direct share of total energy and process-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario) (excluding indirect emissions from the production of the electricity used)



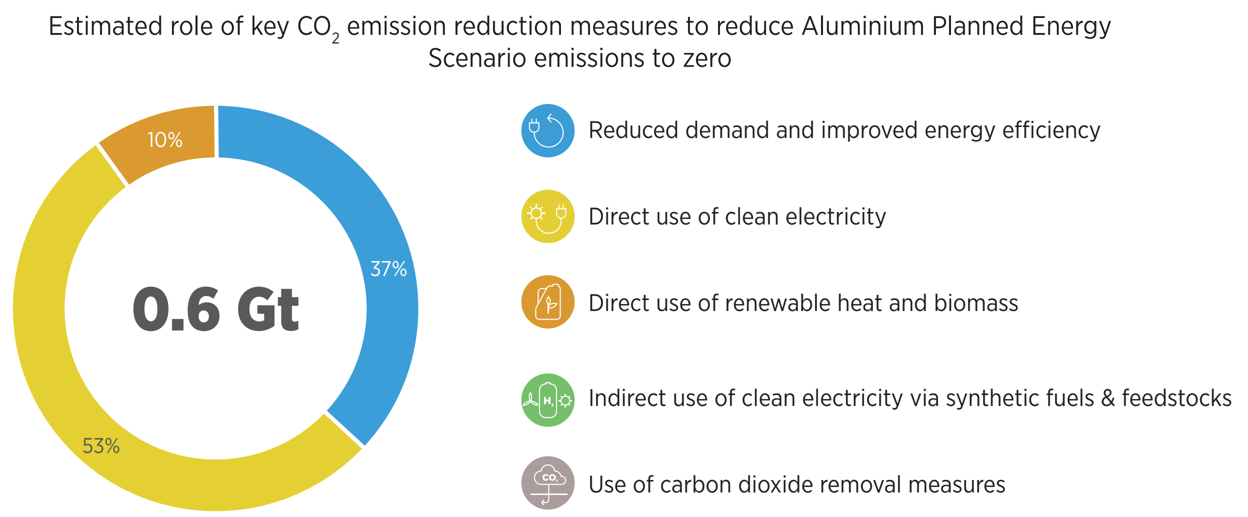
Source: IRENA, 2020a; IEA, 2017

TABLE 12: ALUMINIUM ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Aluminium (energy and process)	Energy (EJ/year)[1]	4.5	5.8	4.0	0.01 Gt/yr reduction (2% of 2017 total)	0.4 Gt/yr reduction (98% of 2017 total)
	CO2 emissions (Gt/year)[2]	0.4	0.6	0.4		
	Renewable energy share[3] (%)	16%	38%	60%		

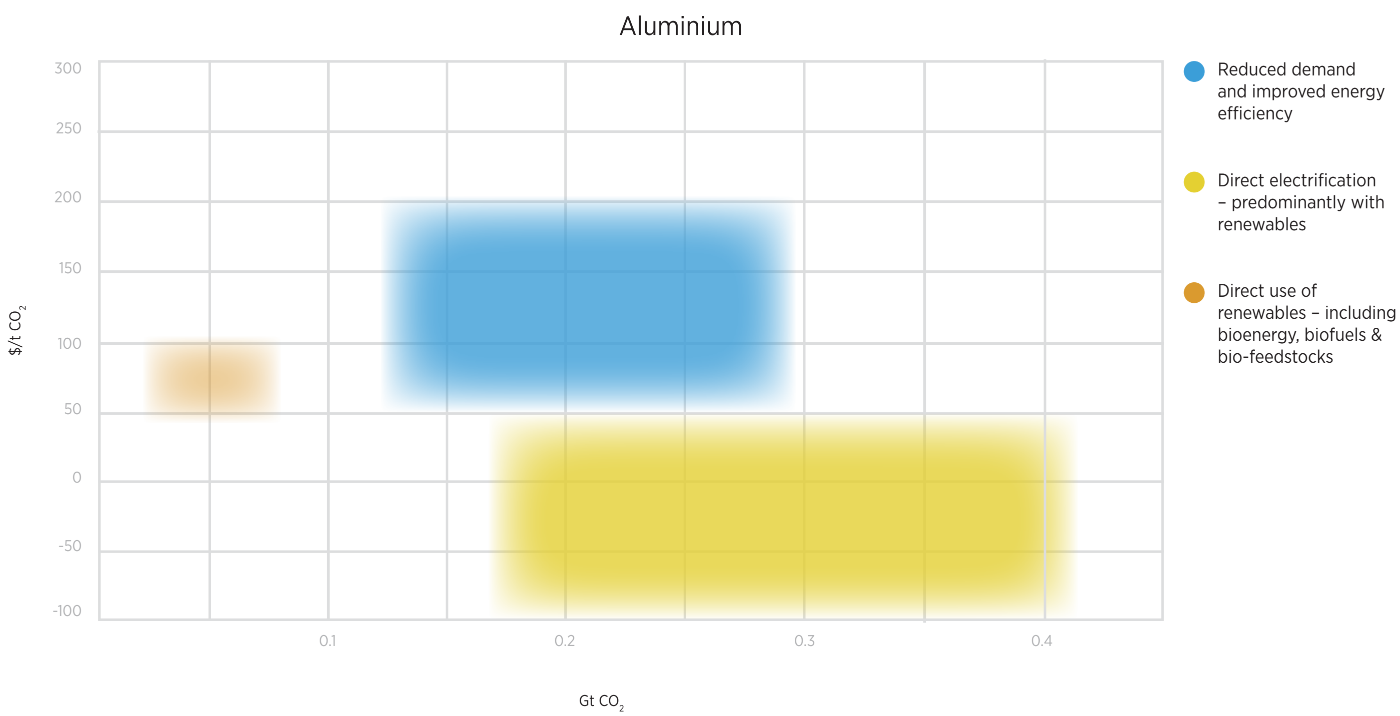
Notes:
1.Energy demand in table includes electricity and district heat.
2. Emissions include direct energy and process emissions.
3. Renewable energy share includes renewable component of electricity and district heat.
Source: *IRENA, 2020a;* IEA, 2017

FIGURE 28: Emission reduction measures to reach zero emissions in the aluminium sector, from Planned Energy Scenario to zero



Source: IRENA analysis

FIGURE 29: Estimated abatement potential of measures to reach zero energy emissions in the aluminium sector plotted against estimates of the cost of abatement



Source: IRENA analysis

Sector overview and the emission reduction challenge

Primary aluminium is produced using the Bayer and Hall-Héroult processes sequentially with 4-7 tonnes of bauxite producing 2 tonnes of alumina, which then yields 1 tonne of aluminium.

In the Bayer process, bauxite is crushed, washed and dried, then dissolved with caustic soda at high temperatures. The mixture is then filtered to remove the impurities and transferred to a precipitator tank, where the hot solution starts to cool and aluminium hydroxide seeds, very small particles, are added. The aluminium hydroxide seeds stimulate the precipitation of solid aluminium hydroxide crystals which settle at the bottom of the tank and can then be removed. Finally, the aluminium hydroxide is washed and dried with the final product being a fine white powder.

The Bayer process requires around 11.4 GJ of energy per tonne of alumina produced, with regional variations from 9.9 GJ in North America to 13.1 GJ in Europe. In 2018, the energy needed to produce 122 Mt of alumina was unequally split between 1.3 EJ of fuel (mainly coal and natural gas) and 0.1 EJ of electricity with almost negligible use of renewable power (IAI, 2020a).

Efforts directed towards the reduction of CO_2 emissions include research to shift to concentrated solar thermal energy, which could displace 45% of natural gas in the Bayer process (Engineers Australia, 2020). Renewable energy sources could be used in various stages of alumina production, such as using heat pumps and solar water heaters in the first stage and heat from biomass or geothermal in later stages.

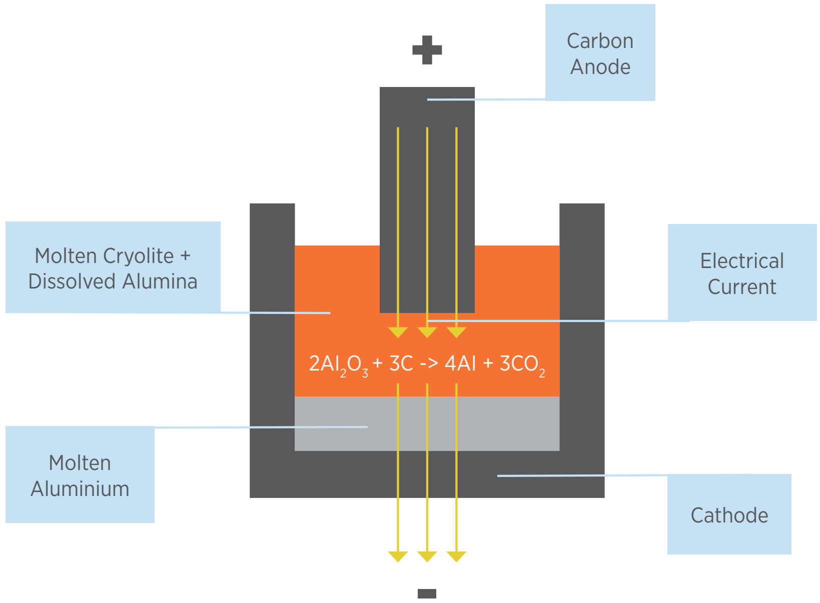
In the Hall-Héroult process, alumina undergoes a smelting process, which uses an electric current in a molten bath to produce pure aluminium (Figure 30). This primary aluminium production requires several energy-intensive steps (Figure 31). Around 14 200 kWh of electricity is needed to produce 1 tonne of aluminium, with regional variation, such as 13 555 kWh in China and 15 919 kWh in South America (IAI, 2020b). Because aluminium smelters use large amounts of electricity, they provide significant demand-side management potential (Box 12).

In 2017, the aluminium sector accounted for more than 863 TWh of electricity and 1.2 EJ of fossil fuel use. Over 90% of current CO_2 emissions from aluminium are related to the production of electricity (referred to as indirect emissions). The remaining 10% are direct process emissions from the production of aluminium (IAI, 2020c).

Indirect CO_2 emissions depend largely on the CO_2 intensity of the electricity and range from zero for renewable energy sources to 15 tonnes of CO_2 per tonne of aluminium produced with coal. Indirect emissions also arise from the consumption of alumina in the smelting process, with around 1.4 tonnes of CO_2 per tonne of aluminium produced.

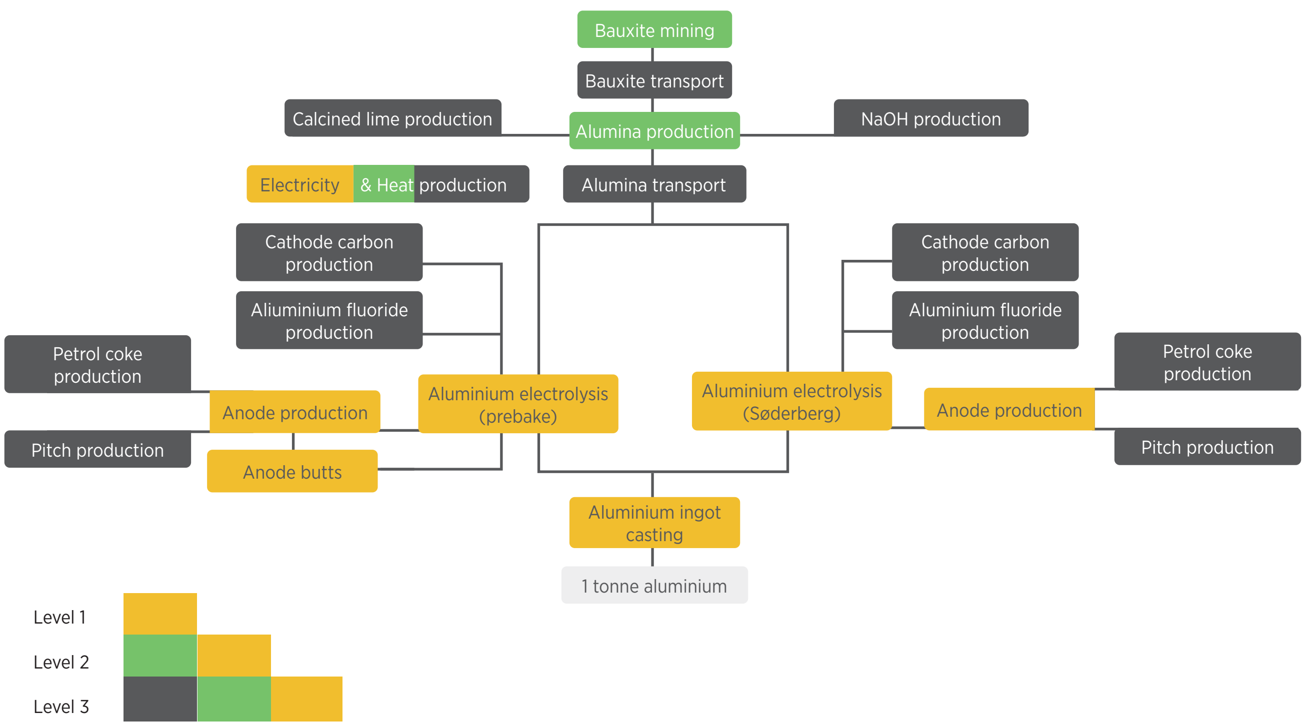
Two-thirds of the direct CO_2 emissions from the aluminium production processes are related to the use of carbon anodes in the Hall-Héroult process. On average, the Hall-Héroult process emits 1.66 tonnes of CO_2 per tonne of aluminium produced (Obaidat *et al.*, 2018).

FIGURE 30: Schematic representation of the Hall-Héroult process



Adapted from Aluminum Production, 2009

FIGURE 31: Processes in the primary aluminium production chain



Source: Adapted from IAI, 2018

Options for reaching zero

Previously, aluminium smelters have sometimes been located close to hydropower dams to benefit from low electricity prices, but in recent years most production expansion has taken place in China, which produces around 60% of aluminium worldwide and where the energy for aluminium production is sourced predominantly from coal.

In IRENA's Transforming Energy Scenario, aluminium production grows from 54 Mt per year in 2019 (IAI, 2020d) to 137 Mt per year in 2050. This sector is projected to have the highest use of renewables (both renewable electricity and biomass) among all industry sectors, reaching 60% of total energy use in the sector by 2050.

In the Transforming Energy Scenario, the shift to renewable energy sources and other measures results in a decline in CO_2 emissions of around 50% by 2050, compared to IRENA's Planned Energy Scenario. Less primary aluminium would be produced because of increased recycling due to better aluminium recovery from waste, while the remaining emission reduction can be attributed to energy efficiency measures (including gains from novel electrolysis technologies) and biofuels use in alumina plants.

To achieve this emission reduction, this calls for significant renewable electricity use in production processes and for enabling the share of recycled aluminium to reach half of total production by 2050. Aluminium recycling requires 95% less energy than primary aluminium production (IAI, n.d.). The average abatement cost of these options would be USD 10 per tonne of CO_2 by 2050, but this would require an additional investment (over and above what is available in IRENA's Planned Energy Scenario) of around USD 0.2 trillion in the period between 2015 and 2050. In the Transforming Energy Scenario, despite an increase in the use of renewables (up to 60% share by 2050), emission levels will still be at 80% of 2017's levels due to the significant growth occurring in the Planned Energy Scenario.

Decarbonising aluminium production will require both the use of renewables for process heat and electricity inputs and eliminating the use of carbon anodes. CCUS technologies do not currently look viable for the aluminium sector, as the CO_2 concentration in the process gas is very low, close to 1% by volume. There are no planned projects to test CCUS technologies in the aluminium industry.

REACHING ZERO – OPTION 1: Renewable heat and electricity, and inert anodes

Smelting aluminium conventionally requires carbon anodes made of carbon-rich material, as carbon is a good conductor of electricity as well as being cheap and plentiful. The carbon anodes are part of the process to release the metal from aluminium oxide. During this process, the carbon anodes are destroyed, releasing CO_2 gas. Estimates suggest that around 0.5 tonnes of carbon anodes are needed per tonne of aluminium produced, yielding around 1.5 tonnes of CO_2.

Instead of using carbon anodes, inert anodes – that is, those which do not react in the electrochemical process – have been a topic of research for decades. A project led by Aluminium Pechiney and funded by the European Commission between 2015 and 2019 developed a multi-material inert anode based on cermet that has shown outstanding properties in high-temperature and corrosive media. This will enable the reduction of CO_2 emissions to zero during the electrolysis process for aluminium production (Agral, 2019). In 2018, Alcoa and Rio Tinto developed a new process involving the use of a proprietary anode material that when used in aluminium smelting releases oxygen instead of CO_2. A joint venture is under way to scale up industrial production, but products using the new technology are not expected to become commercially available before 2024 (Harvey, 2018).

A variety of renewable energy sources could provide the heat needed in the various stages of alumina production, such as using heat pumps and solar water heaters in the first stage and heat from biomass, geothermal or CSP in later stages.

The electricity needed for aluminium production could be sourced from dedicated renewable power production or from power grids with high renewable shares. A majority of aluminium plants rely on fossil-based captive power, mostly coal-based, to produce electricity for smelting (OECD, 2019). A switch to renewable sources could provide increased energy security and lower costs, given the constant price fluctuation of fossil fuels.

Switching electricity supply to renewable energy sources has an additional benefit for the power sector. Aluminium smelters, with slight modifications to current designs, can provide demand-side flexibility (Box 12).

BOX 12: ALUMINIUM SMELTERS AS DEMAND-SIDE FLEXIBILITY PROVIDERS FOR INTEGRATION OF VARIABLE RENEWABLE ENERGY

Switching electricity supply from fossil fuels to renewables is essential to decarbonising aluminium production. Doing so, however, could also assist the power sector in integrating higher shares of variable renewable energy, such as solar PV and wind, by creating a significant source of manageable power demand which can be turned on and off when renewable power is available or scarce. Traditionally, aluminium smelters are operated in baseload mode (*i.e.*, in continual operation), but new strategies have been developed that allow more flexible operation in this sector, which are aligned with the new power sector paradigm in which electrification, decentralisation and digitalisation are key trends. Similar flexibility potentials exist for iron and steelmaking, for example in electric arc furnaces (Beba, 2018).

Overall, the 64 Mt of primary aluminium production worldwide is equal to 2 TWh of potentially manageable load, which is equivalent to 17 minutes of storage. Unlocking some of this flexibility requires a systemic approach combining innovations in enabling technologies (such as digital technologies), business models, market design and power system operation (IRENA, 2019a).

Pilot projects testing the adaption of aluminium smelters to provide flexible loads and demand-side response are emerging. A primary aluminium smelter in Essen, **Germany** has been converted for flexible operation (1.2 gigawatt-hours (GWh), for 48 hrs (+/-25%), or up to 2 GWh for 1 hour (switch off)), based on 55 kilotonnes of production volume. The retrofit cost is USD 40 million for a 55-kilotonne smelter, leading to a cost of 1.2 US cents per kWh for the added demand-side flexibility to the power system. This compares very favourably with battery costs which are currently in the range of USD 200 per kWh (Trimet, 2019). Another primary aluminium smelter in Hamburg, Germany has undergone similar adjustments resulting in an operational flexibility in aluminium electrolysis of 240 MW (–13.2/+6.6 MW) (Beba, 2018).

Such an adaption has also been theoretically studied for 217 aluminium smelters in **China**, where industrial demand response from large smelters could provide estimated flexibility of 2.3% of China's daily electricity demand, or 432.5 GWh. The underlying demand assumption was 13.5 MW per tonne of aluminium produced, implying 774.9 TWh of power to manufacture 57.5 million tonnes per year, or 11.3% of China's electricity consumption in 2018 (dena, 2019a). This example is specific to operations in China but illustrates the potential benefits.

More information on this topic can be found in the following publications and platforms:

Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation (https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/industrial_innovation_part_2_en.pdf)

World Aluminium publications (www.world-aluminium.org/publications)

LeadIT Leadership Group for Industry Transition (www.industrytransition.org)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century (www.energy-transitions.org/mission-possible)

Aluminium for Climate (www.weforum.org/mission-possible/action-areas)

European Aluminium (www.european-aluminium.eu/policy-areas/energy-climate)

3.

TRANSPORT

3 Transport

Transport plays a vital role in the world's economy. It facilitates the movement of people and goods across the globe and enables modern life as we know it. This comes at a cost, however, as the transport sector is also a major source of emissions due to its current heavy reliance on fossil fuels. With the global demand for transport services expected to increase in future years there is an urgent need to identify ways to reduce emissions and advance towards the complete decarbonisation of the sector.

Reducing and eventually eliminating emissions will require substantial changes in propulsion systems and the choice of fuels that the transport sector relies on. In order to drive long-term emission reductions in this sector, co-ordination between public and private actors will be necessary, as well as targeted policy support.

Several countries have acknowledged the importance of transport in their Nationally Determined Contributions (NDCs) under the Paris Agreement, by acknowledging the sector as an important source of emissions. Yet, only 65% of NDCs define specific mitigation actions, and an even smaller number set emission targets for the sector (GIZ, 2017). Beyond this, international aviation and shipping emissions fall outside of national obligations, and therefore national CO_2 abatement policies do not usually tackle them.

The preferable path to low CO_2 emissions has become clear for some but not all transport modes. Electrification is a viable option for rail and light-duty road transport (cars, sport utility vehicles (SUVs), small trucks), assuming that the electricity comes from renewable sources. In the case of rail transport, the use of electricity is already widespread, especially for passenger transport. In the case of light-duty road transport, battery electric vehicles have shown dramatic improvements in range (kilometres/charge), cost and market share in recent years.

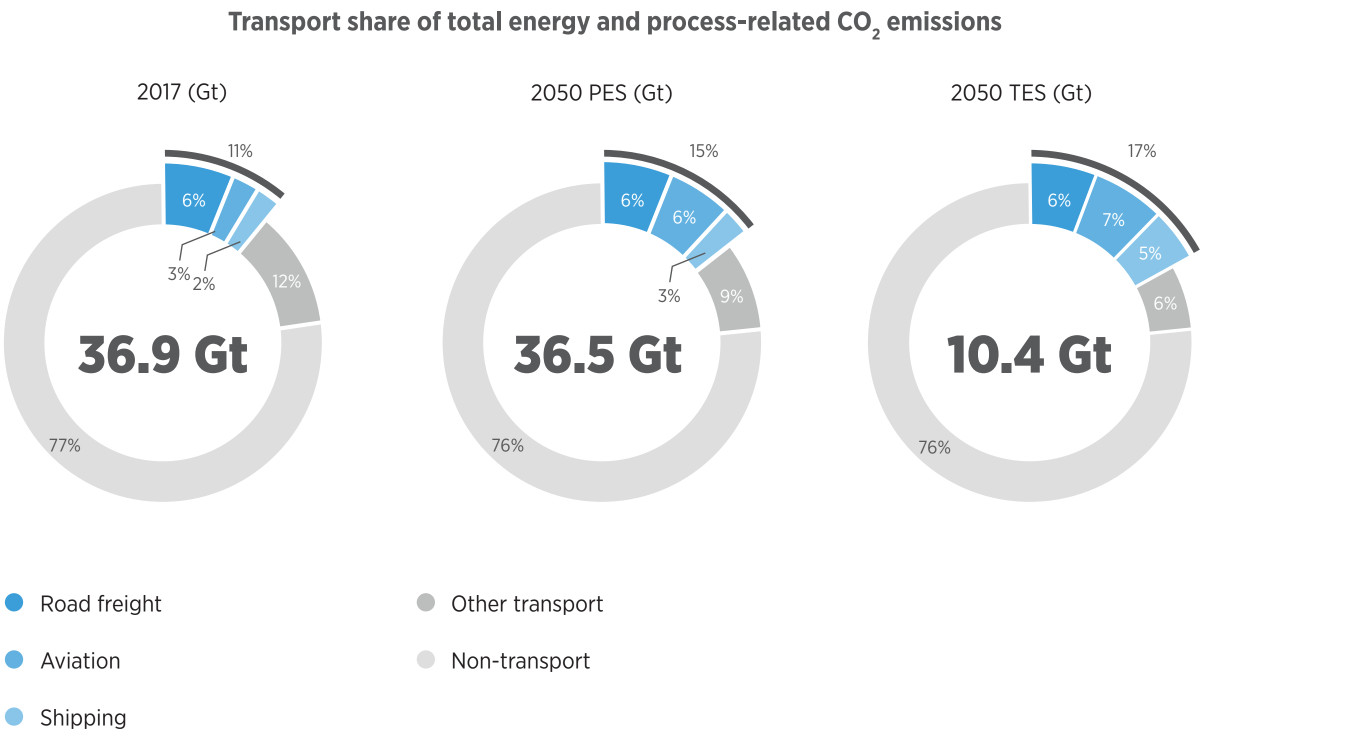
For other transport modes, however, the optimal pathway has yet to become clear. Road freight transport, aviation and shipping are significant energy users and CO_2 emitters, and driving their emissions to zero by 2060 will be a challenge. This chapter examines the challenges and options available to reduce and eventually eliminate direct emissions in these three harder-to-decarbonise sub-sectors.

3.1 Transport emissions and energy use

Transport emissions come from the combustion of fossil fuels in internal combustion engines and turbines. When combusting these fuels, a range of different greenhouse gases and pollutants are emitted, including CO_2, carbon monoxide, nitrogen oxides, hydrocarbons and other particulate matter. The transport sector, as a whole, accounted for about a quarter of global energy-related CO_2 emissions in 2017. That year, the transport sector's total CO_2 emissions reached 8 Gt. A vast majority of transport-related emissions, 97%, come from road, air and marine transport, while rail and other modes of transport account for the remaining 3%.

In 2017, passenger road transport emitted roughly 3.6 Gt of CO_2, making it the transport mode with the largest emissions. It was followed by freight road transport with 2.3 Gt, aviation and shipping with 0.9 Gt each, and rail which was responsible for 0.1 Gt (IEA, 2019b).

FIGURE 32: Selected transport sub-sectors share of total energy-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



Source: IRENA, 2020a; IEA, 2017

Figure 32 shows how the share of total energy and process-related CO_2 emissions from selected transport sectors will need to change over time. In 2017, the selected transport sectors accounted for over 11% of total energy-related CO_2 emissions. Under current planned policy and programmes laid out by governments and companies, these emissions can be expected to increase overall by 2050 (from 4.1 Gt in 2017 to 5.4 Gt in 2050), while CO_2 emissions from other sectors decrease, meaning that the share of total energy-related CO_2 emissions of the selected transport sub-sectors will grow to almost 15%, up from 11%. In the Transforming Energy Scenario, the selected transport sectors' CO_2 emissions more than halve, totalling 1.8Gt, but represent 17% of remaining CO_2 emissions. Achieving the reductions set out in the Transforming Energy Scenario will be challenging, but even more so if the goal is to go further to reach zero emissions.

3.2 Renewables-based emission reductions

The decarbonisation of the transport sector will require a combination of various measures and renewable solutions. As shown in Table 13, under IRENA's Transforming Energy Scenario a combination of energy efficiency improvements, modal shifts, electrification and the use of alternative fuels can reduce the transport sector's energy-related CO_2 emissions by 72% from 8.5 Gt per year in 2017 to 2.4 Gt per year in 2050.

For the three modes of transport that this chapter focuses on – road freight transport, aviation and shipping – the total combined CO_2 emissions in 2017 were 4.1 Gt per year. The Transforming Energy Scenario sees CO_2 emissions in these sectors go down to 1.8 Gt per year in 2050, compared to an increase to 5.4 Gt per year observed in the Planned Energy Scenario.

TABLE 13: TRANSPORT SECTOR ENERGY DEMAND AND EMISSIONS

Sectors	Metric	2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO2 reduction from TES to zero
Transport total	Energy (EJ/year)	117	135	86	6.1 Gt/yr reduction (72% of 2017 total)	2.4 Gt/yr reduction (28% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	8.5	8.6	2.4		
	Renewable energy share (%)	3%	10%	56%		
Road freight	Energy (EJ/year)	32.3	35.1	21.1	1.7 Gt/yr reduction (73% of 2017 total)	0.6 Gt/yr reduction (26% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	2.3	2.3	0.6		
	Renewable energy share (%)	1.5%	9%	62%		
Aviation	Energy (EJ/year)	13.5	30.8	15.1	0.3 Gt/yr reduction (27% of 2017 total)	0.7 Gt/yr reduction (72% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	0.9	2.1	0.7		
	Renewable energy share (%)	-	10%	40%		
Shipping	Energy (EJ/year)	11.3	13.7	7.4	0.4 Gt/yr reduction (43% of 2017 total)	0.5 Gt/yr reduction (57% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	0.9	1	0.5		
	Renewable energy share (%)	-	3%	12%		

Note: *Under IRENA's Deeper Decarbonisation Perspective.
Source: *IRENA, 2020a;* IEA, 2017

Table 13 also shows how the share of renewable energy in transport use could increase from just 3% in 2017 to 56% in 2050 under the Transforming Energy Scenario – more than five times larger in 2050 than in the Planned Energy Scenario. In the Transforming Energy Scenario renewable energy would contribute around 48 EJ to transport's total demand of 86 EJ by 2050. The three selected transport modes (road freight transport, aviation and shipping) also make considerable progress in the 2050 Transforming Energy Scenario, yet they lag behind the transport sector overall.

A number of options can contribute towards reducing emissions including reducing demand such as modal shifts and improved energy efficiency, but only a few can help achieve the complete decarbonisation of these three remaining sectors. Only three major credible pathways are consistent with that goal:

1. Direct electrification – predominantly with renewables
2. Direct use of renewables – particularly biofuels
3. Indirect electrification – with green hydrogen and synthetic fuels.

Some of these options would have been dismissed just a few years ago due to prohibitive costs. However, the dramatic decrease in renewable electricity prices has changed the paradigm, and there is now increased attention to solutions based on renewable electricity. While all of these options look to be technically feasible, each has various barriers that need to be overcome, including technology maturity, fuel availability and sustainability, and high costs. While many of the emission reduction options covered in this chapter are not yet at commercial scale, with adequate policy support, technologies can mature, their adoption can increase, economies of scale will be created, and cost reductions could follow.

3.3 Road freight

Key insights

- Road freight transport accounted for 27% of all transport-related emissions or over 6% of global energy-related emissions in 2017.
- Despite representing only 9% of the global vehicle stock, freight trucks accounted for around 39% of the life-cycle greenhouse gas emissions from road vehicles in 2017.
- Battery electric vehicles are a feasible decarbonisation option for light-duty freight transport (*e.g.*, "last-mile" delivery vehicles).
- Due to their heavy loads and high power requirements, batteries are more difficult to implement in freight road transport. Their kilowatt-hour per kilometre (kWh/km) requirement is 1.1-1.3 kWh/km, compared to 0.2 kWh/km for light-duty vehicles. Existing battery-powered prototypes are projected to be economically competitive with their fossil-powered counterparts, although these are not yet commercially available.
- Fuel cell electric vehicles (FCEVs) are an emerging option for heavy-duty road transport, as they may allow for longer ranges than battery electric vehicles. Existing fuel cell electric long-haul trucks have a range of 1 100 kilometres, compared to the 400-800 kilometre range of their battery electric counterparts. A limited number of heavy-duty FCEV fleets are already in operation.
- Biofuels are already used commercially in some markets; however, their limited production and relatively high cost remain barriers, and feedstock availability is a potential limitation.

Sector emissions and energy use

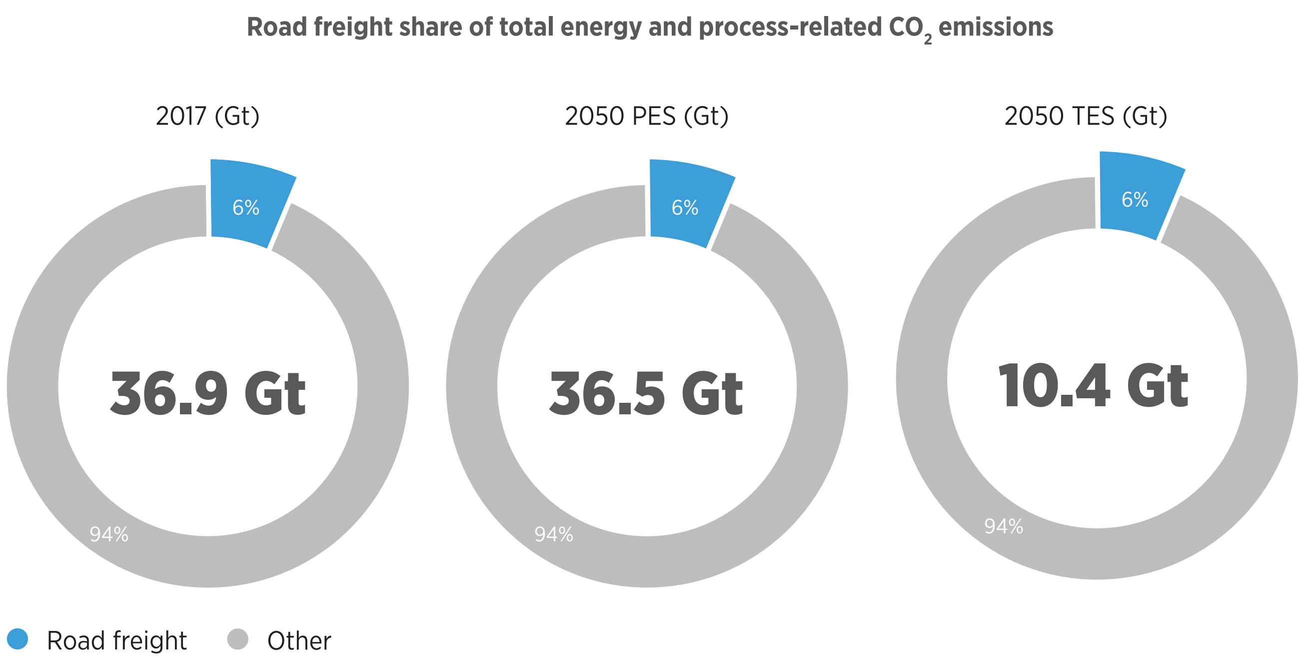
Figure 33 shows how the share of total energy and process-related CO_2 emissions from road freight transport will need to change over time. In 2017, road freight transport accounted for roughly 6% of total energy-related CO_2 emissions. With current planned policies and programmes, the share of emissions from road freight transport is not expected to decrease by 2050. In the Transforming Energy Scenario, the sector's share of emissions would remain unchanged, leaving 0.6 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 14 shows how the share of renewable energy in road freight transport's energy use could increase nearly 40-fold from just 1.5% in 2017 to 62% in 2050 under the Transforming Energy Scenario – more than six times the share in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 13.1 EJ of road freight transport's total demand of 21.1 EJ for energy by 2050. This would be sourced mainly from direct electrification with renewables, indirect electrification with green hydrogen and biofuels.

Delivering zero emissions will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which

IRENA expects to carry out in 2021. Figure 34, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes.

FIGURE 33: Road freight transport share of total energy-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



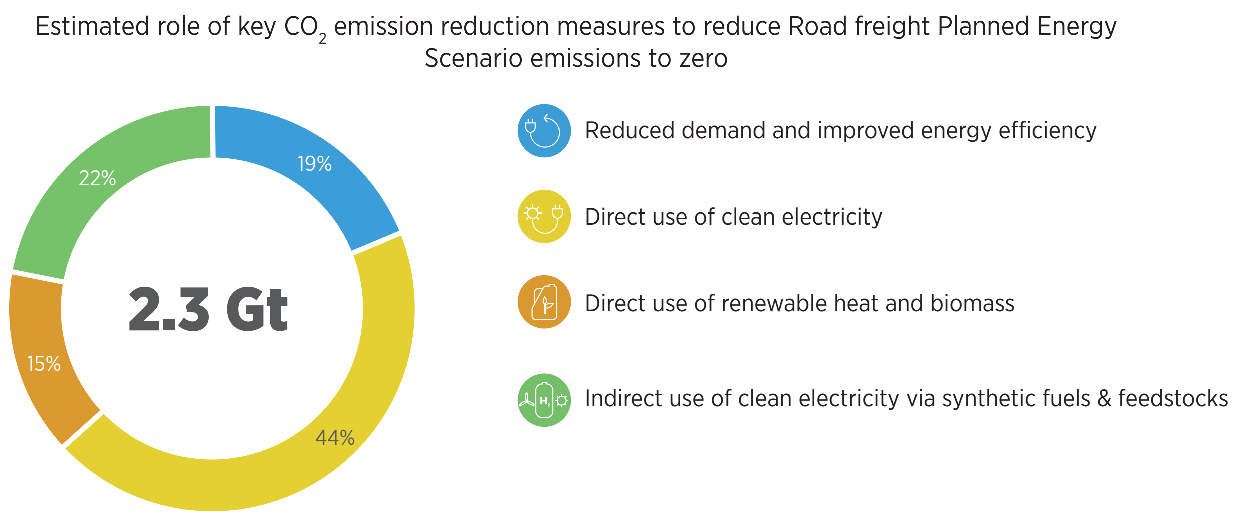
Source: IRENA, 2020a; IEA, 2017

TABLE 14: ROAD FREIGHT TRANSPORT ENERGY DEMAND AND EMISSIONS

		2017	2050 - Planned Energy Scenario	2050 - Transforming Energy Scenario	Progress made in CO_2 reduction from 2017 to TES	Additional progress needed in CO_2 reduction from TES to zero
Road freight	Energy (EJ/year)	32.3	35.1	21.1	1.7 Gt/yr reduction (73% of 2017 total)	0.6 Gt/yr reduction (27% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	2.3	2.3	0.6		
	Renewable energy share (%)	1.50%	9%	62%		

Source: IRENA, 2020a; IEA, 2017

FIGURE 34: Emission reduction measures to reach zero emissions in the road freight transport sector, from Planned Energy Scenario to zero

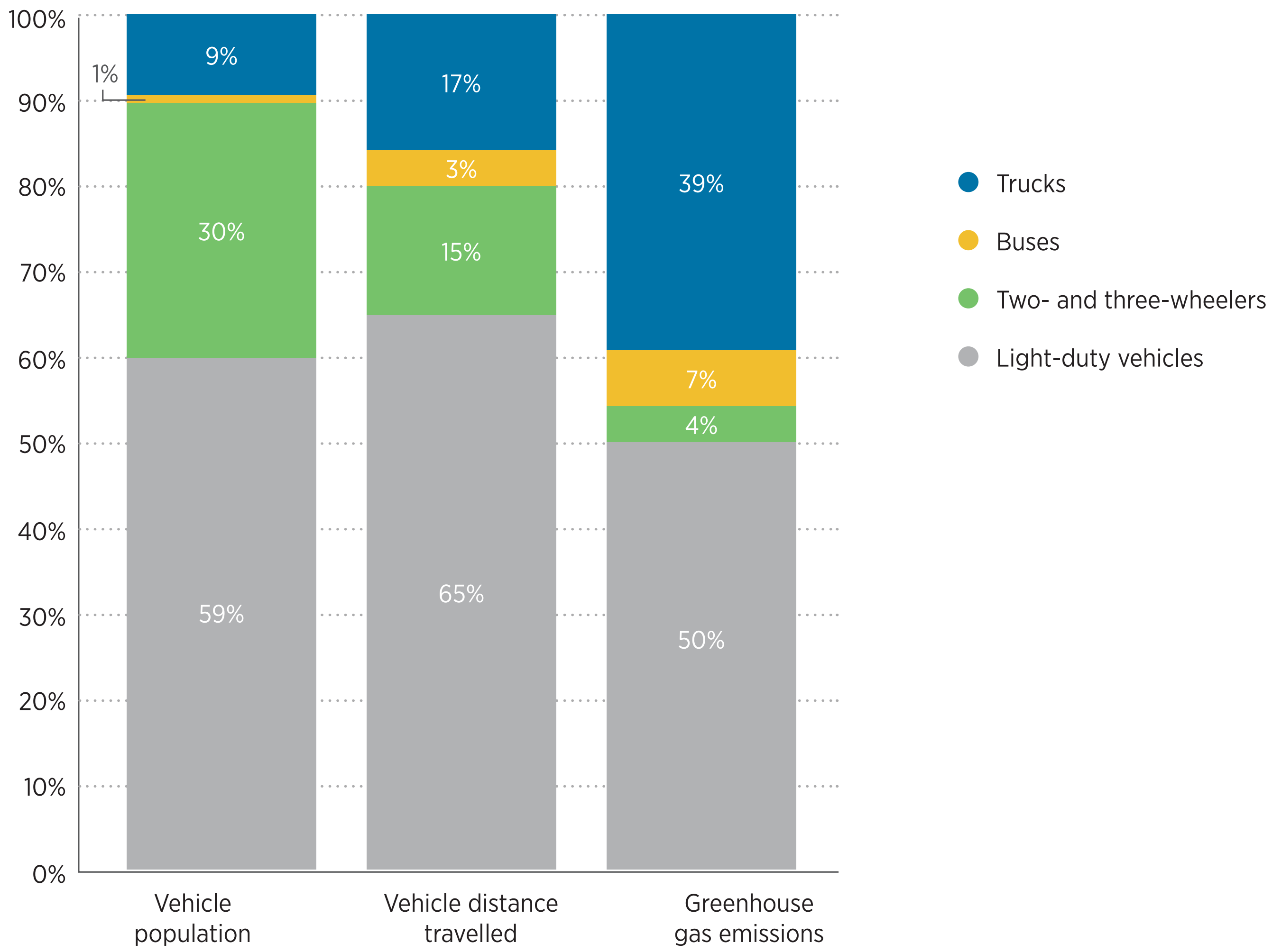


Source: IRENA analysis

Sector overview and the emission reduction challenge

Despite representing only 9% of the global vehicle stock and 17% of the total vehicle-kilometres driven, freight trucks accounted for around 39% of the life-cycle greenhouse gas emissions from road vehicles, and for even higher shares of some other pollutants (ICCT, 2017; Miller and Façanha, 2014). Figure 35 summarises the breakdown of the world vehicle population, travel activity and greenhouse gas emissions.

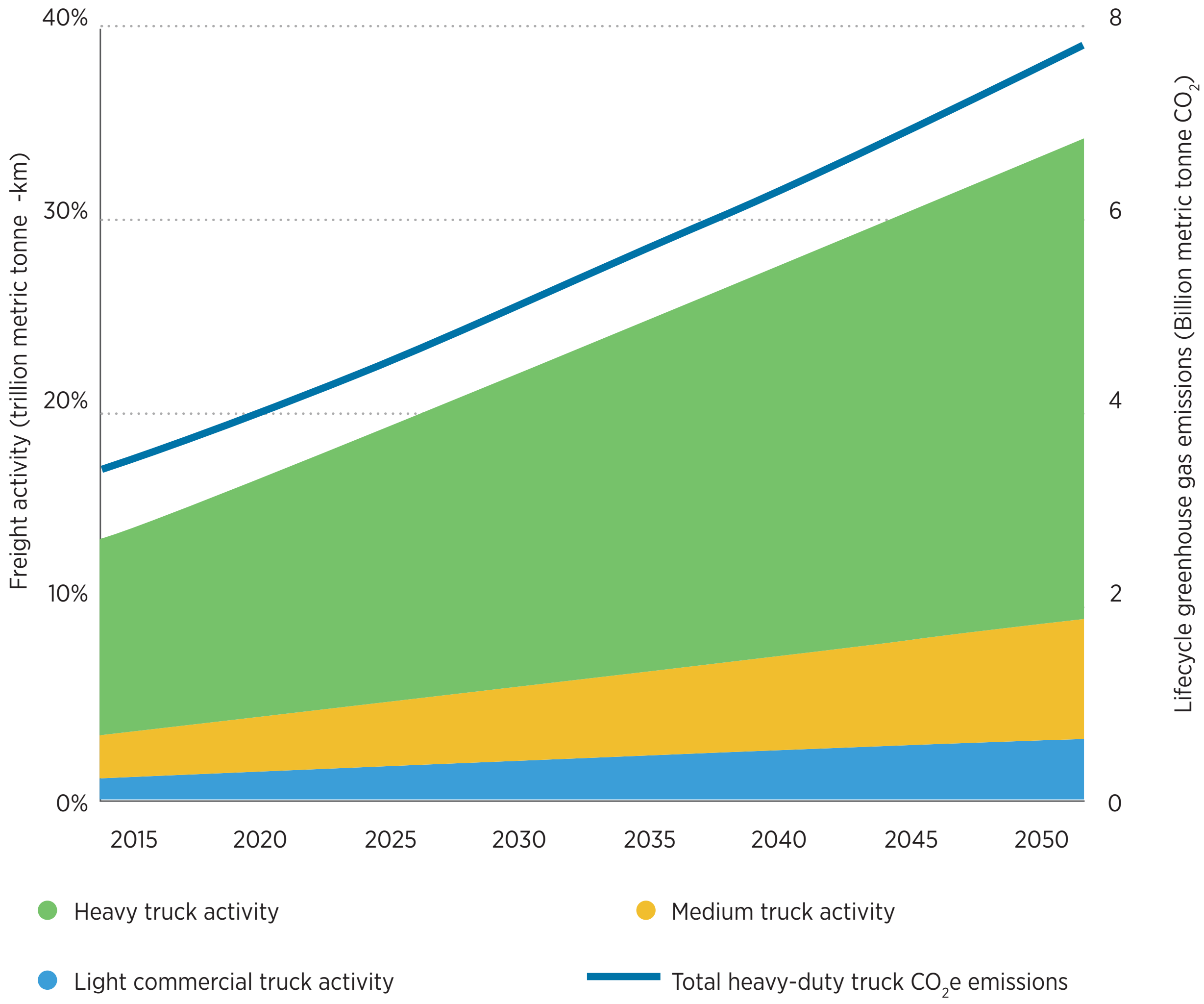
FIGURE 35: Global vehicle stock, distance travelled and life-cycle road transport greenhouse gas emissions by vehicle type in 2015



Source: Moultak et al., 2017

Figure 36 shows the International Council on Clean Transportation estimates that global truck freight activity and truck life-cycle greenhouse gas emissions will more than double by 2050 under a business-as-usual scenario. The figure also illustrates that the heaviest trucks – usually tractor-trailers over 15-tonne weight capacity – are expected to be responsible for more than 75% of all road freight transport activity in 2050.

FIGURE 36: Global road freight transport activity and life-cycle greenhouse gas emissions in a business-as-usual scenario



Source: Moultak et al., 2017

These heavy, long-distance trucks rely almost exclusively on diesel with a small proportion relying on petrol and natural gas. Lighter and shorter-range trucks are starting to see some change in fuels and drive systems, and these new fuels and drive systems may find application in larger trucks over time.

Options for reaching zero

There are three principal options that are consistent with the goal of zero CO_2 emissions from transport:

1. Battery electric vehicles
2. Fuel cell electric vehicles
3. Biofuels.

None of these options are yet in widespread use, but all have been trialled and the issues preventing scale-up are mainly economic and logistical rather than technological. Technology improvement, however, may assist in accelerating uptake.

REACHING ZERO – OPTION 1:
Battery electric vehicles

Battery electric vehicles rely on an electric motor powered by a battery pack instead of an internal combustion engine. The vehicle is plugged into a charging station or wall outlet to charge the battery pack. Since these vehicles run only on electricity, they are a zero-emission option, if they are powered by renewable electricity. Battery electric vehicles are now well established among light-duty vehicles; however, they are just starting to enter the medium- and heavy-duty vehicle markets. Several medium- and heavy-duty vehicle concepts are being developed by different companies (including long-established automotive companies), and some of them are already in production.

The deployment of battery electric vehicles in freight transport poses various challenges. The first one is the suitability of battery storage systems for the conditions demanded by road freight transport. Battery costs are the main barrier, resulting in perceived high costs for such vehicles, although battery costs are expected to fall between 50% and 60% by 2030 (IRENA, 2017c). The energy density and the weight of batteries is also a challenge for heavy-duty long-haul transport, given that it limits the range. A fourth challenge is charging infrastructure and management. Charging infrastructure networks need to be greatly increased, and charging technologies need to improve to reduce the time it takes to fully charge a vehicle, and also need to be deployed at scale. Lastly, high penetration of electric vehicles will have an impact on and might create complications for the power system if not handled appropriately; this additional demand needs to be planned for and should be met with renewables.

Short-haul battery electric vehicles

Short-haul, local delivery vehicles are an ideal candidate for electrification via batteries, since they travel short distances and carry moderate payloads. There have been notable and rapid recent improvements in battery electric short-haul trucks, and these fleets are growing rapidly, although they still represent only a tiny share of the overall truck fleet. Europe and North America are home to an estimated 70 000 and 100 000 electric commercial trucks respectively (Quartz, 2019). These are largely fleet vehicles, used for local (urban) delivery. A few notable examples include:

- The French postal service La Poste owns 35 000 electric vehicles out of its total fleet of 75 000 vehicles (FleetEurope, 2017).
- Amazon recently ordered 100 000 electric delivery vans from the start-up Rivian. The first vans are expected to come into operation in 2021 in the United States, and the whole fleet by 2024-2030 (Ohnsman, 2019).

- IKEA announced in 2018 that zero-emission trucks would make all home deliveries in five cities (Amsterdam, Los Angeles, New York City, Paris and Shanghai) by 2020 (Quartz, 2019).
- Deutsche Post DHL Group operates the largest battery electric vehicle fleet in Germany, composed of a fleet of 11 600 StreetScooter WORK vehicles which were designed and produced by the company. The company also has plans to replace its entire short-haul fleet with electric vehicles that are charged with electricity generated from renewable energy sources (Deutsche Post, 2019).

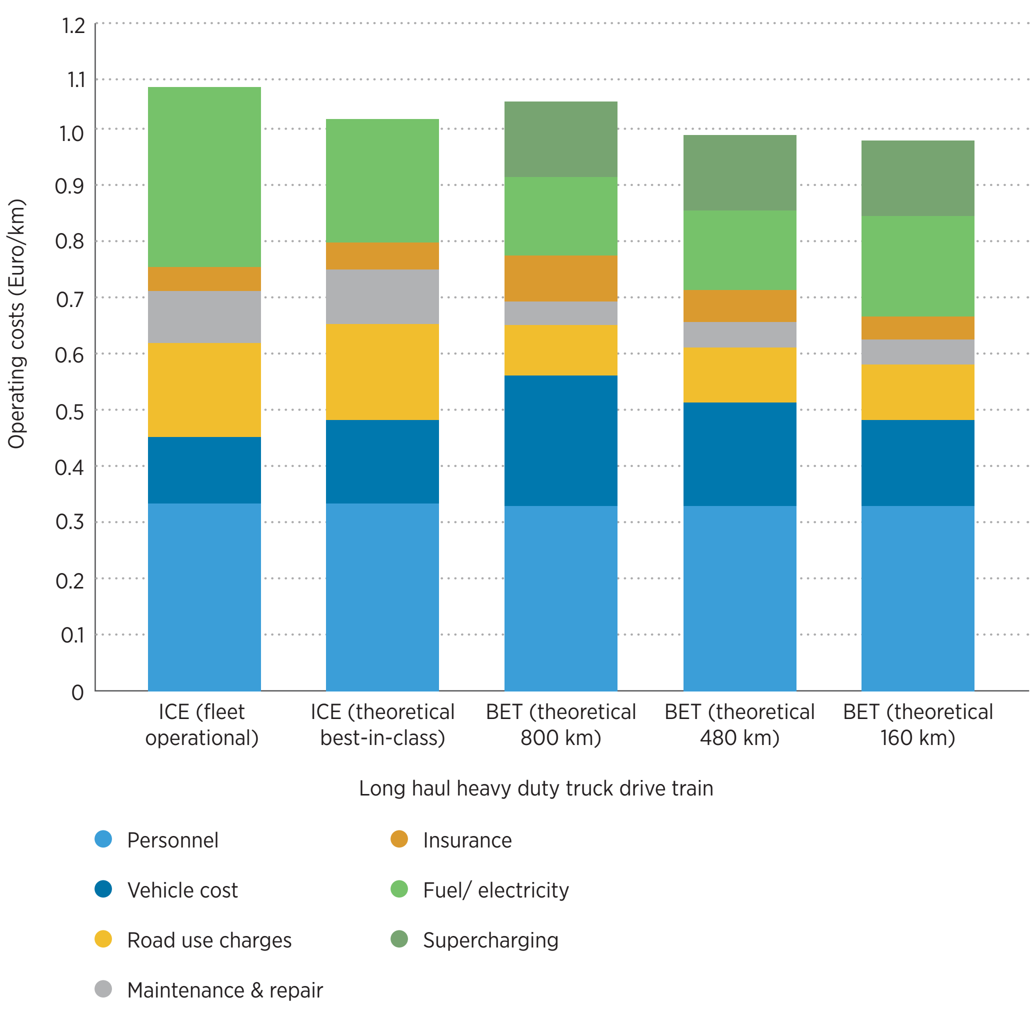
Long haul vehicles

Longer ranges come with greater challenges for direct electrification, especially for heavy-duty transport. The heavier a vehicle is, the more power it needs to pull its payload. In the case of heavy-duty trucks, the kilowatt-hour per kilometre requirement is 1.1 - 1.3 kWh/km, compared to 0.2 kWh/km for light-duty vehicles (Panayi, 2019). A heavy-duty vehicle delivering its payload 1 000 kilometres away would need a 1 000 to 1 300 kWh battery. For comparison, the battery size in a Tesla Model X is 75 kWh. Assuming an energy density of 240 watt-hours per kilogram, the required battery for a heavy-duty vehicle with a range of 1 000 kilometres would weigh 4-5.5 tonnes. Considering a maximum loading capacity of 36 tonnes, and the fact that a full 150-gallon (568-litre) tank will weigh in the range of 500 kilograms, the use of batteries would inevitably result in a loss of payload and a longer payback period. While fully electric longer-haul trucks are not yet commercially available, a few manufacturers have publicly announced plans. Tesla, for example, has announced preliminary specifications for such a vehicle and has publicly shown prototypes. The truck, which is expected to start production in late 2020, will have a maximum range of 800 kilometres (Tesla, 2020). American truck manufacturer Freightliner, working together with Daimler, is also developing a long-haul battery electric truck, the e-Cascadia, which is expected to have a range of 400 kilometres (Daimler, 2018).

BOX 13: TOTAL COST OF OWNERSHIP OF A BATTERY-POWERED HEAVY-DUTY TRUCK

The economic and logistic case of battery electric trucks plays a critical part in defining if they are a feasible option. The all-electric Tesla Semi truck concept was unveiled in 2017. Two versions were announced, one with a range of 480 kilometres and another with a range of 800 kilometres. These versions are expected to come with a price tag of USD 150 000 and USD 180 000 respectively. The purchase price is significantly higher than the cost of a comparable diesel truck, which comes at USD 120 000, but the total cost of ownership needs to be considered. As seen in Figure 37, battery electric vehicles are projected to be economically competitive and in some cases cheaper than their fossil fuel-powered counterparts when taking into account fuel costs, operation and maintenance costs, and road use charges.

FIGURE 37: Five-year total cost of ownership comparison for diesel and battery electric trucks



Note: ICE = internal combustion engine. ICE (fleet operational) represents the average diesel truck fleet. ICE (theoretical best-in-class) represents the best-in-class diesel truck. BET = battery electric truck.
Source: Earl *et al.*, 2018

Catenary systems and e-roads

The use of catenary systems, sometimes called e-roads or e-highways, to power trucks is a potential option to address the range and weight concerns of battery electric vehicles. This concept consists of the electrification of long-haul routes through overhead lines which feed power to trucks along their routes. For this technology to work, trucks likely have to be hybridised with batteries in order to be able to operate when they are not in contact with the overhead lines.

In Germany, three five-kilometre-long overhead charging lines for hybrid diesel-electric trucks are currently being tested. The German government provided around USD 56 million for the three projects (Electrive, 2019) and has also spent roughly USD 77 million developing trucks that can use the system (CNN, 2019). At least one diesel-electric truck has entered service, and preliminary results suggest technological feasibility of the approach that would in principle allow for trucking companies to go electric without limitations on payload, range or operational hours. Other types of "e-roads" are also being researched, including inductive charging and conductive on-road strips.

Although overhead catenary systems are used widely for rail transport and in urban settings for public transport, the implementation of catenary systems and e-roads is still at an early piloting stage for long-distance freight transport. Currently the cost and viability of this option are very unclear, and its role in national strategies to reduce emissions looks limited.

REACHING ZERO – OPTION 2:
Fuel cell electric vehicles

ZERO

Fuel cell electric vehicles, like battery electric vehicles, use electricity to power an electric motor. The difference is that the electricity is produced by a fuel cell powered by compressed hydrogen gas instead of relying on a battery. These vehicles have a fuel tank onboard which has to be filled in a hydrogen charging station. FCEVs do not have harmful tailpipe emissions – they only emit water and heat – and therefore are an option to achieve zero emissions in the freight transport sector, as long as they use green hydrogen.

FCEVs are still at a very early stage of deployment and comprise a negligibly small part of the global road transport fleet. For wider uptake, the high cost of fuel cells needs to fall and a hydrogen charging network needs to be in place (Fraunhofer ISI, 2017).

Interest in FCEVs for passenger vehicles had grown over the last few years but now seems to be declining. Recently, a handful of automakers, such as Daimler and Honda, announced that they would stop developing hydrogen fuel cell passenger cars due to their high manufacturing costs and the improving performance of battery electric vehicles (Electrek, 2020).

However, interest in FCEVs for heavy-duty vehicles may be growing. Daimler also announced that it would continue to work on fuel cell-powered heavy-duty vehicles, due to the better suitability of fuel cells for this category of vehicles (Electrek, 2020).

FCEVs may allow for higher ranges across all truck classes compared to current battery electric vehicle technologies. For example, the Nikola One fuel cell has a maximum range of over 1 100 kilometres for a Class 8 tractor-trailer application (Nikola Corp, 2020). Anheuser-Busch recently ordered 800 hydrogen trucks from Nikola Motors which will be serviced by 28 dedicated hydrogen refuelling stations, with a plan to increase this number to 700 stations across the US and Canada by 2028 (AB, 2019).

China has in recent years been actively exploring the use of fuel cell electric heavy-duty trucks. By the end of 2018, 500 hydrogen fuel cell-powered 7.5 tonne urban logistics vehicles had entered the Shanghai freight market, serviced by two hydrogen fuelling stations (Ballard, 2018). New Energy Automobile Operation, a Shanghai-based venture company, announced the signing of a contract in 2019 to add 1 000 more FCEVs in 2019 (Mitsui, 2019) and has plans to run a fleet of as many as 7 500 vehicles and 25 stations by 2020 (Air Liquide, 2018).

Other examples will be seen in other parts of the world in the near future. Toyota and Kenworth are testing 10 fuel cell electric trucks with a 480-kilometre range in the US (Blanco, 2019). Mitsubishi Fuso will begin series production of fuel cell electric trucks in Japan by the end of 2020 (Mitsubishi Fuso, 2020), and Hyundai is expected to deliver 1 000 fuel cell electric trucks in the Swiss market between 2019 and 2024 (Hyundai, 2018).

REACHING ZERO – OPTION 3: Biofuels

Emission reductions in road freight transport, which relies largely on diesel as its main fuel source, can also be achieved through the use of biomass-based diesel substitutes, such as biodiesels and renewable diesels. These two products are commonly confused with each other; however, they have different characteristics, as explained below. A third option is the use of either biogas or biomethane as an alternative to natural gas for powering trucks.

Biodiesels

Fatty acid methyl esters (FAME) are produced via esterification of vegetable oils and fats, and are also known as biodiesels (see the Annex for a fuller discussion). Biodiesels are not drop-in fuels – that is, they cannot be used directly in conventional diesel engines, other than when blended with diesel in limited amounts.

FAME is already being blended with conventional diesel and used in existing vehicles without any engine modification. The most common FAME blends currently used in road vehicles are 5% FAME (B5), which is the maximum blend allowed in Europe, and 20% FAME, which is the limit in some other parts of the world.

The use of higher FAME blends is possible with engine adaptations, and a number of commercial truck engine manufacturers are reportedly ready to manufacture engines that are compatible with higher FAME blending rates (UFOP, 2018). FAME can also be used without blending (B100) in adapted engines, as long as it complies with the necessary technical standards, for example the EN 14214 standard in Europe and the ASTM D 6751 standard in the US. One of the major truck manufacturers, Scania, produced 220 trucks powered by B100 for the Australian market in 2014 (Reuters, 2014).

Renewable diesel

Hydrotreated vegetable oil (HVO), also known as hydroprocessed esters and fatty acids (HEFA), is commonly referred to as renewable diesel (see the Annex for a fuller discussion). Renewable diesel is produced mainly by hydrotreating vegetable oils and fats (including waste and residues) at high temperature, although it can also be produced via other conversion processes such as gasification and pyrolysis. Renewable diesels have higher compatibility with conventional engines than biodiesel and can be used as drop-in fuels. This implies no additional costs related to the adaptation of engines, storage and distribution infrastructure.

The use of renewable diesel, mainly HVO, has been tested in some pilots. SNEL Logistic Solutions has run tests in the town of Deinze, Belgium using HVO in its commercial trucks. The result was an 89% reduction in CO_2 emissions, 33% less particulate matter and 9% fewer nitrogen emissions (DAF, 2018).

Biogas and biomethane

Biogas or biomethane can be used as transport fuel. In the case of biomethane it can be used as a drop-in substitute for natural gas, given its near-identical properties. Biomethane is the result of upgrading biogas by removing hydrogen sulphide, water vapour and hazardous trace compounds. Biogas is produced mostly through the anaerobic digestion of organic matter, although it can also be produced via gasification of biomass (see the Annex for a fuller discussion).

Biomethane can be used in both light- and heavy-duty natural gas-powered vehicles without requiring any specific adaptation. Dedicated gas engines are already typically used in light-duty commercial vehicles, city buses and urban service fleets, for example for delivery and refuse collection. These engines usually have a maximum power output of around 400 horsepower (IRENA, 2018a).

Some truck manufacturers are looking to develop biogas-fuelled trucks for heavy and long-haul transport operations (Volvo, 2017), and there are examples of the use of biogas in commercial freight transport. For example, in 2018 the grocery store chain Lidl started using trucks fuelled with liquefied biogas (LBG) in Finland. The LBG was produced from the stores' own wastes (Gasum, 2018a). The introduction of these trucks was expected to cut CO_2 emissions by up to 85% compared with traditional fossil fuels, and Lidl has plans to increase the number of LBG trucks in the future.

More information on this topic can be found in the following publications and platforms:

IRENA's *Technology brief: Biogas for road transport* (www.irena.org/publications/2017/Mar/Biogas-for-road-vehicles-Technology-brief)

IRENA's *Technology brief: Electric vehicles* (www.irena.org/publications/2017/Feb/Electric-vehicles-Technology-brief)

IRENA's *Innovation outlook: Advanced liquid biofuels* (https://irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels)

IRENA's report *Hydrogen from renewable power: Technology outlook for the energy transition* (www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power)

IRENA's report Hydrogen: A renewable energy perspective (www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective)

International Transport Forum (www.itf-oecd.org)

International Council on Clean Transportation (https://theicct.org)

SLOCAT – Partnership on Sustainable, Low Carbon Transport (https://slocat.net)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, with an appendix on heavy-duty road transport (www.energy-transitions.org/mission-possible)

Clean Road Freight Coalition (www.weforum.org/mission-possible/action-areas)

3.4 Aviation

Key insights

- Aviation accounts for 11% of all transport emissions, or roughly 3% of global energy-related CO_2 emissions.
- Demand for aviation is expected to more than double by 2040, making decarbonisation of the sector a priority.
- Aviation is dependent on high-energy-density fuels due to mass and volume limitations of aircrafts. With current aircraft designs, this limits the options of alternative fuels suitable for replacing jet fuel to some advanced biofuels and synthetic drop-in fuels.
- Advanced biofuels, in the form of biojet, are the most technologically straightforward pathway to decarbonise the aviation sector. However, advanced aviation biofuel production today is only able to meet 0.004% of global jet fuel demand. Perceived barriers for biofuels include regulatory shortcomings, availability of financing, and feedstock costs and accessibility.
- Synthetic aviation fuels produced from green hydrogen could also play a role in decarbonising aviation as drop-in fuels. The main barrier for scale-up and widespread use of synthetic fuels is their relatively high costs, exacerbated by a lack of demand for them at the current price point.
- Electric propulsion has some advantages over jet engines such as lower complexity and maintenance costs. However, due to technical limitations related to mass, weight and volume, the technology is currently only feasible for small planes and short-haul flights.

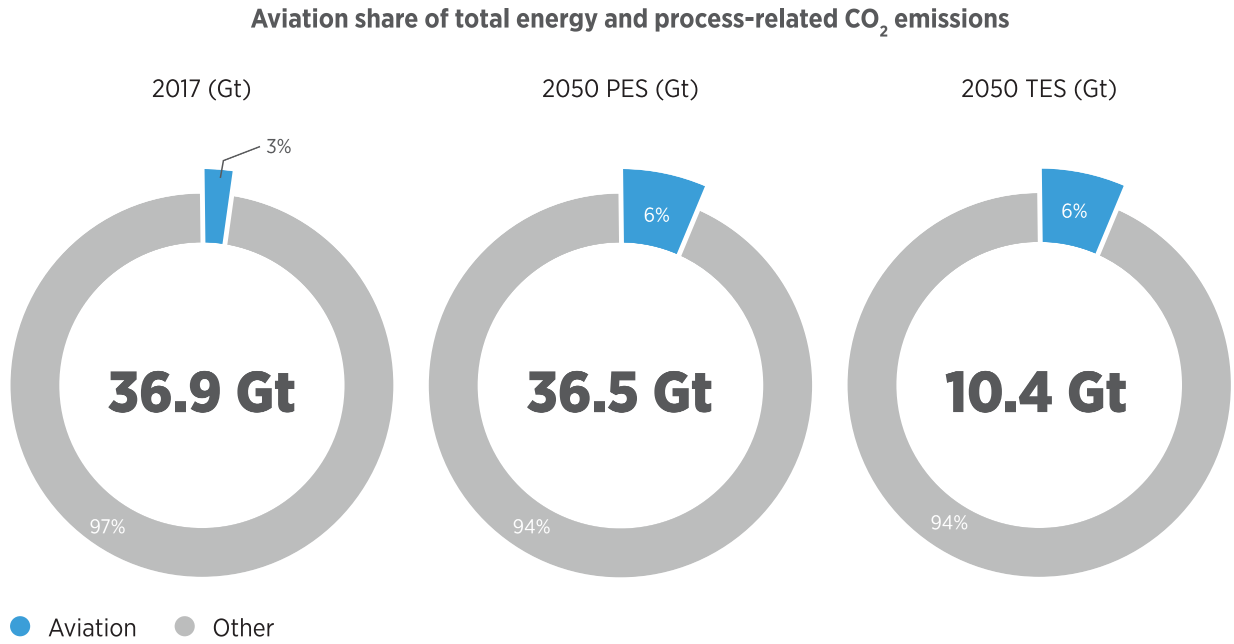
Sector emissions and energy use

Figure 38 shows how the share of total energy and process-related CO_2 emissions from aviation will need to change over time. In 2017, aviation accounted for roughly 3% of total energy-related CO_2 emissions. With current planned policies and programmes, the share of emissions from aviation will more than double by 2050. In the Transforming Energy Scenario, the sector's share of emissions would double to 6% (as other sectors decarbonise more quickly), leaving 0.7 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 15 shows how the share of renewable energy in aviation's energy use could to 40% in 2050 under the Transforming Energy Scenario – more than four times the share in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute around 6 EJ of aviation's total demand of 15.1 EJ for energy by 2050. This would be sourced mainly from indirect electrification with green hydrogen and biofuels.

Delivering zero energy emission will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 39, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policy and programmes.

FIGURE 38: Aviation share of total energy-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



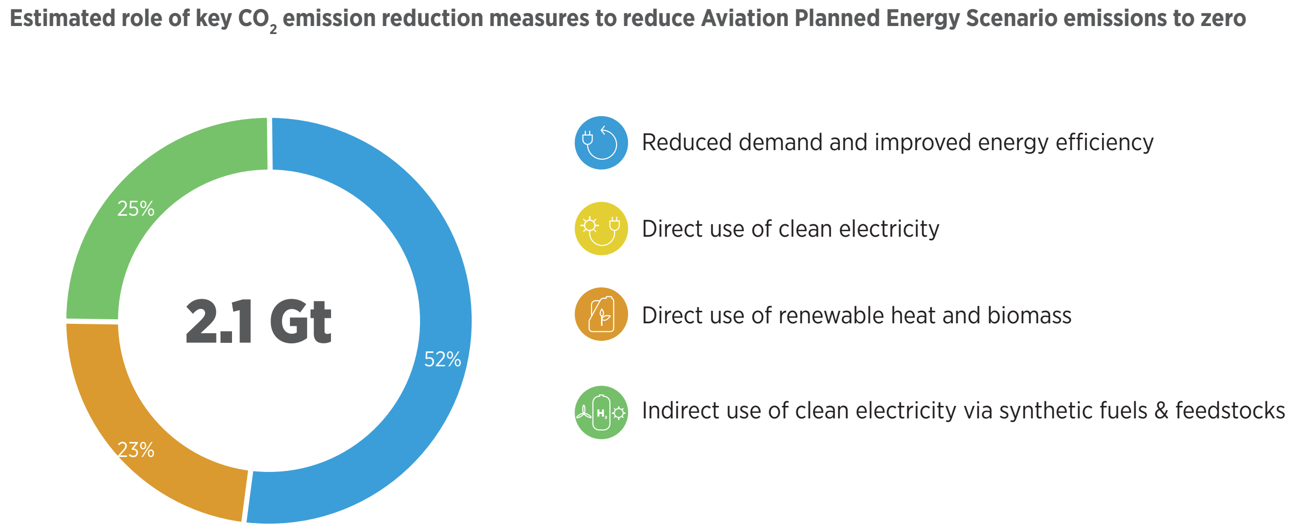
Source: IRENA, 2020a; IEA, 2017

TABLE 15: AVIATION ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO2 reduction from 2017 to TES	Additional progress needed in CO2 reduction from TES to zero
Aviation	Energy (EJ/year)	13.5	30.8	15.1	0.3 Gt/yr reduction (27% of 2017 total)	0.7 Gt/yr reduction (73% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	0.9	2.1	0.7		
	Renewable energy share (%)	-	10%	40%		

Source: IRENA, 2020a; IEA, 2017

FIGURE 39: Emission reduction measures to reach zero emissions in the aviation sector, from Planned Energy Scenario to zero



Note: Energy efficiency includes modal shifts and behavioural changes.
Source: IRENA analysis

Sector overview and the emission reduction challenge

Aviation, and jet fuel use in particular, is one of the fastest-growing sources of greenhouse gas emissions. Emissions from aviation in 2017 were around 0.9 Gt of CO_2 per year, or 2.5% of global emissions, and the climate impact is higher if upstream emissions in fuel production and non-CO_2 greenhouse effects are considered. By 2050 in the Planned Energy Scenario, emissions would increase to 2.1 Gt per year, whereas in the Transforming Energy Scenario they decline to around 0.7 Gt per year, despite an expected increase in passenger activity of more than 200%.

Demand for aviation services – the movement by air of passengers and freight – is growing quickly. Aviation passenger traffic[9] grew at an average rate of 7.3% per year from 2014 to 2018 (IATA, 2020a), and the industry's 20-year forecast suggests that total passenger traffic volume will almost double by 2037 (IATA, 2018). The bulk of these passenger movements are by jet. Although passenger traffic, and consequently aviation emissions, were considerably reduced due to the COVID-19 crisis, the aviation sector is expected to rebound. Passenger traffic and emissions will return to previous levels, and the industry is expected to keep growing. The COVID-19 crisis, however, presents an opportunity for the aviation industry to take advantage of recovery packages from governments to invest in sustainable technologies.

A large passenger jet consumes around 3.85 litres of jet fuel per 100 passenger-kilometres (Burzlaff, 2017). This is less than the average car, but the distances travelled are much longer. Global jet fuel consumption totalled 430 billion litres in 2017, or around 8% of total oil production, and this may double or triple by 2050 (Gielen and Oksanen, 2019).

Both oil-derived jet fuel and biofuel combustion cause contrails, possible cirrus cloud formation and nitrogen oxide emissions, which combined may be of a comparable magnitude to the warming impact of the CO_2 emitted (Teoh *et al.*, 2020).

9 By the standard industry measure, which is RPK (revenue passenger kilometres).

BOX 14: CLEAN SKIES FOR TOMORROW COALITION

The Mission Possible Platform's Clean Skies for Tomorrow (CST) initiative, led by the World Economic Forum, is a collaborative global public-private partnership among major businesses, non-governmental organisations, inter-governmental organisations and governments designed to facilitate a global transition to net-zero aviation by mid-century. With aviation a "hard-to-abate sector", CST provides the essential mechanism for leaders throughout aviation's diverse value chain to facilitate the transition to sustainable aviation fuels as part of a pro-active industry decarbonisation pathway.

Stakeholders partner to overcome the chicken-and-egg scenario in which producers and consumers are either both unwilling or unable to shoulder the initial cost burdens associated with the technology and infrastructure required to produce sustainable aviation fuels at a scale and price competitive with existing fossil fuels.

The Coalition is co-developing and scaling elements to solve this challenge, advancing the commercial scale of viable sustainable aviation fuels for broad adoption in the industry by 2030. Initiatives include a mechanism for aggregating demand for carbon-neutral flying, co-investment finance vehicles, ambitious and industry-aligned public policy guidance, and geographically specific value-chain pilots.

Source: WEF, 2020

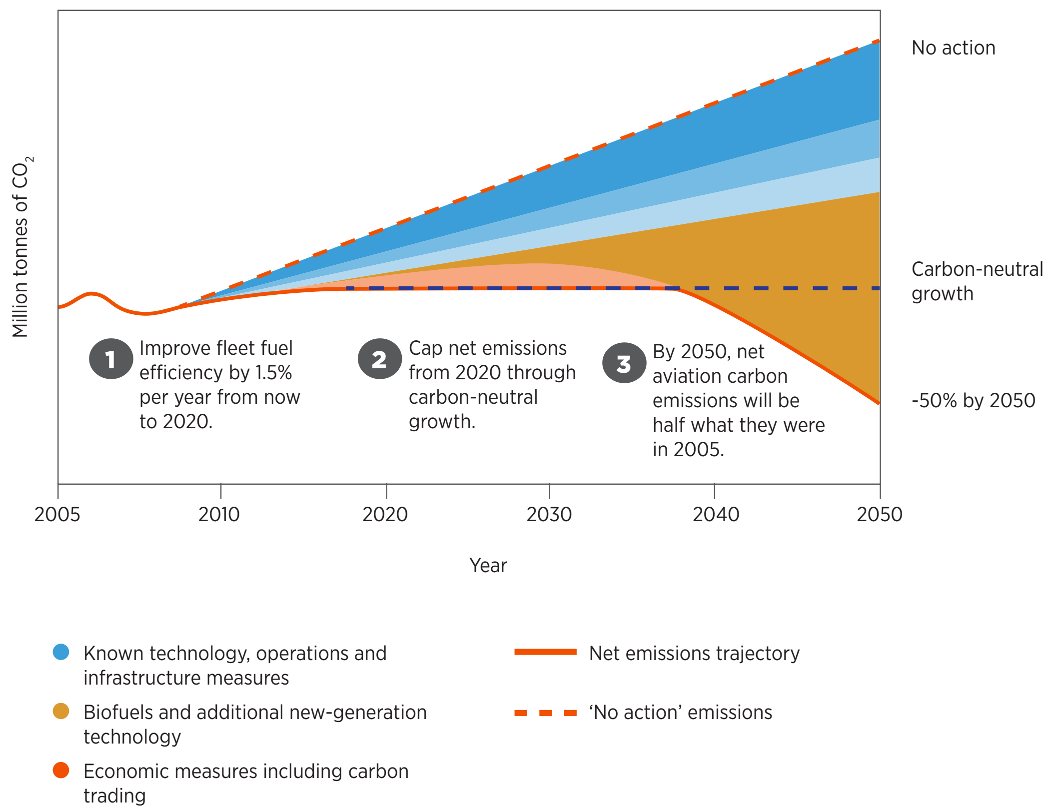
Options for reaching zero

There are three principal options that are consistent with the goal of zero CO_2 emissions from aviation:

1. Replace jet fuel with biofuels
2. Replace jet fuel with e-fuels
3. Move to electric propulsion with batteries or hydrogen fuel cells.

The International Air Transport Association (IATA) has called for a transition to halve CO_2 emissions in aviation between 2010 and 2050, a four-fold reduction compared to a no-action scenario (Figure 40). In IATA's scenario additional technologies (*i.e.*, underdeveloped technologies and biofuels) would account for half of total CO_2 emission reduction efforts. A global objective of reaching zero emissions by 2060 would require a much higher ambition for the aviation sector.

FIGURE 40: Aviation industry roadmap for emissions mitigation



Source: IATA, 2013; IRENA, 2017d

REACHING ZERO – OPTION 1: Biofuels

Aviation biofuels production

Global biofuels production totalled 150 billion litres in 2018, but just 17 million litres of advanced biofuels for aviation was produced, all from a single plant in California. That is equal to 0.004% of total aviation fuel consumption (Gielen and Oksanen, 2019). To make progress towards zero emissions, aviation biofuel is likely to be needed in substantial quantities after 2030, given the lack of technical maturity of the other options explored in this chapter. Rapid upscaling of production of biofuel for aviation is therefore urgently needed, and the share of aviation fuel in total biofuel must increase rapidly.

HEFA (hydrotreated esters and fatty acids) is the easiest solution to decarbonise aviation today. This is similar to the biodiesel mentioned in the previous sub-section; however, it undergoes a more severe cracking process. HEFA capacity is at present around 6 billion litres per year, with Neste, a Finnish refinery, being the largest producer. Scaling up production is a difficult task, given that residue oils and fats are scarce, and cultivation of dedicated oil-bearing crops is land intensive. Additionally, not all feedstocks can be used freely, for example the use of palm oil is banned in Europe. Efforts are ongoing to develop new feedstocks based on oil crops on marginal lands.

Jet fuel and diesel are similar products. This gives producers some flexibility to adjust their product mix, and biojet production and cost reduction will benefit from ongoing work to find bio-based diesel replacements.

Other production options include gasification and Fischer-Tropsch synthesis, ethanol-to-jet and iso-paraffins. These biojet alternatives were recently authorised by the American Society for Testing and Materials (ASTM International) for use in airplanes, but production remains very limited.

Given the low volumes produced today, there is not an active market for biojet, and price information is limited. To provide an indication of the importance of fuel cost: an illustrative fuel price that is 60% higher than regular jet fuel would translate into a ticket price for a flight that is around 20% higher (Gielen and Oksanen, 2019). With increasing public awareness of the climate change impact, consumers have been progressively willing to pay higher prices for reduced carbon emissions in the aviation sector. However, this is limited to a certain level of price increase and depends on different socio-economic factors (Rains *et al.*, 2017; Rice *et al.*, 2020). Therefore, governments may need to create binding standards for alternative fuel shares or to introduce carbon pricing for an accelerated deployment of biojet.

Challenges for aviation biofuels

Although biofuels for aviation are a proven technology, various interrelated challenges remain that inhibit widespread use. These include, in particular, accessibility of sustainable feedstocks, a lack of investment in both R&D and production, and the current high costs of biofuels. That latter point is made even more challenging by the economic impact on the aviation industry of the COVID-19 pandemic.

Investments in production and distribution infrastructure of around USD 20 billion per year would be needed to meet 2050 biofuel demand; however, actual investments have declined from 2006/2007 levels to less than USD 3 billion per year in 2018 (IRENA, 2019e). The vast majority of investment is for conventional biofuels, and investment in advanced biofuels is lagging.

To close the cost gap with conventional jet fuel, longer-term cost reductions will be critical. HEFA is the lowest-cost advanced biofuel today. However, the volumes and the potential for cost reduction for HEFA are limited. An IRENA review of recent literature indicates a future biojet cost of USD 1 per litre at the lower end (Gielen and Oksanen, 2019), compared to the USD 0.5 per litre of jet fuel at the end of 2019 (IATA, 2020b). Although ethanol-to-jet and gasification are costlier today, the potential for cost reductions is greater, potentially dropping to below USD 0.6 per litre. However, these cost projections have significant uncertainties, since they are heavily influenced by feedstock costs, and as with all bioenergy feedstocks, costs may rise as demand increases. A starting point could be to create sufficient early demand so that investments in technology development and scale-up follow, as it is scale that drives deep cost reductions.

Government regulations and/or industry agreements that mandate minimum levels of sustainable aviation fuel use, including biofuels, can help create initial demand and can be ratcheted up over time. Captive fleets, such as the military, could also help create early demand. The Indian Air Force, for example, tested a 10% biojet blend on a Russian-made AN-32 transport aircraft and plans to expand the use of biojet fuel in its transport fleet and helicopters before applying it to fighter aircraft (Economic Times, 2019).

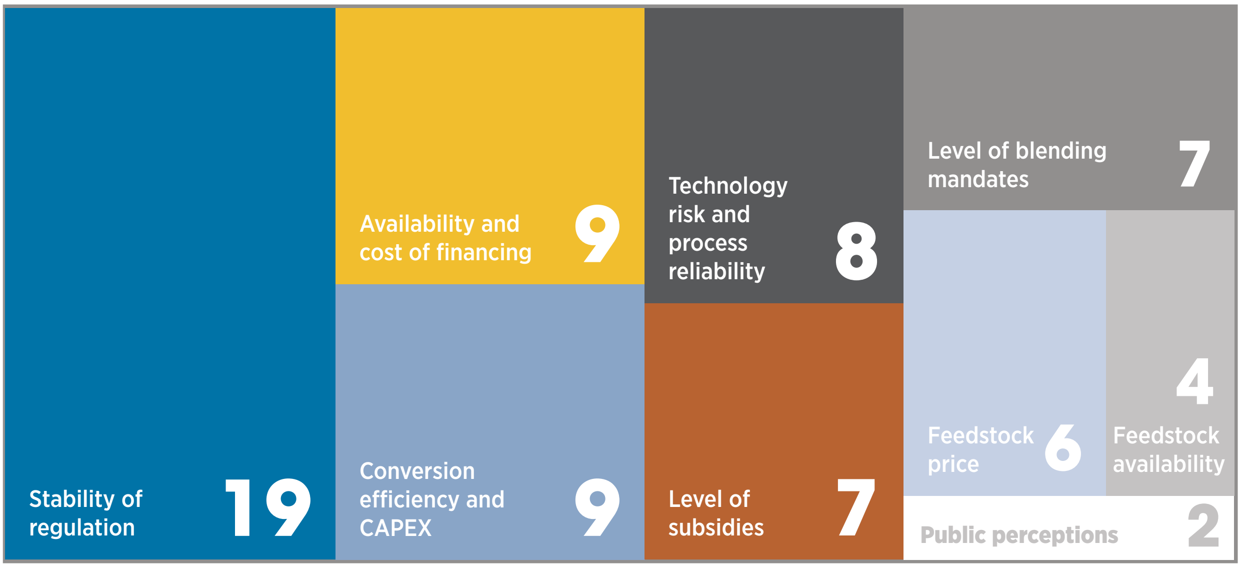
Industry commitments and agreements are important, but widespread use of sustainable aviation fuels will require a strong supportive regulatory framework or significant carbon pricing.

BOX 15: PERSPECTIVES FROM BIOFUEL INVESTORS

IRENA surveyed leading advanced biofuel investors from Europe, Brazil, China and North America to obtain their perspectives on industry development and the main barriers for deployment*. The sample covered nearly half of all companies worldwide with assets in this sector. Major aviation biofuel producers were included, and half of all respondents anticipated producing aviation biofuels by 2030. Questions spanned a broad range of topics from feedstocks, technologies and financing, to policies, consumer demand, and environmental and social issues.

A high-level overview of the findings is provided in Figure 41. It shows that concerns about the stability of regulation are dominant, including the level of blending mandates and subsidies. However, economic concerns are also key, including feedstock cost, conversion efficiency and capital expenditure. Public perception, notably, does not represent a major concern.

FIGURE 41: Barriers to advanced biofuels deployment, according to survey respondents



Note: Area is in relation to perceived importance. CAPEX = capital expenditure.
Source : IRENA, 2019e

A higher level of disaggregation shows distinct answers from HEFA producers and others. For HEFA producers, access to feedstock and feedstock pricing are important concerns. For other pathways that are based on ligno-cellulosic feedstock, the main concerns were on the technology side.

Most executives surveyed see fewer problems with technology and costs than a decade ago. Lignocellulosic ethanol and thermo-chemical producers still encounter more unresolved technical challenges and financing issues than HEFA producers. Investors are calling on policy makers to establish more stable and predictable investment environments for advanced biofuels, given the high investment cost, long planning horizon and project duration.

The majority of the executives surveyed regard the EU's upcoming Renewable Energy Directive (RED II) as a good enabling framework, but the path to get there was rocky and time consuming. European regulation brought fundamental changes (*e.g.*, the Indirect Land-use Change Directive 2015) to the investment environment in the middle of the 10-year RED I period (2011-2020).

*The survey results can be found in IRENA (2019d).

REACHING ZERO – OPTION 2: E-fuels

As discussed in Chapter 2, e-fuels are produced by synthetising CO_2 and green hydrogen. In the case of aviation, there is one e-fuel alternative that can replace fossil jet fuels and biofuels. This e-fuel is synthetic paraffinic kerosene (SPK), also known as synthetic kerosene. SPK can be chemically identical to fossil kerosene, and it could in theory meet all aviation performance and safety specifications. The two main ways to produce SPK from green hydrogen are the Fischer-Tropsch and the methanol pathways. These processes are more fully discussed in Chapter 2.

In the Fischer-Tropsch process, syngas, carbon monoxide and hydrogen are fed into a reactor to produce a mixture of saturated hydrocarbons which can then be refined into a kerosene substitute. This fuel is referred to as Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK). Synthetic fuels for aviation need to comply with standard ASTM D7566 for their use to be approved. FT-SPK is currently approved for use in blends of up to 50%.

Another alternative to the Fischer-Tropsch process is to produce SPK from e-methanol[10]. In this case, e-methanol is produced via methanol synthesis and later converted into SPK. This production pathway has not yet received approval for use under standard ASTM D7566; however, this pathway is suitable to produce a synthetic fuel that could potentially be used as a drop-in, not just in blends (Schmidt *et al*., 2018).

Since both pathways use CO_2 and hydrogen as feedstocks, the ability to capture CO_2 at low cost is critical, as is the availability of low-cost renewable power to produce hydrogen. Today, e-fuels made from hydrogen and CO_2 captured from air cost around USD 6 per litre, compared to the USD 0.50 per litre of jet fuel at the end of 2019 (IATA, 2020b), but this could drop to around USD 1 per litre over time (IRENA, 2019c). Hydrogen-powered planes are also technically feasible, although they would require a radical redesign of airframes.

10 The term e-methanol refers to methanol synthetised from green hydrogen produced via electrolysis.

BOX 16: OFFSETTING CARBON FOR INTERNATIONAL AVIATION

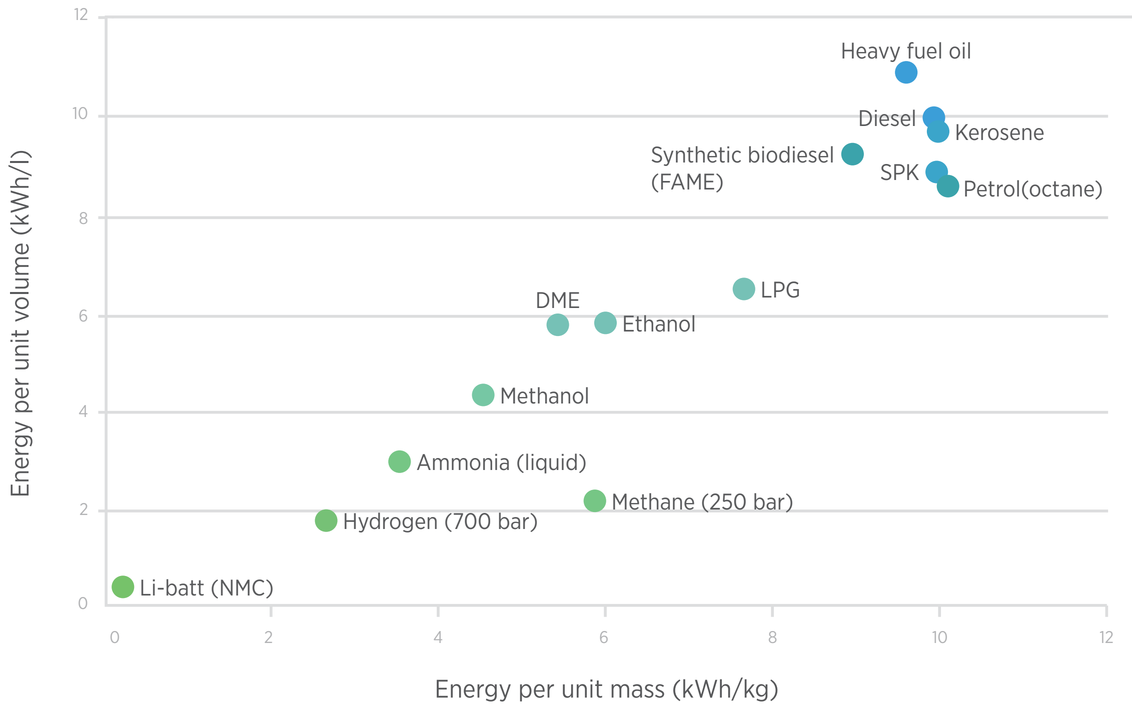
The voluntary Carbon Offsetting Scheme for International Aviation (CORSIA) allows airlines to reduce their offsetting obligation through the purchase of "CORSIA eligible fuels" – that is, alternative fuels which have lower associated greenhouse gas emissions. The CORSIA target was originally set to stabilise emissions from international aviation at the baseline of average 2019-2020 emission levels; however, due to the effects of the COVID-19 crisis on the aviation sector and to emission reductions in 2020 resulting from flight cancellations, the International Civil Aviation Organization's (ICAO) governing council agreed to change the baseline year used for calculating emissions under the global CORSIA deal to 2019.

REACHING ZERO – OPTION 3: Electric propulsion

Electric propulsion systems are just starting to appear in aviation fleets. Several small manufacturers offer electric planes for general aviation use, and a handful of test flights for commercial aviation service, initially targeted at short-haul routes, have been completed (Harbour Air, 2019). Hybrid-electric small commercial planes are being tested as well. Electric propulsion systems offer many advantages over jet engines: lower complexity, fewer moving parts, lower maintenance costs, lighter weight and smaller volume, improved safety and reliability, and lower operating costs.

There are two main challenges for the use of electric propulsion in aviation. Firstly, is the issue of energy density: jet fuel has significantly more energy per kilogram and per cubic metre than current lithium-ion batteries and hydrogen fuel cell systems (Figure 42). This gap might narrow as battery technology improves, but it is not yet clear whether and how electricity could fuel large, long-haul passenger aircraft. Secondly, jet engines burn jet fuel to produce thrust; moving to electricity would require an entirely different propulsion system. This might, for example, consist of multiple propellers driven by electric motors. Unless and until significant breakthroughs are made in these two areas it seems likely that electric propulsion in aviation will be limited to short- and medium-haul smaller planes. That said, there is an area of opportunity for hydrogen fuel cells in powering ancillary and non-essential systems.

FIGURE 42: Volumetric and gravimetric densities of potential transport fuels



Note: The values take into account typical tank weights. kWh/l = kilowatt-hour per litre, SPK = synthetic paraffinic kerosene, Li-batt (NMC) = lithium nickel manganese cobalt oxide battery, LPG = liquid petroleum gas, DME = dimethyl ether, FAME = fatty acid methyl esters.
Source: Royal Society, 2019

BOX 17: URBAN AIR MOBILITY

The concept of urban air mobility is that there will be a growing fleet of electricity-powered flying vehicles, such as drones and small passenger planes, moving passengers and freight short distances in urban areas. Fossil-fuelled helicopters already offer such services in a handful of areas (*e.g.*, Uber Copter); however, newer vehicle technologies and growing urban congestion make concepts such as electric flying taxis and package delivery drones more interesting. Several companies are already testing such drones, and the autonomous urban aircraft market is expected to see rapid growth.

Urban air mobility concepts will not necessarily replace existing demand. In fact, they might create more demand, and thus their energy and CO_2 impacts are unclear. However, they are likely to be electric powered, and as long as this power comes from renewable sources, their impact should be positive overall, especially if they manage to partially displace fossil fuel-powered delivery vehicles.

More information on this topic can be found in the following publications and platforms:

IRENA's report Hydrogen from renewable power: Technology outlook for the energy transition (www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power)

IRENA's report Hydrogen: A renewable energy perspective (www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective)

IRENA's Technology brief: Biofuels for aviation (www.irena.org/publications/2017/Feb/Biofuels-for-aviation-Technology-brief)

IRENA's report Advanced biofuels: What holds them back? (www.irena.org/publications/2019/Nov/Advanced-biofuels-What-holds-them-back)

IRENA's Innovation outlook: Advanced liquid biofuels (https://irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels)

The outlook for powerfuels in aviation, shipping (https://energypost.eu/the-outlook-for-powerfuels-in-aviation-shipping)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, with an appendix on aviation (www.energy-transitions.org/mission-possible)

Clean Sky for Tomorrow (www.weforum.org/agenda/2019/08/carbon-neutral-flying)

ICAO's Environmental protection (www.icao.int/environmental-protection/Pages/default.aspx)

IATA publications (www.iata.org/en/publications)

International Transport Forum (www.itf-oecd.org)

International Council on Clean Transportation (https://theicct.org)

3.5 Shipping

Key insights

- Shipping accounts for around 10% of transport emissions or 2% of global energy-related emissions.
- Fuel costs can account for 24-41% of total shipping costs. Since shipping relies on inexpensive refining residues as fuels, a major barrier and a decisive factor for the adoption of cleaner alternative fuels is their higher cost.
- Around 20% of the global shipping fleet is responsible for 85% of the net greenhouse gas emissions associated with the shipping sector. Therefore, a limited number of interventions might have a large impact in decarbonising the shipping sector.
- Biofuels are an immediately available option to decarbonise the shipping sector either in blends or as drop-in fuels. However, their potential is currently limited by uncertainties in the industry regarding their availability, sustainability and cost.
- Hydrogen and e-fuels, produced from renewable power, could play an important role in decarbonising shipping. While their adoption would require substantial adaptations to existing onboard and onshore infrastructure, and thus costs, a complete decarbonisation of the sector might not be possible without them.
- Ammonia, methanol and biomethane, produced from renewable power or biomass, are emerging as the most feasible low-carbon fuel pathways for ocean-going vessels, while electrification via batteries or fuel cells could play an important role for short-distance vessels (*i.e.*, ferries, and coastal and river shipping).

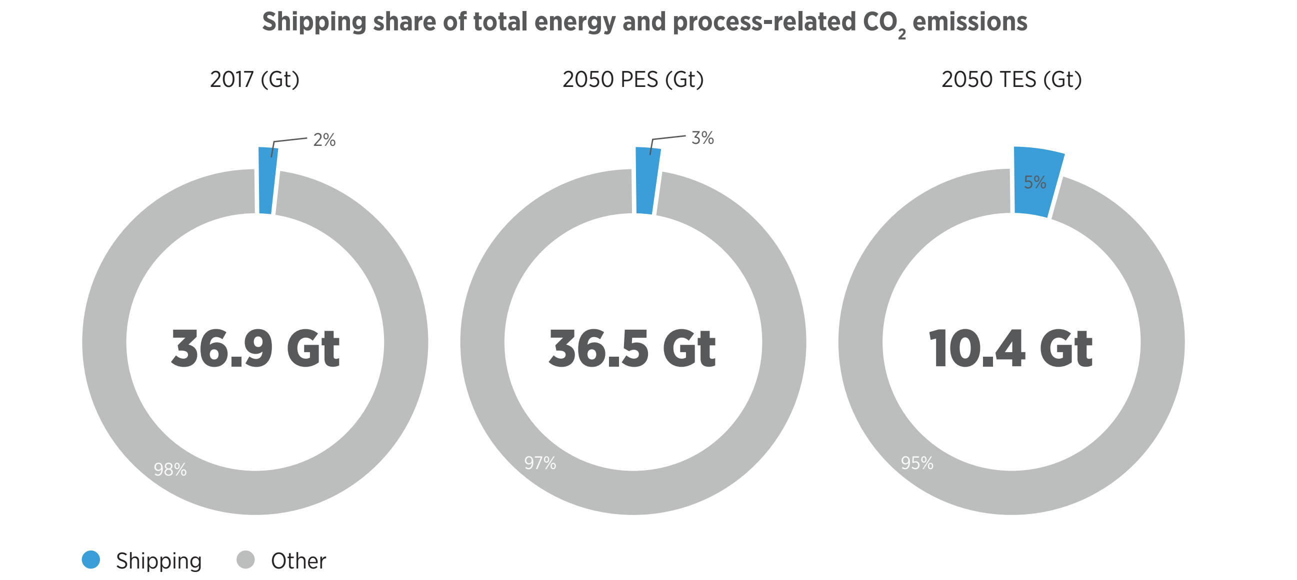
Sector emissions and energy use

Figure 43 shows how the share of total energy and process-related CO_2 emissions from shipping will need to change over time. In 2017, shipping accounted for roughly 2% of total energy-related CO_2 emissions. With current planned policies and programmes, the share of emissions from shipping will increase to 3% by 2050. In the Transforming Energy Scenario, shipping emissions will more than double (as other sectors decarbonise more quickly), reaching 5%, and leaving 0.5 Gt of emissions to be eliminated. Achieving the reduction realised in the Transforming Energy Scenario will be challenging, but even more so if the goal is zero emissions.

Table 16 shows how the share of renewable energy in shipping's energy use could increase substantially from virtually no renewables in 2017 to 12% in 2050 under the Transforming Energy Scenario – more than four times the share in 2050 in the Planned Energy Scenario. In the Transforming Energy Scenario, renewable energy would contribute almost 1 EJ of shipping's total demand of 7.4 EJ for energy by 2050. This would be sourced mainly from indirect electrification with green hydrogen and biofuels.

Delivering zero energy emissions will require 100% of the energy demand to be met by clean, predominantly renewable, energy sources. Determining the detailed energy and renewable implications of eliminating those remaining emissions will require further analysis – which IRENA expects to carry out in 2021. Figure 44, however, summarises some initial analysis which provides an indication of the contribution that different emission reduction measures are likely to make in reaching zero emissions, over and above current planned policies and programmes.

FIGURE 43: Shipping share of total energy-related emissions in 2017 and 2050 (Planned Energy Scenario and Transforming Energy Scenario)



Source: IRENA, 2020a; IEA, 2017

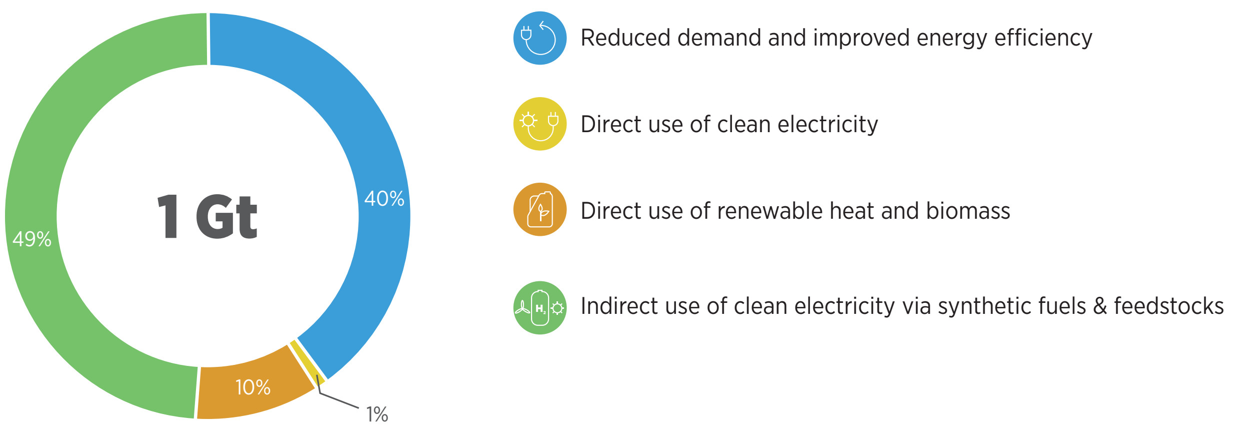
TABLE 16: SHIPPING ENERGY DEMAND AND EMISSIONS

		2017	2050 – Planned Energy Scenario	2050 – Transforming Energy Scenario	Progress made in CO2 reduction from 2017 to TES	Additional progress needed in CO2 reduction from TES to zero
Shipping	Energy (EJ/year)	11.3	13.7	7.4	0.4 Gt/yr reduction (43% of 2017 total)	0.5 Gt/yr reduction (57% of 2017 total)
	Energy-related CO_2 emissions (Gt/year)	0.9	1	0.5		
	Renewable energy share (%)	-	3%	12%		

Source: IRENA, 2020a; IEA, 2017

FIGURE 44: Emission reduction measures to reach zero emissions in the shipping sector, from Planned Energy Scenario to zero

Estimated role of key CO_2 emission reduction measures to reduce Shipping Planned Energy Scenario emissions to zero



Note: Energy efficiency includes structural change.
Source: IRENA analysis

Sector overview and the emission reduction challenge

International shipping is responsible for 90% of the world's trade (ICS, 2020). By the end of 2018, the global shipping fleet had a capacity of nearly 2 Gt and transported 8.7 Gt of freight. In 2017, port container traffic amounted to 753 million twenty-foot equivalent units (TEUs)[11] of containers. Global international bunkering for shipping totalled 8.9 EJ in 2017 (around 215 Mt of fuel), with 82% being heavy fuel oil and the remaining 18% being marine gas and diesel oil. Container ships, bulk carriers and oil tankers together make up more than half of total fuel use.

The shipping sector is responsible for 2% of annual global CO_2 emissions, or 0.9 Gt in 2017. International shipping bunker fuel use accounts for around 10% of global emissions associated with the transport sector. In the absence of suitable mitigation policies, the International Maritime Organization (IMO) estimates that greenhouse gas emissions associated with the shipping sector could grow between 50% and 250% by 2050 (IMO, 2015). In this context, the IMO also states that CO_2 emissions from shipping need to fall urgently, by at least 50% by 2050, compared to 2008.

By 2050, IRENA's Transforming Energy Scenario expects to see CO_2 emissions from the shipping sector go down from 0.9 Gt per year to 0.5 Gt per year, compared to a slight increase observed in the Planned Energy Scenario, where CO_2 emissions go up to 1 Gt per year. Most of these emission reductions come from improvements in energy efficiency, with the remainder coming from the introduction of biofuels and e-fuels such as ammonia and methanol.

Despite efficiency gains, without additional actions these emissions are expected to continue to rise as trade volumes grow. With global GDP expected to

11 A twenty-foot equivalent unit (TEU) is a shipping container whose internal dimensions measure around 20-feet long, 8-feet wide and 8-feet tall.

increase between 2019 and 2024, global trade volume could grow at a similar annual rate over the next five years. At present the tighter regulations on sulphur oxide reductions are expected to be the key driver impacting CO_2 emission reductions in the shipping sector. Fleet owners are considering transitional solutions such as the incorporation of exhaust gas scrubbers and the switch to fossil-based liquefied natural gas (LNG); however, this will not be enough to achieve the IMO's decarbonisation targets, let alone the complete decarbonisation of the shipping sector.

The shipping sector will eventually need to shift to renewable fuels and to alternative means of propulsion. There is growing recognition of this in the sector with, for example, Maersk, the world's biggest container shipping company, aiming to have carbon-neutral vessels commercially available by 2030 and to be fully carbon neutral by 2050 (Jacobsen, 2018).

The shipping sector is heavily dependent on inexpensive, low-grade refining residues. Although several lower-carbon alternatives exist that can function well technically, they all come at a considerable cost premium. Therefore, a combination of cost reduction and regulatory change will be needed to shift shipping off its current fuel.

BOX 18: GETTING TO ZERO COALITION

The Getting to Zero Coalition is an alliance of more than 90 companies within the maritime, energy, infrastructure and finance sectors that is part of the Mission Possible Platform. The coalition is also supported by several governments, non-governmental organisations and inter-governmental organisations, and IRENA is a knowledge partner for the initiative. The main objective of the coalition is to get commercially viable deep-sea zero-emission vessels powered by zero-emission fuels into operation by 2030.

To reduce greenhouse gas emissions from shipping by at least 50% by 2050 and to make the transition to full decarbonisation possible, commercially viable zero-emission vessels (ZEVs) must start entering the global fleet by 2030, with numbers to be radically scaled through the 2030s and 2040s. The coalition will develop and deliver a roadmap with tangible steps to accelerate the deployment of ZEVs, including:

- Visible and transformative leadership that can shift the industry consensus, increase understanding of what is possible and raise ambitions.
- Develop a shared knowledge base of integrated decarbonisation pathways to enable alignment and critical mass that can help shift the entire sector.
- Invest in analytics to focus on the fuels, ships, market drivers and policies necessary to make the transition to commercially viable and scalable ZEVs possible through technology, safety, economic incentives and regulation.
- Catalyse demonstrations, pilot projects and tests that can show the viability of different technologies, leverage best practices, and inform investment decisions and regulations to speed up the deployment of ZEVs.

Source: UN, 2019; GMF, 2020

Options for reaching zero

The shipping sector is one of the most difficult to decarbonise because today's bunker fuels consist of inexpensive refining residues, and therefore more expensive alternative fuels are not economically competitive. Moreover, international shipping is outside national greenhouse gas emission accounting frameworks.

Biofuels, renewable hydrogen and other hydrogen-derived fuels such as ammonia are being considered as fuel alternatives. Although electric battery systems are being introduced for short-range ferries, they are not yet an option for long-range ocean-going vessels.

The shipping sector is an energy-intensive sector where bunker fuel costs can account for 24-41% of total shipping costs (Notteboom and Vernimmen, 2009; IRENA, 2019d); therefore, competitive fuel prices are key. Low-carbon fuel options currently have costs ranging from two to five times that of heavy fuel oil. This gap, however, could narrow in the medium to long term as the adoption of clean technologies grows across sectors and as technology improvements and supportive regulations drive scale-up. Other decisive factors will include fuel availability and competition for scarce biomass, infrastructure adaptation costs, technological maturity, toxicity and sustainability issues.

One factor that may assist is that the industry is relatively concentrated and so a limited number of interventions could have a significant impact on emissions in this sector. For example, bulk and container carriers, and oil and chemical tankers, represent 20% of the global shipping fleet. Together these vessels are responsible for 85% of the net greenhouse gas emissions associated with the shipping sector. Seven countries together account for 57% of global bunkering; Singapore alone accounts for 22%, and the Netherlands is the largest bunkering country in Europe with a 6% global share.

REACHING ZERO – OPTION 1: Biofuels

Advanced biofuels could play a key role in the decarbonisation of the shipping sector. They can be used in blends or as drop-in fuels, and they can offer reduced greenhouse gas, nitrogen oxide and sulphur oxide emissions compared with fossil fuel alternatives. Additionally, due to their biodegradability, they are safer for the environment in the case of spills when unblended. In the context of shipping, four main biofuels are being considered: biodiesel, renewable diesel, bio-fuel oil and liquefied biogas (LBG). The idea of methanol as a marine fuel is also gaining traction in the shipping sector, thus bio-methanol could also be considered an option.

Biodiesel, also known as FAME[12], produced from vegetable oils and fats, can be used to replace marine diesel oil (MDO) and marine gasoil (MGO) in marine engines. The use of biodiesel in engines can have advantages such as improved lubricity of the engine; however, it can also create some issues with other engine components due to acid degradation. Other concerns that pertain to biodiesel are stability, water separation and microbial growth. Even though biodiesel could theoretically be used directly in marine diesel engines, standard ISO 8217, which established the requirements for fuels used in diesel engines, only allows the use of biodiesel in blends of up to 7% by volume. These 7% blends are already commercially available from major marine fuel producers. The use of 100% biodiesel would require engine modifications; therefore, it cannot be considered a drop-in fuel.

Renewable diesel[35], also known as HVO, produced from the hydrotreatment of vegetable oils and fats, can also be used to replace MDO and MGO in marine engines. Renewable diesel has similar qualities to its fossil fuel counterparts, and it does not present the stability,

12 See the Biofuels section in Chapter 2 (Biofuels) and the Road freight transport section in Chapter 3 for more information on biodiesel (FAME) and renewable diesel (HVO).

water separation and microbial growth issues observed in biodiesel. Renewable diesel can thus be considered a drop-in fuel and used directly in marine engines without modification. An alternative to renewable diesel (HVO) could be biomass-based Fischer-Tropsch diesel[13]. The Norwegian transport company Hurtigruten AS successfully tested the use of HVO in one of its cruise ships at the end of 2019 (Biofuels International, 2019).

Bio-fuel oil (BFO) can be produced from waste oil and crude tall oil[14] through an upgrading process and can be used as a replacement for heavy fuel oil and MDO. GoodFuels, a Dutch advanced biofuel manufacturer, estimates CO_2 emission reductions from the use of BFO to be up to 90% and a complete elimination of sulphur oxide emissions (GoodFuels, 2020a). BFO is considered to be a drop-in fuel, although its use is still being tested. In late 2018, GoodFuels and Danish shipping company A/S Norden completed the first successful trial of BFO on a tanker vessel. As of the first quarter of 2020 testing of this fuel continued, with further tests being carried on a medium-range tanker owned by the Swedish shipping company Stena Bulk (Stena Bulk, 2020) and on a large container ship owned by French shipping company CMA CGM (GoodFuels, 2020b).

Liquefied biogas (LBG) could be an option for LNG-powered ships. Despite it being called liquefied biogas, LBG is composed entirely of biomethane, not biogas[15], and therefore its characteristics are identical to LNG and it can be used as a drop-in fuel. There are already examples of LBG use in ships, as seen on the tanker *Fure Vinga*, owned by the Swedish shipping company Furetank Rederi AB (Gasum, 2018b).

Some major shipping lines are already using biofuel blends in their fleets. For example, the MSC Mediterranean Shipping Company started using 30% biofuel blends in all of its vessels calling at the port of Rotterdam. The company expects a 15-20% reduction in their overall CO_2 emissions (MSC, 2019).

Despite having advantages, three main barriers limit the potential of biofuel in the shipping sector: economics, sustainability and availability concerns. These limitations, however, are not enough to discard biofuels as a decarbonisation option. Even advanced biofuels are more expensive than their fossil counterparts; however, they are currently a cheaper solution than hydrogen and other fuels like ammonia and methanol due to their high technical compatibility with present ship engine technologies and bunkering infrastructure, and so would require little to no additional investments in infrastructure. Sustainability considerations are very important but can be managed, for example with the use of advanced biofuels, which are produced from residues and lignocellulosic crops and would therefore not compete with food crops. Finally, while the production volume of advanced biofuels is currently limited, capacity can be increased significantly. Total volumes might not be enough to fully cover the demand of shipping, aviation and road transport, and further discussion is needed as to where to prioritise biofuel use, but biofuels look likely to play a part in decarbonising shipping.

ZERO

REACHING ZERO – OPTION 2: Hydrogen and e-fuels

Hydrogen is a clean energy carrier that can play an important role in the transition to zero-emission shipping (see Chapter 2 for a fuller discussion of hydrogen). Other e-fuels such as green methanol,

13 For more on the Fischer-Tropsch process, see Chapter 2.

14 Crude tall oil is a liquid by-product of wood pulp manufacture.

15 The difference between biomethane and biogas is explained in Chapter 2.

ammonia and methane are also being considered as potential replacements for conventional marine fuels, due to their emission reduction potential (see Chapter 2 for a fuller discussion). It is important to note, though, that for these fuels to be emission-free they need to be produced with both green hydrogen and sustainably sourced carbon monoxide, CO_2 and nitrogen.

Hydrogen can be used directly as a shipping fuel, but its storage poses challenges. Hydrogen in its liquid form is more technically challenging to store than other fuel alternatives, even though there are commercial solutions available, as it must be stored at high pressure or under cryogenic temperatures (Table 17). That is one of the main reasons why other hydrogen-based synthetic fuels, such as methanol and ammonia, are being considered. Methanol is beginning to be utilised as shipping fuel. By 2016, seven ocean-going cargo ships of 50 000 tonnes each were operating on methanol through a dual-fuel engine produced by MAN SE, and 11 vessels were expected by the end of 2019 (Waterfront, 2019).

Vessels can also be retrofitted with methanol engines: the Stena Germanica ferry, for example, was retrofitted to operate with methanol in about four months, at a cost of roughly USD 27 million. These vessels were powered with conventional methanol produced with natural gas, so cannot be considered to run on a zero-emission fuel yet; however, as green e-fuels start to penetrate the market this can change. For example, BioMCN (BioMethanol Chemie Nederland) in the Netherlands currently produces 15% of its methanol from biogas (equivalent to 67 kilotonnes per year of capacity), and plans exist for upscaling based on green hydrogen (Bilfinger, 2018).

So far ammonia is not deployed for shipping, but Delft University of Technology recently published a design study for such a vessel (de Vries, 2019), and in January 2019 MAN Energy Solutions announced that it was developing an ammonia-fuel engine, based on one of its LPG engines. The engine is expected to be ready in 2024. In early 2020, MISC Berhad, Samsung Heavy Industries (SHI), Lloyd's Register and MAN Energy Solutions announced that they are working together to develop an ammonia-fuelled tanker (Lloyd's Register, 2020). The ammonia pathway is gaining traction.

The production of these hydrogen-based e-fuels, however, implies additional cost and efficiency losses, as discussed in the Annex. Another hurdle is that both ammonia and methanol are more toxic than conventional bunker fuels. However, in theory, the toxicity of ammonia and related safety concerns could be managed via regulation and technical measures, which could benefit from the decade-old ammonia production industry.

TABLE 17: COMPARISON OF DIFFERENT MARINE FUEL CHARACTERISTICS

Fuel type	Lower heating value [MJ/kg]	Volumetric energy density [GJ/m³]	Storage pressure [bar]	Storage temperature [°C]
Marine gas oil	42.7	36.6	1	20
Liquefied natural gas	50	23.4	1	-162
Methanol	19.9	15.8	1	20
Liquid ammonia	18.6	12.7	1/10	-34/20
Liquid hydrogen	120	8.5	1	-253
Compressed hydrogen	120	7.5	700	20

Source: Based on de Vries, 2019

More information on this topic can be found in the following publications and platforms:

IRENA's report Navigating the way to a renewable future: Solutions to decarbonise shipping (https://irena.org/publications/2019/Sep/Navigating-the-way-to-a-renewable-future)

IRENA's Technology brief: Renewable energy options for shipping (https://irena.org/publications/2015/Feb/Renewable-Energy-Options-for-Shipping)

IRENA's report Hydrogen from renewable power: Technology outlook for the energy transition (www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power)

IRENA's report Hydrogen: A renewable energy perspective (www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective)

IRENA's Innovation outlook: Advanced liquid biofuels (https://irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels)

Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century,
with an appendix on shipping (www.energy-transitions.org/mission-possible)

Getting to Zero Coalition (www.globalmaritimeforum.org/getting-to-zero-coalition)

Sustainable Shipping Initiative (www.ssi2040.org)

International Transport Forum (www.itf-oecd.org)

International Council on Clean Transportation (https://theicct.org)

4.

PLOTTING A WAY FORWARD

4 Plotting a way forward

4.1 Key challenges

This report has explored a range of options that, if applied comprehensively around the world, could reduce emissions in these seven sectors to near zero. However, none of the options listed will be easy to adopt. The reasons are varied and complex, but Table 18 summarises some of the most significant challenges and why they are significant. Addressing these challenges needs to be the focus of far more attention and creativity than is currently being applied.

TABLE 18: KEY CHALLENGES FACED BY INDUSTRY AND TRANSPORT SECTORS

Challenge	Discussion
High costs of new technologies and processes	In most cases the capital and/or operational expenditures (CAPEX and/or OPEX) of the technology options identified are higher than those they seek to replace, making commercial investments hard to justify without other incentives.
Gaps in knowledge and confidence	Many uncertainties remain about which options to pursue, how the technology options can be utilised to best effect and how they will perform in practice. Decision makers lack evidence and cannot make informed choices or plan with confidence.
Need for new enabling infrastructure or upgrades to existing infrastructure	New technologies and processes will require substantial new infrastructure or upgrades of existing infrastructure for fuel production, storage, distribution, storage and use that must be enabled by substantial investment. This infrastructure must be in place ahead of the demand if early progress is not to be stifled. Securing investment without confidence that the demand will emerge is challenging.
Highly integrated operations and long-established practices	The sectors discussed have well-established and often complexly interconnected infrastructure and well-established operational practices. Replacing one part of the operation – such as the fuel type – may have far-reaching consequences across multiple parts of the operation or require major changes in practices. For example, given that co-generation is widely deployed, a shift to renewable power may also require a change in heat supply. Careful, long-term planning to minimise disruption is needed.
Uneven, large and long-term investment needs	Material production plants or new fuel production infrastructure often have long lifespans and require large upfront capital investments. Missed opportunities to invest in clean infrastructure at, for example, key refurbishment milestones risk locked-in emissions and/or stranded assets. Innovative approaches to financial support schemes will be needed that are tailored to the end-use sectors' project needs and risks.

Dependency on progress in the energy sector	End-uses sector changes are often reliant on power or fuels supplied by the wider national energy system. While good progress is being made in many countries towards renewable-based energy systems, in some locations it will be decades before the energy supplies are fully decarbonised. In some cases, end-use sector companies may need to take their own steps to ensure a low-carbon energy supply.
Gaps in carbon accounting	Current greenhouse gas emission accounting frameworks do not cover all aspects of all sectors' emissions. International shipping and aviation, for example, are often outside national accounting systems. Feedstock carbon and biomaterial carbon "storage" are also not counted in sector emissions. And emissions in waste incineration are allocated to no one. This creates several "blind spots" for carbon release in the sector, with no incentive for action.
Competitiveness and carbon leakage risks for first-movers	Stringent standards in some countries but not others can lead to carbon leakage – that is, the shift of production to other, cheaper, more carbon-intensive production areas. Early-adopter countries or companies therefore risk facing higher costs than competitors, and the impact on emissions is weakened.
Legacy policy and regulatory framework	Policy and regulatory frameworks have been established on the basis of past technical knowledge that may now be outdated, and do not automatically catch up with new low-emissions processes. Similarly, regulators sometimes favour specific emerging technologies and implicitly hamper competition and innovation. Careful regulatory design is critical to minimise the risks of unintentional consequences. Beyond the national level, better alignment of policies across countries could also boost exchanges of knowledge and best practices.
Insufficient research, development and demonstration (RD&D)	Technology innovation through RD&D can be both evolutionary and disruptive. R&D efforts are needed for end-use sectors where technology solutions for decarbonisation are not yet operationally or commercially viable. However, investment in clean energy technology RD&D has been comparatively limited in the past years, and much of it has been directed at the power sector rather than at end-use sectors. Innovation in end-use sectors also needs to be broader than technology RD&D, taking a systemic approach that includes creating new ways of operating systems, including aspects such as new market designs, standards and innovative infrastructure.

4.2 Towards a renewables-based strategy

As the preceding sections showed, there are potential solutions that can be pursued in each sector, and equally there are significant challenges. Making progress in addressing the challenges and in scaling up the adoption of solutions will require actions by a wide range of actors, across all countries. The starting point to catalyse that action must be to build a broad understanding across decision makers of the challenges and opportunities and to develop a consensus on the broad strokes of a plan to address them. Each sector will need dedicated plans at the global, regional and national levels, but a number of common elements can form the starting point for that more detailed collaborative work. In particular a central feature of all sector plans should be to dramatically expand the use of renewables.

Sectors should not work in isolation. Partnerships that work between industry and government, across sectors and across borders will be key to sustained progress. Countries should be developing national plans that include sector-specific actions but that also work cross-sectorally to exploit synergies.

Those plans and activities need to begin now. Delivering the scale of technology change required in time to make a difference will require policy makers and industry to begin stepping up planning activity, RD&D and proof-of-concept projects in the 2020s so that deployment can be scaled up through the 2030s and 2040s and be complete by the 2050s.

Each sector is different, but a number of commonalities and cross-cutting themes lead to some shared recommendations. Working across sectors, industry and governments should together develop and implement plans as elaborated in Table 19.

TABLE 19: RECOMMENDATIONS FOR INDUSTRY AND GOVERNMENTS TO BEGIN THE TRANSITION TO ZERO EMISSIONS

1. Pursue a renewables-based strategy for end-use sectors with an end goal of zero emissions.	**This involves developing linked sectoral strategies at the local, national and international levels built on five technology pillars:** ➔ Reduced energy and materials intensity through efficiency measures and circular economy principles; ➔ Expanded renewables-based (direct) electrification through local generation and an accelerated greening of the electricity grid; ➔ Expanded use of sustainably sourced biomass and biofuels; ➔ Expanded renewable-based (indirect) electrification, *i.e.*, expand the production, distribution and use of e-fuels; ➔ Selective deployment of carbon capture, utilisation and storage.

2. Develop a shared vision and strategy and co-develop practical roadmaps involving all major players.	In the early stages of what will be a long haul – a 40-year transition – establishing a shared vision of the goal and the broad strategy to achieve that is critical. Crucially that vision must be broadly shared by all key actors – across political parties, across competing companies, by consumers and by the wider public. Roadmaps to build consensus and guide the delivery of that vision must be co-developed and co-owned by governments and key industrial actors. It is too often the case that the production of roadmaps is an academic or isolated exercise – produced by one subset of actors and not bought into by other groups. To be impactful roadmaps must be grounded in the realities of sectoral circumstances and constraints and must consider the impact on businesses and consumers. The best way to achieve that is to ensure that all key players are actively involved in the development of the roadmap. This work can be aided by international and inter-governmental bodies and initiatives such as IRENA, the World Economic Forum's Mission Possible Platforms, the United Nations-mandated Leadership Group on the Energy Transition (LEADIT), Mission Innovation and others.
3. Build confidence and knowledge among decision makers.	To enact the major policy and regulatory changes needed and to invest at the scale necessary, decision makers need to be confident that they understand the risks. Early action should therefore focus on building confidence among industry decision makers, regulators and investors by showing what is possible to do now and by sharing experiences (of both successes and failures) and key data. Those who can must lead – that is, developed countries, major economies and major companies need to step up and show what is possible. Currently, a small number of countries, and a few companies, are leading the way in the development and successful deployment of technologies for the full decarbonisation of end-use sectors. More need to follow. Many more demonstration and lighthouse projects and targeted "early-adopter" applications are needed. Public and private sector "coalitions of the willing" need to be built to lead the way in each sector. Every major economy should establish several projects in each end-use sector in the next five years.
4. Plan and deploy enabling infrastructure early on.	New technologies and processes will require substantial new infrastructure. For example, the use of green hydrogen and e-fuels at scale will require large amounts of renewable power, a large number of electrolysers, hydrogen storage, conversion technologies, distribution systems such as pipelines or shipping, and changes and new designs among the end-use technologies – for example, hydrogen-DRI plants or ammonia-fuelled ships, etc. The difficulty is that investment in this infrastructure needs to come ahead of the demand if early progress is not to be stifled. Carefully co-ordinated planning coupled with targeted incentives will be needed to ensure that the right infrastructure is built at the right time.

5. Foster early demand for green products and services.	Creating early sources of demand for green fuels, materials, products and services will help build the scale of production needed and so help in the reduction of costs. There are already good examples of this in some sectors but also some examples where the intended impact was not realised. A range of options can help do this – tailored to the sectors – including: public procurement, corporate sourcing, regulated minimum percent requirements for the use of green products, regulated maximum emission requirements per project and consumer-driven demand, for example for green products or green flights. Regulated requirements should be ratcheted up progressively but predictably over time.
6. Develop tailored approaches to ensure access to finance.	Considering the specificities of these sectors – *i.e.*, high CAPEX, long payback periods, etc. – tailored financial instruments along the whole innovation cycle are needed. Co-operation between public and private financial institutions will help to design financial products (equity and debt) to allow risk sharing. Co-operation between financial institutions and credit rating agencies can also incentivise sector players to further decarbonisation efforts. For example, credit rating agencies could incorporate criteria that reflect decarbonisation efforts into their rating which could result in various advantageous financial products where, for example, companies with higher ratings get access to lower interest rates. Public investment in RD&D is crucial for innovation through the whole technology life cycle. This also includes the jump from demonstration to commercialisation, which needs a healthy investment environment, but also strong institutional and governmental support. Joint ventures, crowdfunding, technology incubators and patents are some of the tools that policy makers can use to match supply and demand (*i.e.*, innovation initiators and the innovation recipients) and thus enable the market diffusion of innovative technologies.
7. Collaborate across borders.	This is a global challenge, and solutions need to be globally applicable. While each country will need to consider its national requirements, it should do so in the context of what is happening elsewhere, working in partnership where possible. The solutions needed are complex and expensive, and it is very unlikely that countries alone will be able to explore all options in the necessary depth. International collaboration can help countries share the burden of developing the different solutions simultaneously by identifying common challenges, tackling pressing technology and/or policy gaps, pooling experiences and sharing best practices to improve performance, reducing costs and reaching broad technology deployment.

8. Think globally, utilise national strengths.	The technology shifts required to decarbonise some industrial sectors could have geopolitical and global economic implications. For example, one strategy that has been barely explored to date is the potential to relocate industrial production to locations with better access to clean low-cost energy. For example, the shift from BF-BOF to the green hydrogen DRI-EAF route could enable a wider relocation of the iron and steel sector to areas where relatively low-cost and abundant renewable electricity sources are available. It is in countries' interest to see comparable progress across a range of economies in order to minimise carbon leakage and support fair competition. Developing economies are set to have a growing energy demand and growing shares of production in many sectors. The actions taken in developing economies therefore will become very important, and those economies should be supported to start early on the right (zero-carbon-compatible) track to avoid locked-in emissions or stranded assets and higher cost in the long term.
9. Establish pathways for evolving regulation and international standards.	Regulations and standards are key enablers of change but can also be barriers. Regulations and standards require careful planning to ensure that they shift at the same pace as the technological changes. Regulations can act as a pull for innovative low-carbon technologies. For example, in April 2019 the European Parliament and the Council adopted the Regulation (EU) 2019/631 which sets the "CO_2 emission performance standards" for new passenger cars and new light commercial vehicles in the EU after 2020. From 2021, the EU fleet-wide average emission target for new cars will be 95 grams of CO_2 per kilometre. Such a CO_2 limit makes the case for electric vehicles as the only available option at present to comply with this limit if the electricity fuelling those cars is renewable. This regulation has resulted in ambitious plans from European car manufacturers to accelerate the development and commercialisation of electric vehicles, not just in the region but globally. Comparable approaches could drive change in other sectors. International standards are a key component of successful global markets. The global adoption of low-carbon technologies requires a level playing field. Internationally harmonised standards can be a major enabler of the adoption of those technologies also resulting in cost reductions due to economies of scale. Furthermore, standards can ensure environmental integrity, for example by establishing certificates of origin for green hydrogen or green electricity used in industrial processes.
10. Support RD&D and systemic innovation.	Large gaps in capability and large cost differences between new renewables and established fossil fuel options still remain. Action is needed across a range of technologies to reduce costs, improve performance and broaden applicability. RD&D as an enabler of technology innovation plays a key part in achieving those goals, but RD&D investment for these sectors is very low compared to other parts of the energy transition and compared to other sectors of the economy. Significantly increased and better targeted public and private investment in RD&D are needed. Support to innovation must be systemic – that is, not exclusively focused on technology innovation. To be successfully deployed, technology innovation needs to go hand-in-hand with innovation in business models, in market design, in system operations and in regulation.

4.3 Options for reaching zero

As the preceding chapters illustrate, the objective of reaching zero CO_2 emissions requires a different mindset to that of merely reducing emissions. A wide range of potential options quickly collapse down to a handful when that filter is applied. This report identifies 18 principal options across seven sectors. Each of these options is being researched or piloted to some degree, but most are not mature, and most still face significant challenges to scale-up. The following pages summarise those options and some of the sector-specific actions needed to begin making progress towards widespread adoption.

TABLE 20: THE EMISSION REDUCTIONS TECHNOLOGIES AND PROCESSES THAT COULD REDUCE EMISSIONS TO ZERO OR NEAR-ZERO IN KEY INDUSTRIAL SECTORS AND THE EARLY ACTIONS NEEDED IN EACH SECTOR

Iron and steel

2 options compatible with reaching zero emissions

ZERO

Hydrogen-based direct reduction of iron and electric arc furnace-based steel production

- Produce iron via the direct reduction process using clean, preferably green, hydrogen as a reducing agent.
- Produce steel using electric arc furnaces.
- Source all heat and electricity inputs from renewables.

Capturing and storing process and waste emissions, and using renewables for energy

- Apply CCUS to existing iron and steel production processes.
- Source all heat and electricity inputs from renewables.

Priorities for action:

- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).
- Create early demand for "green" steel despite higher costs early on (*e.g.*, through public procurement, corporate sourcing and minimum percent requirements); creating a market can incentivise improvements in technologies and costs and reduce the risk of "carbon leakage".
- Increase public and private funding and cross-border collaboration for RD&D into hydrogen-based DRI and BF-BOF-based designs with CCUS.
- Exploit cross-sectoral synergies to reduce the cost of green hydrogen; many sectors will need lower-cost green hydrogen, and improving electrolysers, scaling up demand and creating distribution infrastructure will help.
- Explore opportunities to relocate iron production to areas with potential for low-cost renewable energy; this can create new value and supply chains while also delivering emission reductions.
- Ensure that countries with large or expanding iron and steel production can utilise zero-emission-compatible production technologies; emerging economies will account for high shares of future production.

Chemicals and petrochemicals

3 options compatible with reaching zero emissions

ZERO

Using biomass for feedstocks and renewables for energy

- Source all heat and electricity inputs from renewables.
- Use biomass for chemical feedstocks – replacing primary petrochemicals with bio-based chemicals or replacing fossil fuel-derived polymers (particularly plastics) with alternatives produced from biomass.

Using synthetic hydrocarbons for feedstocks and renewables for energy

- Source all heat and electricity inputs from renewables.
- Use synthetic hydrocarbons – produced from green hydrogen and clean CO_2 sources – for chemical feedstocks.

Capturing and storing process and waste emissions, and using renewables for energy

- Apply CCUS to existing production processes.
- Source all heat and electricity inputs from renewables.
- Apply measures for the permanent storage of the carbon in products – *e.g.*, a highly efficient circular economy, the long-term storage of waste products or CCUS applied to end-of-life combustion.

Priorities for action:

- Adopt a full life-cycle approach when considering the sector's emissions – one that accounts for the carbon in chemical-based products and their use and end-of life disposal.
- Transition to a truly circular economy, greatly increasing recycling and reuse rates and so reducing demand for new chemicals production.
- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).
- Create early demand for "green" chemicals and products (mandate if necessary); creating a market can incentivise improvements in process efficiency and costs and reduce the risk of "carbon leakage". Certification of green supply chains may be required.
- Increase public and private funding and cross-border collaboration for RD&D into bio-based or synthetic chemicals as drop-in replacements or alternative substitutes for existing products.
- Decouple fossil fuel refining from chemical production and establish stronger collaboration between the chemical industry and the clean energy sector to ensure complementary strategies and access to renewable energy.
- Address issues in how carbon emissions are measured and accounted for – for example, need to consider the "storage" of carbon in materials and emissions resulting from waste incineration.

Cement and lime

4 options compatible with reaching zero emissions

Reducing clinker use

- Partially substitute clinker with alternative binders, *e.g.*, blast furnace slag or fly ash.

Reducing demand for conventional cement

- Use alternative construction techniques to reduce cement use, and/or use renewable building materials, such as wood, instead of cement.
- Avoid clinker emissions by using alternative cement formulations.

Fuel switching to renewables

- Use direct electrification or the use of biomass and waste for process energy.

Capturing and storing CO_2 emissions

- Apply CCUS to abate remaining energy and process emissions.
- Use biomass with CCS (BECCS) to produce negative emissions that can offset some uncaptured clinker emissions.

Priorities for action:

- Explore a portfolio of options to eliminate the sector's emission through a combination of approaches; offsetting emissions from some plants with carbon removal measures elsewhere will be needed.
- Establish many more demonstration / lighthouse projects to show what can be done and to collate and share the learning (currently very few examples of such projects exist worldwide).
- Create demand for "green" cement (despite higher costs early on) and incentivise the use of alternative building materials (*e.g.*, through public procurement, corporate sourcing and minimum percent requirements); creating a market will incentivise improvements in technologies and costs and reduce the risk of "carbon leakage".
- Increase public and private funding and cross-border collaboration for RD&D into clinker alternatives, alternative construction techniques and materials, and the use of carbon removal technologies including CCUS and BECCS.
- Ensure that countries with large or expanding cement demand and production can utilise zero-emission-compatible approaches; emerging economies already account for high shares of current production and will account for high future shares.

Aluminium

1 option compatible with reaching zero emissions

ZERO

Renewable power and inert anodes

- Source all heat and electricity inputs from renewables.
- Develop and adopt inert anodes.

Priorities for action:

- Establish many more demonstration / lighthouse projects that combine renewable electricity sources with aluminium production (including business models) to show what can be done and to collate and share the learning (currently only a handful of such projects exist worldwide).
- Create early demand for “green” aluminium (mandate if necessary); creating a market can incentivise improvements in process efficiency and costs and reduce the risk of “carbon leakage”. Certification of green supply chains may be required.
- Establish closer collaboration between companies in the aluminium and power sectors – to ensure plans are compatible and to exploit synergies, particularly around new business models that create value from flexibility in demand and so help manage the increased deployment of variable renewable energy sources, such as solar and wind.
- Increase public and private activities and cross-border collaboration for RD&D into alternative ”inert” anode designs.
- Explore opportunities to relocate more aluminium production to areas with the potential for low-cost renewable electricity supply; this can reduce costs while delivering emission reductions.

Road freight

3 options compatible with reaching zero emissions

ZERO

Battery electric vehicles

- Use electric motors powered by a battery pack, charged with renewable electricity.

Fuel cell electric vehicles

- Use electricity produced by fuel cells powered by compressed (green) hydrogen.

Advanced biofuels

- Use biomass-based fuel substitutes, such as biodiesels and renewable diesels.

Priorities for action:

- Co-develop national and international roadmaps that have wide stakeholder support with clear milestones that show the sector-specific pathway towards full decarbonisation; a shared industry vision and a broad buy-in to the trajectory is a key enabler of investment.
- Establish many more demonstration / lighthouse projects involving small fleets of vehicles, to show what can be done and to collate and share the learning (some low-carbon freight vehicle designs are emerging, but they remain niche).
- Create incentives for low-carbon road freight deliveries (*e.g.*, through progressively tightening standards and through corporate commitments; creating demand can incentivise investment in technologies and so reduce costs.
- Increase public and private funding and cross-border collaboration for RD&D into battery performance improvements and cost reductions, vehicle designs, hydrogen, synthetic fuel, and biofuels production and supply.
- Exploit cross-sectoral synergies such as the need for lower-cost batteries, the need for lower-cost green hydrogen and hydrogen supply chains, and the need for expanded sustainable sources of biomass and biofuels, and the associated supply chains infrastructure.

Aviation

3 options compatible with reaching zero emissions

Biojet fuel

- Use fuels produced from sustainably sourced biomass.

E-fuels

- Use synthetic fuels produced from cleanly sourced CO_2 and green hydrogen.

Battery-powered aircraft

- Use propulsion systems powered by batteries charged with renewable electricity.

Priorities for action:

- Maintain support for and implement industry-wide international agreements on emission reduction mechanisms and build on those to establish a shared zero-emission vision and strategy for aviation.
- Develop (and ideally mandate) goals for domestic (in-country) aviation and develop national roadmaps to reach zero emissions that are co-owned by all stakeholders.
- Establish many more demonstration / lighthouse projects involving low-carbon fuel use or new aircraft designs, to show what can be done and to collate and share the learning (some low-carbon aircraft designs are emerging, but they are currently small aircraft only).
- Create incentives for low-carbon flights (*e.g.*, through progressively tightening standards, through corporate commitments and through consumer support); creating demand can incentivise investment in technologies and support scale-up which can reduce costs.
- Increase public and private funding and cross-border collaboration for RD&D into sustainable biomass supply, biofuels production, synthetic fuels production, electricity storage and alternative aircraft designs (particularly urgent to begin now because of very long development and licencing timelines of large aircraft).
- Develop a more detailed and shared understanding of the realistic potential future availability of key fuels (*i.e.*, biojet and synthetic fuels) in different locations and for different applications – to inform choices and trade-offs both in the aviation sector and across other sectors.
- Exploit cross-sectorial synergies such as the need for expanded sustainable sources of biomass and biofuels, the need for lower-cost green hydrogen and synthetic fuels production, and the associated supply chains' infrastructure.

Shipping

2 options compatible with reaching zero emissions

Advanced biofuels

- Use biomass-based fuels such as biodiesel, renewable diesel, bio-methanol, bio-fuel oil and liquefied biogas.

E-fuels

- Use green hydrogen or synthetic fuels such as green methanol, ammonia and methane.

Priorities for action:

- Maintain support for and implement industry-wide international agreements on emission reduction mechanisms and build on those to establish a shared zero-emission vision and strategy for shipping.
- Develop (and ideally mandate) goals for specific shipping routes and develop roadmaps to reach zero emissions that are co-owned by all stakeholders.
- Establish many more demonstration / lighthouse projects involving low-carbon fuel use on specific ships or on specific shipping routes and new ship propulsion designs, to show what can be done and to collate and share the learning (some projects are emerging, but they remain niche).
- Create incentives for low-carbon shipping (*e.g.*, through progressively tightening standards, and through corporate commitments including companies whose goods are shipped); creating demand can incentivise investment in technologies and support scale-up which can reduce costs.
- Increase public and private funding and cross-border collaboration for RD&D into sustainable biomass supply, biofuels production, synthetic fuels production and alternative ship propulsion designs.
- Develop a more detailed and shared understanding of the realistic potential future availability of key fuels (*i.e.*, biofuels synthetic fuels) in different locations and for different applications – to inform choices and trade-offs both in the shipping sector and across other sectors.
- Exploit cross-sectoral synergies such as the need for expanded sustainable sources of biomass and biofuels, the need for lower-cost green hydrogen and synthetic fuels production, and the associated supply chains' infrastructure.

The world has made remarkable progress in the last decade in developing renewable energy sources and has made positive steps towards decarbonising power systems. Collectively it must now seek to make comparable progress in addressing carbon emissions in end-use sectors. That 40-year transition has barely begun, but it warrants far greater attention, planning, ingenuity and resources now if progress is to be made fast enough. There are significant challenges but also a range of promising options – particularly those that make use of low-cost and abundant renewable resources. With the right plans and sufficient support, the goal of reaching zero emissions in key transport and industry sectors is achievable.

To engage further on this topic:

Join IRENA's virtual Innovation Week 2020 (5-8 October) or view the recordings, at http://innovationweek.irena.org.

Visit http://irena.org/industrytransport for further reports including upcoming *Reaching Zero* briefing papers which will provide short, decision maker-focused insights on specific topics.

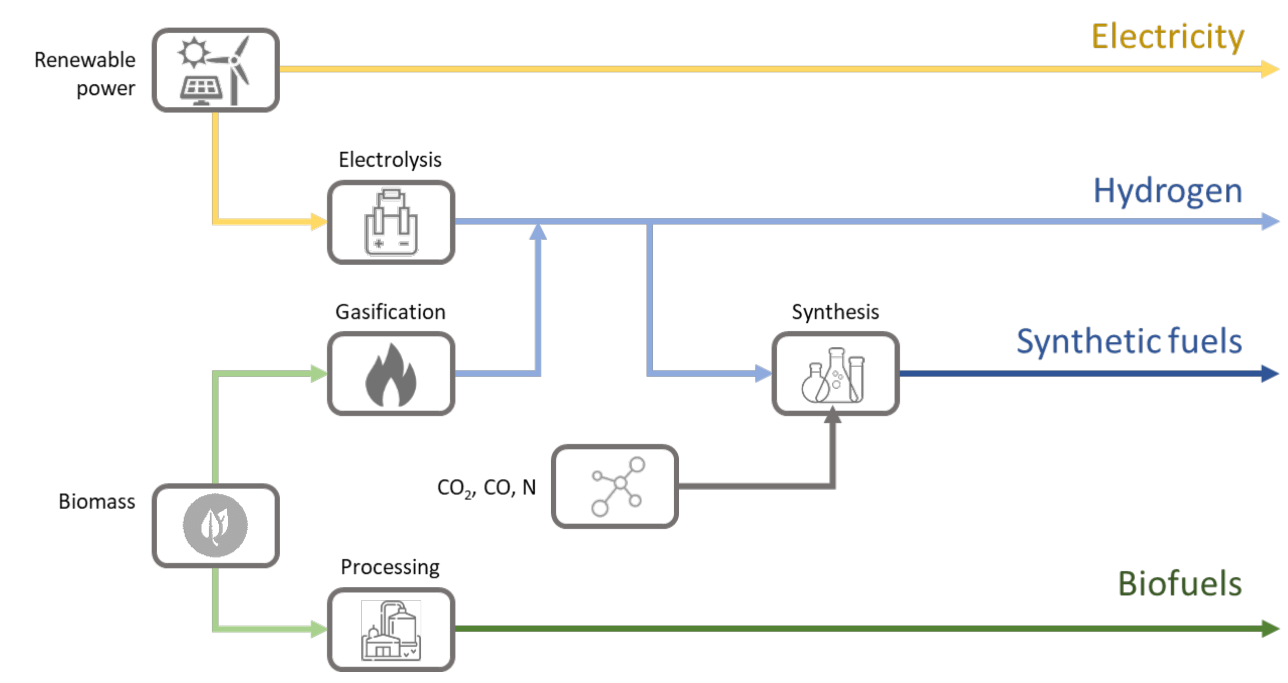
A.

Annex: Renewable energy carriers

Annex: Renewable energy carriers

Renewable energy carriers[16] such as electricity, hydrogen, synthetic fuels and biofuels will all play an important role in decarbonising the most challenging end-use sectors. This Annex provides context and supporting information for the sector-specific discussions in the main report by describing the production routes and challenges and opportunities of each carrier.

FIGURE 45: Overview of select renewable energy carriers



Renewable electricity

Renewable electricity is the backbone of the global energy transition. Given the dramatic reduction in cost in recent years renewable-sourced electricity is set to become the dominant energy carrier in the global energy system and can play a major role in decarbonising end-use sectors.

In IRENA's Transforming Energy Scenario (IRENA, 2020a), the world reaches an around 50% share of electricity in final energy use by 2050, equivalent to 49 000 TWh of consumed electricity. Around 86%, or 42 000 TWh, of this electricity is expected to be renewable in this scenario, with the remainder being nuclear and fossil-based. This implies that electricity consumption would more than double by 2050, and renewable electricity consumption would need to grow by a factor of seven to meet this 86%.

Electricity consumption in 2017 was roughly 21 000 TWh or 18.9% of the final energy demand that year. This share has grown by 0.2% per year for the last two decades. Some countries have reached much higher shares, for example Norway had a 47.5% share that year. At the same time, in 2017, consumption of

16 An energy carrier is a substance or a phenomenon that can store energy which can be converted into other forms of energy at a later stage. Energy carriers include electricity, as well as other solid, liquid and gaseous fuels.

renewable electricity was around 6 000 TWh – that is, over one-quarter of all electricity consumed that year came from renewable sources.

Challenges and opportunities

Electricity production costs have fallen dramatically in the last decade, driven by improving technologies, economies of scale, increasingly competitive supply chains and growing developer experience. As a result, renewable power generation technologies have become the least-cost option for new capacity in almost all parts of the world.

The levelised cost of electricity (LCOE) of solar PV has fallen 82% since 2010, followed by CSP at 47%, onshore wind at 39% and offshore wind at 29%, while the LCOE of more mature technologies such as biomass, geothermal and hydropower has remained stable (IRENA, 2020b). These cost developments have made renewable electricity competitive with fossil-based electricity, and in many cases renewable electricity can be even cheaper. Solar PV and onshore wind technologies are particularly relevant for a swift transition, since they offer easy roll-out possibilities. In the case of onshore wind, the weighted average LCOE in 2019 was USD 0.053 per kWh, while for solar PV it was USD 0.068 per kWh (IRENA, 2020b).

Two main challenges that lie ahead for the power sector are ensuring the availability of enough renewable electricity to cover the increased demand caused by end-use decarbonisation (*i.e.*, direct and indirect electrification of end uses), and ensuring that power systems are capable of handling increasingly higher shares of variable renewables. However, the latter challenge could be mitigated with the direct and indirect electrification of end-use sectors which will add flexible sources of demand that could help integrate high shares of VRE.

A 50% share of electricity in final energy will involve significant direct electrification of end-use sectors. Direct electrification, in the context of this report, refers to the replacement of an energy, power or heat source with renewable electricity. This comes with a reduction in the demand of non-electricity carriers and considerable efficiency improvements. Examples of these technologies include electric heaters, boilers and ovens; heat pumps; and electric vehicles. Direct electrification is a clear trend in mobility, driven by rapid progress in battery and charging technology as is evident for cars and delivery vans, although heavy-duty long-distance trucks still remain a challenge (see Chapter 3). Electricity is also increasingly being used for heating. Particularly in low-temperature applications – the bulk of domestic and industrial heat use – heat pumps can be applied to raise the conversion efficiency and increase the useful energy yield per unit of electricity consumed.

Some of the remaining 50% of final energy use may be able to rely on direct electrification for its decarbonisation, but a high proportion will not – due to technological, logistical or economic factors. For this portion to be emissions-free, there will need to be an expanded use of biofuels and indirect electrification. Indirect electrification, in the context of this report, refers to the use of renewable electricity as an input to an upstream process rather than the end-use application – for example, the production of hydrogen or other synthetic fuels with renewable electricity. This will likely be the case, at least partially, for the aviation sector, the shipping sector, some heavy-duty road transport and some industrial sectors such as the iron and steel industry and chemical manufacturing.

Direct electrification is usually to be preferred over indirect electrification, given that it is an overall simpler, cheaper and more efficient approach, as it mainly requires only a change in the end-use application or appliance. Indirect electrification of end-use sectors will require changes across the value chain, from production to consumption, which results in higher costs and lower efficiencies since it involves several conversion processes. Regardless of these facts, some applications simply cannot be directly electrified, which makes the role of indirect electrification in the decarbonisation of end-use sectors also extremely important.

A deeper look into the topic of renewable electricity and of electrification is provided in a wide range of IRENA publications. Particularly relevant in the context of end-use sectors is IRENA's report *Electrification with renewables: Driving the transformation of energy services. Preview for policy makers* (IRENA, 2019f). This report offers a preview of findings from a forthcoming scoping study that will be released later in 2020.

More information on this topic can be found in the following publications:

IRENA's report Innovation landscape for a renewable-powered future (www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future)

IRENA's Innovation landscape briefs (www.irena.org/publications/2019/Sep/Enabling-Technologies)

IRENA's report Electrification with renewables: Driving the transformation of energy services. Preview for policy makers (www.irena.org/publications/2019/Jan/Electrification-with-Renewables)

IRENA's report Renewable power generation costs in 2019 (www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019)

IRENA's report Future of wind (www.irena.org/publications/2019/Oct/Future-of-wind)

IRENA's report Future of solar photovoltaic (www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic)

IRENA's Technology brief: Solid biomass supply for heat and power (www.irena.org/publications/2019/Jan/Solid-Biomass-Supply-for-Heat-and-Power)

Unlocking the potential of ocean energy: From megawatts to gigawatts (https://energypost.eu/unlocking-the-potential-of-ocean-energy-from-megawatts-to-gigawatts)

Green hydrogen

Green hydrogen is likely to play a significant role in the global energy transition. Green hydrogen can provide a clean source of energy for sectors that are difficult to electrify directly, such as transport and industry. It can also help provide clean feedstock for syngas[17] or synthetic fuel production or for use in industrial processes for the production of iron and steel, and/or chemicals. Using green hydrogen as an energy carrier effectively widens the applications of renewable power. Its higher energy density makes it more suitable than the use of batteries in some applications. In cases where it can be more readily transported over large distance, in pipelines, it provides a relatively low-cost distribution and energy storage option. Lastly, green hydrogen production via electrolysis is a controllable source of electricity demand that can help provide flexibility in power systems.

The versatility and range of applications of hydrogen make it an important part of emissions mitigation efforts. IRENA's Transforming Energy Scenario indicates an 8% hydrogen share of total final energy consumption by 2050 (IRENA, 2020a), while the Hydrogen Council[18] has suggested that an 18% share can be achieved by 2050 (Hydrogen Council, 2017).

In the Transforming Energy Scenario, green hydrogen demand reaches around 240 Mt per year by 2050, double today's demand for grey hydrogen. The growth potential is much higher if the full hydrogen and synthetic potential described in this report is utilised. Whereas in the Transforming Energy Scenario, 8% of final energy demand is electricity used for hydrogen production, more than 20% could be feasible. That would imply that up to 40% of all electricity would be used for hydrogen production.

In the Transforming Energy Scenario, around 1 700 GW of hydrogen electrolyser capacity would be needed in 2050. That number would grow to 4 000 to 5 000 GW if the full hydrogen potential would be utilised and the majority of hydrogen used would be green. In comparison, today only 0.2 GW of electrolyser capacity is in operation. A large and rapid ramp-up of electrolyser capacity would be needed.

Demand forecasts need to be matched ideally by supply expansion. A larger issue is the composition of hydrogen. Around 96% of all hydrogen is generated from natural gas and coal, and around 4% is generated as a by-product from chlorine production through electrolysis.

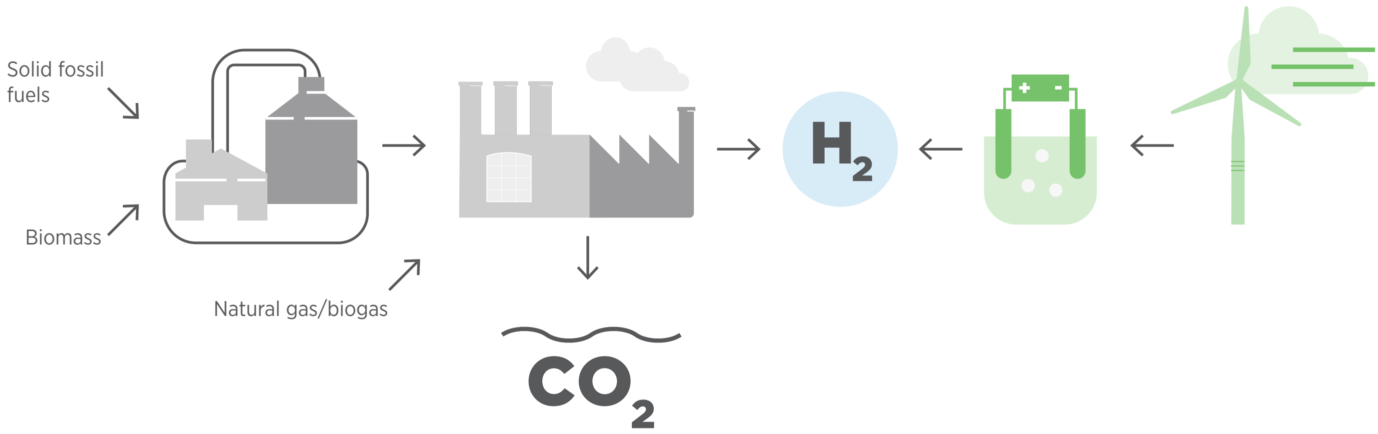
Production

There are several different ways of producing hydrogen (Figure 46). Today it is produced mainly from fossil fuels through processes such as steam methane reforming and coal gasification (grey hydrogen). The carbon emitted during these processes could in principle be captured via carbon capture, utilisation and/or storage (CCUS) technologies. When that is the case, the hydrogen is commonly referred to as blue hydrogen. Hydrogen can also be produced cleanly via the electrolysis of water powered by renewable electricity or through the gasification of biomass (green hydrogen). Green and blue hydrogen are both low-emission production routes, but green hydrogen from renewable sources provides the lowest, near-zero, emissions option.

17 Syngas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide and very often some CO_2.

18 The Hydrogen Council is a global initiative of leading energy, transport and industry companies launched during the 2017 World Economic Forum.

FIGURE 46: Hydrogen production pathways



Source: Adapted from SINTEF, 2019

The production of green hydrogen via electrolysis involves passing electricity through water to separate hydrogen from oxygen. There are several different types of electrolysis technologies including the following:

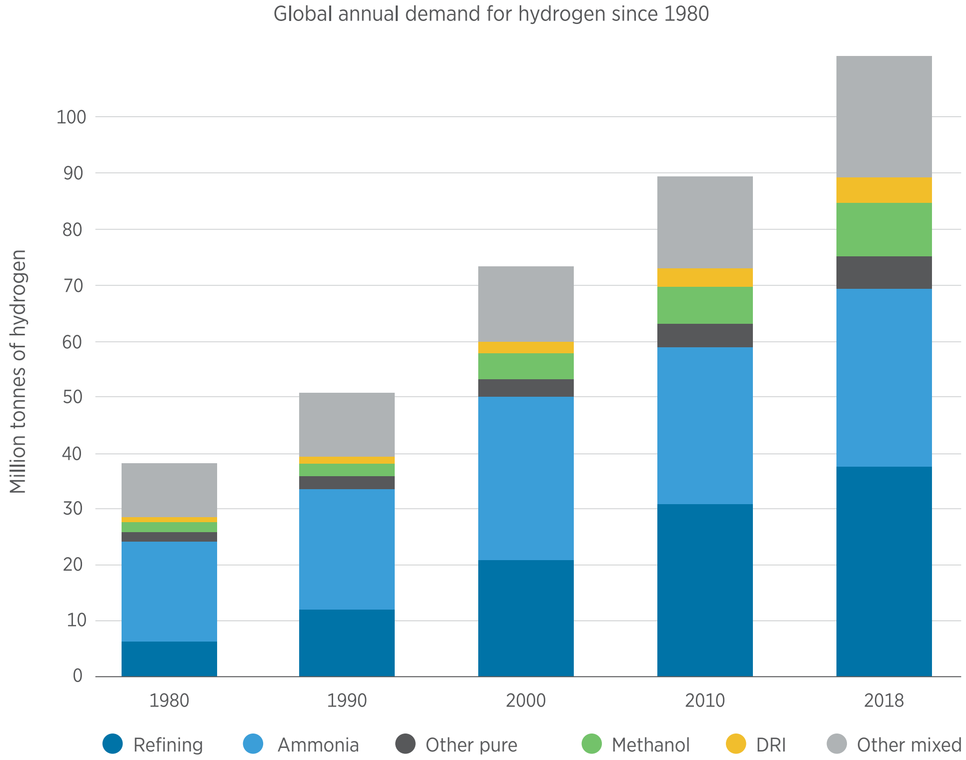
- **Alkaline electrolysis** is a fully mature technology that has been used by industry since the 1920s, mainly for non-energy purposes, particularly in chlorine manufacture. While fully mature, more research is needed into how the use of variable renewables may affect the operation and maintenance of these plants.

- **Proton exchange membrane (PEM) electrolysis** has been deployed at a commercial scale, but not widely so and is not yet a fully mature technology. While some PEM manufacturers, such as ITM Power from Germany, have expressed their readiness to increase their capacity following the launch of the European Hydrogen Strategy (ITM, 2020), further improvements in the materials, membranes, balance of the system, upscaling and testing and design of stacks (including large-area stacks) that might improve performance and reduce costs are expected in the coming years.

- **Electrolysis through solid oxide electrolyser cells (SOEC)**, which is a type of high-temperature electrolysis, has potential advantages for the production of low-cost green hydrogen, with higher overall efficiencies. SOEC is less mature than other electrolysis technologies with some small-scale pilot projects currently under way (dena, 2019b; IRENA, 2018b). Other designs are being explored but are still at a very early stage of development.

By the end of 2019, yearly production of hydrogen was close to 120 million tonnes, of which roughly 60% corresponds to dedicated hydrogen production, with the remaining share corresponding to by-product hydrogen as part of a mixture of other gases, for example syngas. In total that equals 14.4 EJ, or around 4% of global final energy and non-energy (feedstock) use (IRENA, 2019c). The vast majority of hydrogen today is produced and used on-site in industrial processes. The production of ammonia and oil refining are the main purposes, together accounting for two-thirds of hydrogen use (see Figure 47 for a breakdown).

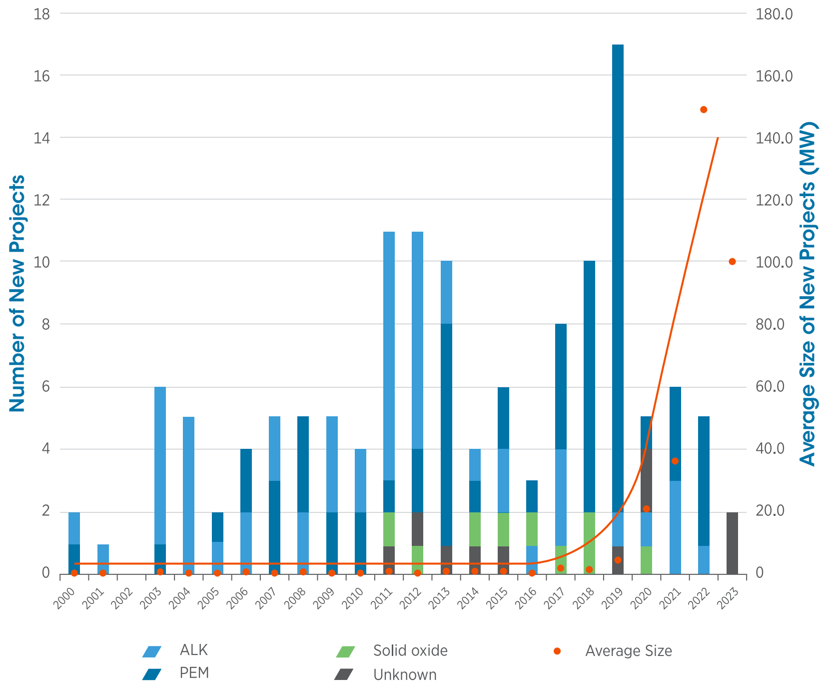
FIGURE 47: Hydrogen use trends, 1980 to 2018



Note: DRI = direct reduced iron.
Source: IRENA, 2019c

The scale of hydrogen production is slowly but steadily increasing. Figure 48 shows that between 2017 and 2019, 35 projects that are focused on the production of hydrogen via electrolysis began operating, with an additional 5 projects expected to enter operation by the end of 2020. Furthermore, another 8.2 GW of electrolyser projects were in the pipeline as of March 2020. These are spread worldwide, with projects above 100 MW realised or planned in countries such as Australia, France, Germany, the Netherlands, Paraguay, Portugal, the UK and the US (gtm, 2020).

FIGURE 48: Timeline of projects by electrolyser technology and project scale



Note: ALK = alkaline, PEM = proton exchange membrane. SOEC = solid oxide electrolyser cells
Source: IRENA, 2019c, based on Quarton and Samsatli, 2018

Challenges and opportunities

The scale of hydrogen use and the speed with which it influences transformation will depend on how markets for hydrogen can be enabled. Making hydrogen an internationally traded commodity – with an emphasis on green hydrogen – can promote shifts in the right direction, while presenting new opportunities for today's fossil fuel-exporting countries, or those with low-cost renewables potential. Some optimistic developments are under way signalling the emergence of such a market, for example the first green hydrogen shipment was delivered from Australia (a major fossil fuel consumer, producer and exporter) to Japan in 2019. Pipeline imports from the Middle East and North Africa region are a possibility for Europe.

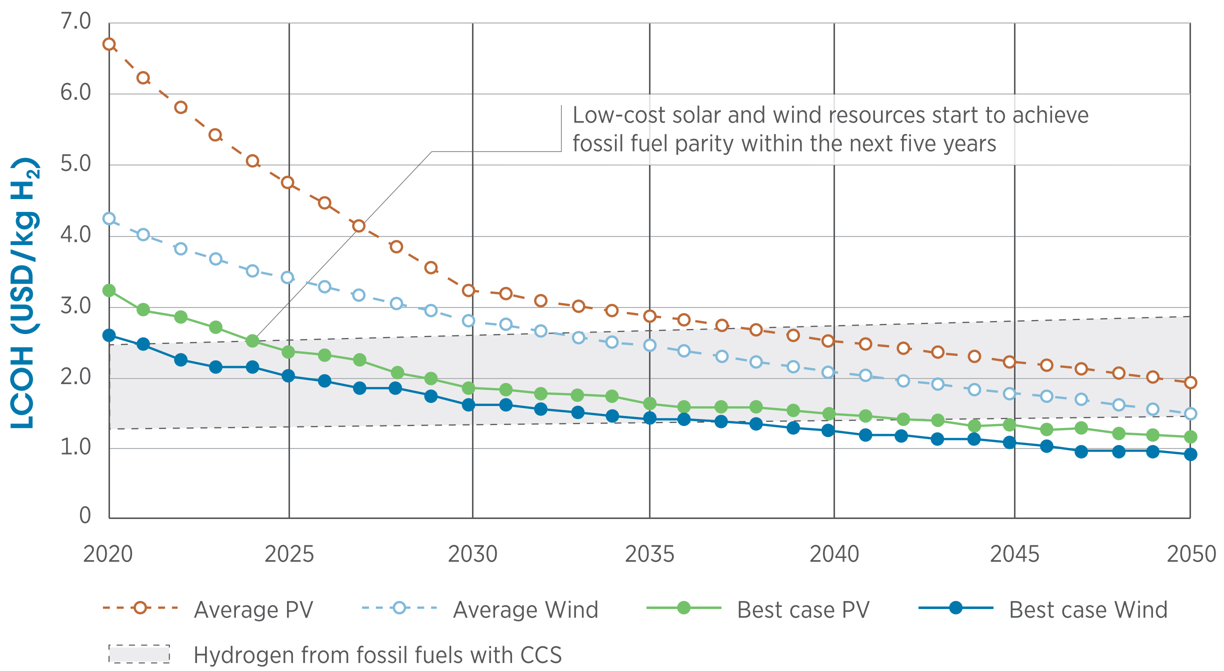
Cost is the main barrier that needs to be overcome for the widespread deployment of green hydrogen. The supply of low-cost green hydrogen to the consumer will ultimately be influenced by three key factors: electrolyser costs and efficiencies, renewable power costs and logistical costs (such as transport and storage infrastructure costs).

Green hydrogen production costs are falling and could reach a range of USD 1-3 per kilogram[19] in the medium to long term with low-cost renewable electricity, cost reductions for electrolysers and improvements in efficiency (IRENA 2019c; Deutsch and Graf, 2019; Bloomberg, 2019; Hydrogen Council, 2020).

19 Around 8 kilograms of hydrogen has the same energy content as 1 GJ of gas (around 30 m^3). The target cost per unit of delivered clean hydrogen energy (USD 15-25/GJ) is 2-3 times that of pipeline natural gas (at USD 5-10/GJ). This translates to a target cost of around USD 1.8–2.4/kilogram of hydrogen.

As seen in Figure 49, production costs of around USD 2.5-3 per kilogram for green hydrogen can be achieved by 2025 at sites with lowest-cost solar and wind resources, which already brings competitiveness with hydrogen from fossil fuels with CCS. This cost reduction also seems feasible for other locations from 2030 onwards. The cost could halve again between 2040 and 2050, with further expansions of renewable electricity and process improvements in the production of green hydrogen.

FIGURE 49: Green hydrogen production cost projections



Note: Remaining CO2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: USD 770/kW (2020), USD 540/kW (2030), USD 435/kW (2040) and USD 370/kW (2050).
CO2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050). LCOH = levelised cost of hydrogen; CCS = carbon capture and storage.
Source: IRENA, 2019c

In the next five years, green hydrogen may achieve competitiveness with blue hydrogen in the regions with the best solar and wind resources. By 2030, these regions could reach competitiveness also with grey hydrogen. However, in average solar and wind spots, green hydrogen is likely to only be competitive with blue hydrogen from 2030-35 and to start being competitive with grey hydrogen from 2040.

Interest in the role of hydrogen in national and regional energy transitions has grown significantly in the last few years. Several countries including Australia, Brunei, China, Germany, France, Japan, the Netherlands, Norway, the Republic of Korea and the UK as well as the EU either have adopted hydrogen strategies or roadmaps in recent years, or are in the process of adopting one.

Recently, there has also been a surge in discussions and debates on the use of hydrogen. Key drivers for the increased attention include:

- The now-widespread recognition that a global energy transformation towards zero carbon emissions needs to progress much faster, faster even than anticipated at the time of the adoption of the Paris Agreement.

- Increased acknowledgement that direct electrification can well address half of all final energy use by 2050, shifting attention to decarbonising the remaining half, where indirect electrification via green hydrogen and other synthetic fuels will have to play an important role.
- The numerous areas of application of hydrogen and an increasing attention to its derivatives such as green ammonia, green methanol and other green chemicals or synthetic fuels.
- The possibility of transporting hydrogen relatively cheaply, by retrofitting existing natural gas pipeline systems.
- The use of hydrogen as a clean energy carrier where grid constraints exist. This might be the case with offshore wind, where hydrogen could be produced offshore and then transported to shore via pipelines which may be easier to build than an electricity transmission line.
- The possibility of storing hydrogen seasonally, similar to natural gas, that can help utilise and manage the seasonal availability of excess renewable power.
- The potential for integration of flexible hydrogen production units that may help to increase the flexibility of power systems and so help increase the uptake of VRE sources.

More information on this topic can be found in the following publications:

IRENA's report Hydrogen from renewable power: Technology outlook for the energy transition **(www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power)**

IRENA's report Hydrogen: A renewable energy perspective **(www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective)**

IRENA's Innovation landscape brief: Renewable power-to-hydrogen **(www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf)**

Hydrogen Council studies **(https://hydrogencouncil.com/en/category/studies)**

International Partnership for Hydrogen and Fuel Cells in the Economy studies **(www.iphe.net/resources)**

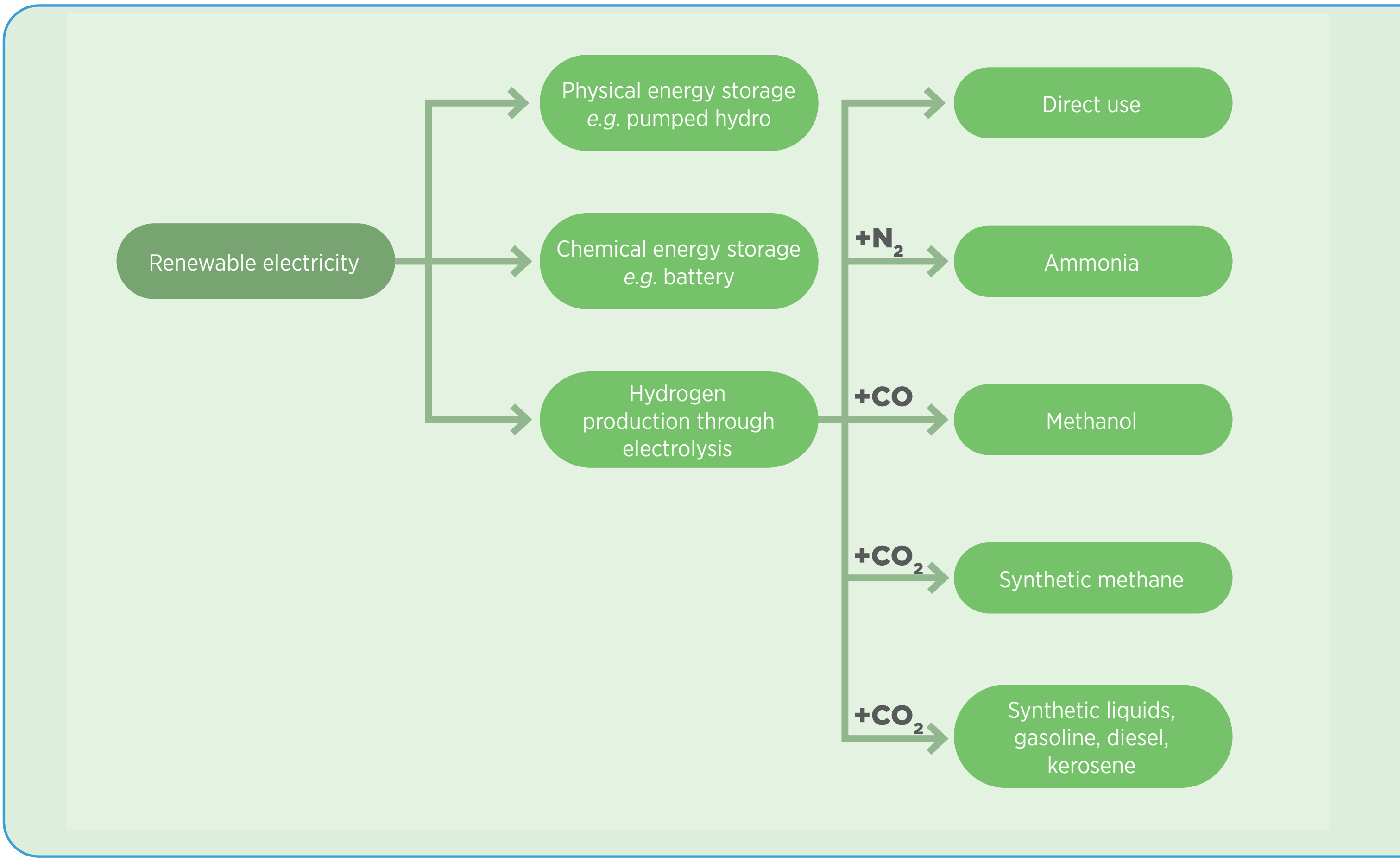
Green synthetic fuels

The term synthetic fuels refers to a range of hydrogen-based fuels obtained from syngas which have conventionally been produced through chemical processes from a carbon-based source such as coal or natural gas. Synthetic fuels are therefore not necessarily a low-emission option. However, they can also be produced from renewables – either through biomass gasification or by synthesising green hydrogen with a source of carbon (carbon monoxide and CO_2 captured from emission streams, biogenic sources or directly from the air) or with nitrogen (in the case of ammonia).

When synthetic fuels are produced using renewable electricity, via so-called power-to-X routes, they are sometimes called synfuels, powerfuels or e-fuels[20]. The main advantage of these fuels is that they can be used to replace their fossil fuel-based counterparts and in many cases be used as direct replacements – that is, as drop-in fuels. While these synthetic fuels will still produce carbon emissions when combusted, if they are produced via power-to-X routes, their production process will consume CO_2, instead of emitting it, in principle allowing them to have net-zero carbon emissions.

20 The term e-fuels usually includes the green version of hydrogen, synthetic gas (*e.g.*, methane, propane) and synthetic liquid fuels and chemicals (*e.g.*, methanol, diesel, gasoline, kerosene, ammonia, Fischer-Tropsch products).

FIGURE 50: Schematic representation of power-to-X routes



Source: IRENA, 2019d

Production

The production of green synthetic fuels requires green hydrogen, which is then synthesised with carbon or nitrogen via three main production pathways. The first two, Fischer-Tropsch and methanol synthesis, are used to produce methane and other alkanes[21]. The third, the Haber-Bosch process, is used to produce ammonia. These are well-established production processes that have already been used in some industries (see Chapter 2) for decades. To be classified as "green", it is imperative that the synthetic fuels produced with these processes use renewable energy inputs alone. Additionally, the carbon and nitrogen also need to come from a clean source, for example captured from the air, or using biomass as feedstock, as opposed to processes where the carbon has been sourced from natural gas or from the gasification of other fossil fuels. The production pathways are described below.

Fischer-Tropsch synthesis

This process relies on green hydrogen and carbon monoxide. Instead of obtaining the carbon monoxide from the gasification of biomass or coal, typically CO_2 is converted to carbon monoxide through a reverse water-gas shift reaction[22]. In the synthesis process, hydrogen is used with carbon monoxide to produce a wide range of hydrocarbons, ranging from lighter to heavier products (C1 to C40, *i.e.*, compounds with from 1 to 40 carbon atoms), to petroleum-like liquids. The portion of each of these compounds in the final synthetic product depends on the reaction conditions and the catalytic bed in which the synthesis is conducted (Mahmoudi *et al.*, 2017; Hanggi *et al.*, 2019; Ail and Dasappa, 2016).

The final output product can then be further refined in a range of different processes. These are conventional refinery processes such as hydrocracking, reforming, isomerisation, alkylation, distillation, among others, and they are widely known by the industry (see section 2.4).

Fischer-Tropsch synthesis using fossil fuels as a feedstock is a mature process and has been used for almost a century. Renewable routes are, however, less mature and are only just entering the early stages of commercialisation (dena, 2019b; UBA, 2016; Jarvis and Samsatli, 2018).

Methanol synthesis

Methanol is a liquid at room temperature and has easier storage and transport characteristics than alternative energy carriers such as methane or hydrogen (Marlin *et al.*, 2018).

Conventionally, methanol is produced on an industrial scale from fossil fuel-based syngas, mostly from natural gas or coal. In this process, the synthesis results in the production of many light and heavy by-products along with the methanol itself, as well as carbon emissions. However, methanol can also be produced from green hydrogen and a carbon source, in which case the synthesis is considerably simpler and reaction parameters are more easily controlled than in the conventional route (Pérez-Fortes *et al.*, 2016; Marlin *et al.*, 2018). The source of carbon for this process is typically carbon monoxide, but if the source of carbon is CO_2, a reverse water-gas shift reaction can be used to convert CO_2 into carbon monoxide before it is hydrogenated.

The synthesised methanol can be used directly as a fuel or a fuel additive. It can also be further refined into other by-products or it can be used to make a wide range of industrial chemicals (see section 2.4). In this case, the upgrading of methanol to other hydrocarbons,

21 An alkane consists of hydrogen and carbon atoms arranged in a tree structure in which all the carbon–carbon bonds are single. Examples of alkanes are methane (CH_4), ethane (C_2H_6) and propane (C_3H_8).

22 The water-gas shift reaction is $CO + H_2O \rightarrow CO_2 + H_2$.

fuels or industrial compounds is carried out through a range of processes such as dimethyl ether (DME) and olefin synthesis.

The green methanol synthesis process is being increasingly employed, and a number of plants are in operation in Japan and Iceland. For instance, the Carbon Recycling International (CRI) plant in Iceland has operated since 2012 with a capacity of 4 000 to 5 000 tonnes per year of methanol. The green hydrogen used as an input is produced with alkaline electrolysers powered by renewable electricity, while CO_2 is extracted from the nearby geothermal power plant (Marlin *et al*., 2018). The plants in operation to date are still in a precommercial stage: demonstration projects have proven the technical viability of the technology, but further refinements are still necessary (Pérez-Fortes *et al*., 2016; dena, 2019c).

Ammonia synthesis

Global production capacity of ammonia in 2018 was around 220 million tonnes (IFA, 2019). Approximately 90% of ammonia is produced through the Haber-Bosch process where hydrogen (H_2) and nitrogen (N) are bound together to produce ammonia (NH_3). Nitrogen makes up 78% of the atmosphere (*i.e*., air) and is easily extracted. Around 1.6 to 3.8 tonnes of CO_2 are emitted when producing a tonne of ammonia depending on whether natural gas, naphtha, heavy fuel oil, or coal were used as feedstock.

Ammonia production accounts for around 2% of the world's total energy consumption (Giddey *et al*., 2017). The use of green hydrogen can reduce some of the overall process carbon emissions of ammonia production (see also section 2.4). It enables flexible operations that can be run at 20-30% minimum loads if needed, in combination with renewable power sources (Tang and Qiao, 2019).

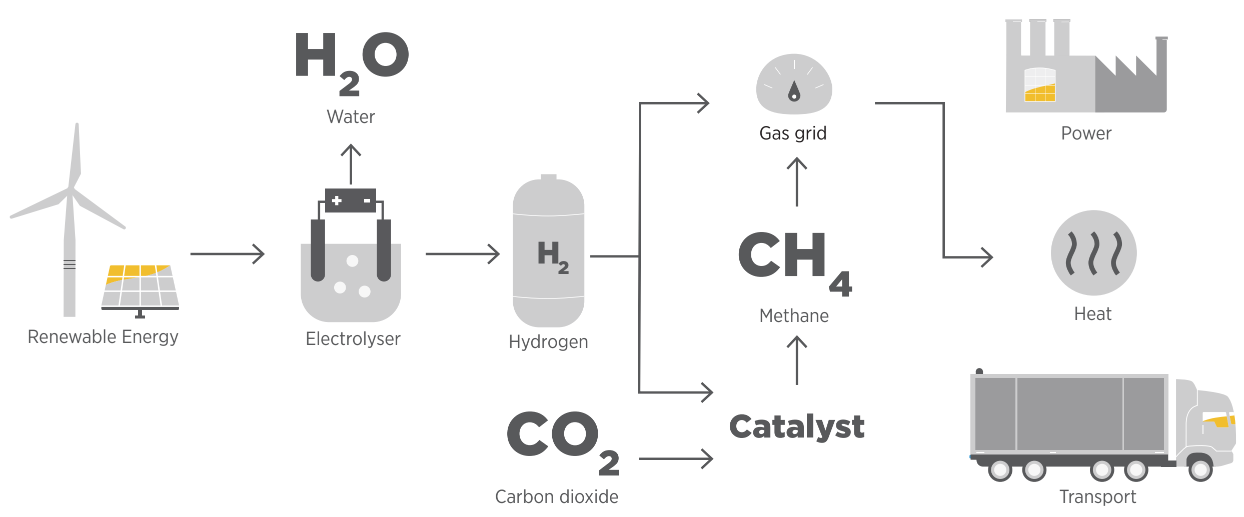
Conventional ammonia production is a mature technology, and the use of green hydrogen does not require any significant changes to the process beyond the supply of green hydrogen. No commercial-scale plants are in operation to date (dena, 2019b), but there are several ongoing pilot projects, which are listed in Chapter 2.

Methanation

The power-to-gas process involves a methanation process in which one molecule of CO_2 reacts with four molecules of hydrogen to form one molecule of methane (CH_4) and two molecules of liquid water (the Sabatier reaction). The reaction is exothermic and as such releases heat which can be later used in processes such as CO_2 direct air capture or high-temperature electrolysis (Lecker *et al*., 2017).

The methanation process can involve either catalytic methanation or biological methanation. Catalytic methanation uses nickel to catalyse the reaction, while biological methanation relies on microorganisms known as methanogens to catalyse the reaction. Both of these technologies are in commercial use.

FIGURE 51: Power-to-gas process



The power-to-gas process also has synergies with conventional biogas plants based on anaerobic digestion. Anaerobic digestion results mainly in methane and CO_2; this CO_2 can be used to feed a power-to-gas process to create an additional methane stream, allowing biogas plants to nearly double their methane output. While this application is not mature, several demonstration projects are under way, such as a plant in Germany, run by Audi, a German car maker. That plant has a capacity of 6 MW and it produces methane for use in vehicles from wind-powered hydrogen and CO_2 from a food waste digester (Long and Murphy, 2019).

Challenges and opportunities

Synthetic fuels are chemically identical to their fossil fuel counterparts and therefore offer a pathway to reduce and potentially eliminate emissions across end-use sectors by directly replacing them. This is particularly relevant for applications that are hard to electrify, for example in shipping and aviation. The downside of this is that the use of synthetic fuels is much less energy efficient than direct electrification given transmission and conversion processes. The Royal Society (2019) found that it would take around five times more renewable electricity to power a vehicle with synthetic fuels than with a battery-powered electric motor.

An advantage of synthetic fuels is that they can be stored, distributed and consumed with existing infrastructure without the need to adapt it. Yet, for these benefits to be realised, some challenges need to be overcome including high costs and the need for a cheap and clean carbon source.

Costs

The cost of producing synthetic fuels today is still relatively high when compared to their fossil-based alternatives, with electrolyser and carbon costs being the two largest cost components. Green ammonia, green methanol and synthetic oil products have production costs that are two to three times higher than fossil-based products, while the cost of synthetic methane shows a much higher price differential. Synthetic methane costs are higher than the low end of biomethane cost estimates and are at least three times the price of natural gas for non-household consumers in Europe.

Further cost reductions can be expected as electrolyser capacity is scaled, but the improvements must be significant to promote broad commercial adoption.

TABLE 21: SYNTHETIC FUEL COSTS

Synthetic fuels	Total production cost (USD/t)	Fossil-based product price (USD/t)
Ammonia	500-600	200-350
Methanol	675	300-350
Methane	1 380	100-500
Synthetic oil products	1 000	500-800

Source: Adapted from IRENA, 2019d

CO_2 sourcing

Synthetic fuel production (excluding ammonia) requires a carbon source, *i.e.*, carbon dioxide or carbon monoxide. This carbon can come from different sources including the combustion of fossil fuels, or from green sources such as the combustion of biomass or CO_2 captured directly from air. However, if fossil CO_2 is captured, used and subsequently emitted, emissions are not eliminated but only, at best, halved. In practice, the benefit may be even smaller because of additional process energy needs. The capturing of fossil CO_2 in this manner is therefore not in line with a zero emissions objective. In order to achieve zero emissions, carbon will need to be sourced cleanly from sustainable biomass sources or direct air capture (DAC). In regions with limited access to biomass resources, DAC may be more suitable, but DAC costs are currently high. The source of carbon is highly relevant since carbon represents a large share of synthetic fuel costs.

Bioenergy with carbon capture

Bioenergy with carbon capture is a negative emission technology that is becoming critically relevant in carbon emission reduction scenarios. Bioenergy with carbon capture and storage (BECCS) involves the permanent storage of captured CO_2, while bioenergy with carbon capture and utilisation (BECCU) utilises captured CO_2 as a carbon feedstock in the production of energy carriers, chemicals and materials. The utilisation of captured carbon becomes relevant when considering the economics of carbon capture, by offering a potential revenue stream and avoiding the need for geological storage.

According to the Global CCS Institute (2019a), 10 BECCS/BECCU projects are operating today, one of which is a large-scale project, and at least 7 more projects are in the pipeline. This translates into a wide cost range of USD 15 to USD 400 per tonne of CO_2 (IRENA, 2020c).

Despite the considerable benefits of BECCS and BECCU technologies, there are a number of uncertainties, particularly regarding their large-scale deployment, including: their sustainability, especially considering land-use change and food security; lifecycle emissions, especially if large amounts of forest land were to be used for energy crops; and the response of natural carbon sinks to negative emissions.

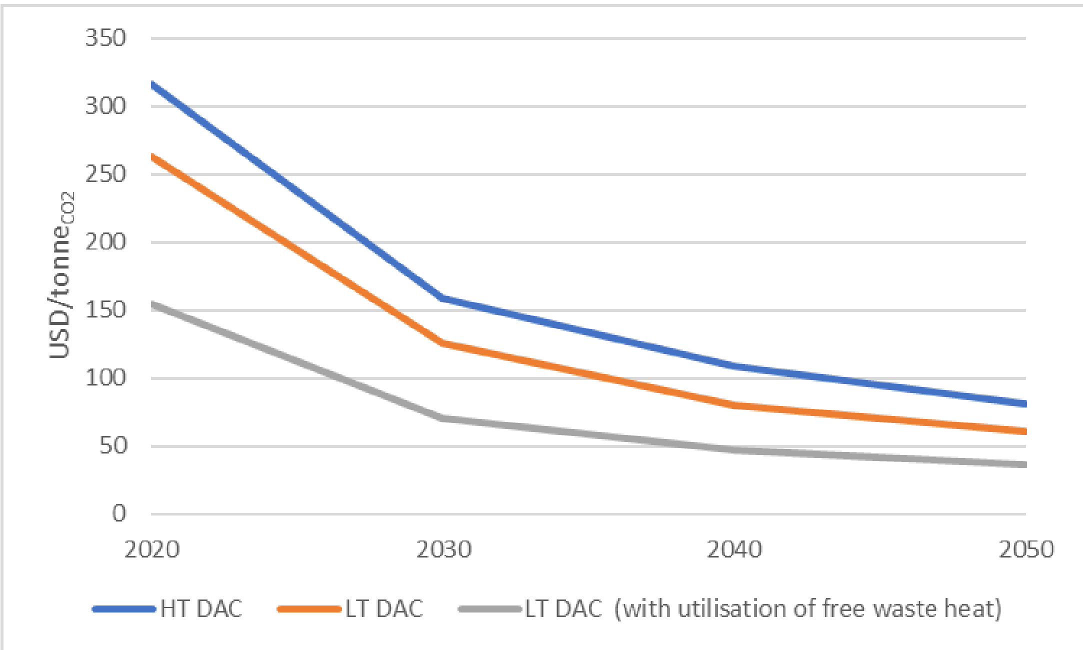
Direct air capture

Direct air capture describes a range of technologies to capture CO_2 directly from ambient air. These technologies typically use fans to move air through a chemical or physical sorbent which captures the CO_2. They can be categorised as high-temperature aqueous solutions (HT DAC) or low-temperature solid sorbent (LT DAC) systems. Carbon capture takes place at low temperature or high pressure and is released at high temperature or low pressure. In addition to CO_2 capture, compressing and storage may be needed.

DAC is at an early stage of development and costs are currently high. Cost estimations vary substantially. Recent cost estimates for pilot-scale projects range from USD 94 to USD 232 per tonne of CO_2, with some pilot projects having higher costs. According to some estimates however, costs could fall drop below USD 60 per tonne by 2040 (Sutherland, 2019). The sorbent life cycle and stability are critical parameters that affect the cost.

Fasihi *et al*. (2019) conducted a techno-economic assessment of DAC and found that system costs could be lowered significantly with commercialisation in the 2020s followed by massive implementation in the 2030s and 2040s, making them cost competitive with point source carbon capture (*i.e.*, applied to power generation or industrial process) and an affordable climate change mitigation solution. LT DAC systems could be considered favourable due to lower heat supply costs and the possibility of using waste heat from other systems. Estimates of CO_2 capture costs of LT DAC systems powered by hybrid PV-wind-battery systems are presented in Figure 52.

FIGURE 52: Levelised cost of direct air capture systems



Note: Based on a conservative scenario, based on 800 full-load hours. LT DAC = low-temperature direct air capture, HT DAC = high-temperature direct air capture.
Source: Adapted from Fasihi *et al.*, 2019

BOX 19. CO_2 COSTS AND THE IMPACTS ON SYNTHETIC FUELS

Fehrenbach *et al.* (2019) provide an example where flue gas from a natural gas plant is captured and used for methanol production to substitute gasoline, achieving a net CO_2 reduction effect of 35%. This is an improvement that can offer a transitional solution to reduce carbon emissions until direct air capture becomes mature, but it is not itself consistent with the zero emissions goal. The only other climate-neutral option is to use CO_2 from biomass combustion processes (*e.g.*, power plants, waste incinerators, ethanol plants, bagasse and black liquor boilers, etc.). These processes tend to be smaller in size than large fossil fuel-based facilities but capture costs are typically still relatively low at USD 40-50 per tonne of CO_2.

Assessing the precise costs of synthetic fuel production is difficult, but a simple calculation can provide valuable insights into the economics of their production. A typical oil product has the composition CH_2. Thus, to obtain one molecule of CH_2, then one molecule of CO_2 and three molecules of H_2 are needed*. In mass terms, this means that to produce 1 tonne of CH_2, 3.14 tonnes of CO_2 and 0.4 tonnes of H_2 are needed. The conversion efficiency of this process is usually not 100% and some energy input is needed. However, these aspects are secondary for the following cost calculation.

CO_2 sourced from large-scale industrial processes and cement kilns could have costs in the range of USD 60 to USD 120 per tonne (IEA, 2019c); that order of costs would have only a limited impact on the product price. However, direct air capture costs are currently in the range of USD 200 to USD 600 per tonne (Wijesiri, 2019; Gertner, 2019a, 2019b), which makes the price impact substantial. The cost of hydrogen in sites with cheap renewable electricity can be assumed to be between USD 1 500 and USD 3 000 per tonne (see earlier section).

Based on the cost ranges presented above, to produce 1 tonne of CH_2, the feedstock costs are USD 188 to USD 1 880 for 3.14 tonnes of CO_2, and USD 600 to USD 1 200 for 0.4 tonnes of H_2. Assuming an 80% conversion efficiency, this yields a total cost of around USD 985 to USD 3 850 per tonne of CH_2. Given that a tonne of oil product is in the range of USD 400 to USD 800, in this case only the combination of cheap CO_2 and cheap H_2 offers a prospect of economic competitiveness. The cost of direct air capture needs to decrease by a factor of 20 in order to be competitive.

*Based on the following reaction: $CO_2 + 3H_2 \rightarrow CH_2 + 2\ H_2O$.

More information on this topic can be found in the following publications:

IRENA's report Hydrogen from renewable power: Technology outlook for the energy transition (www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power)

IRENA's report Hydrogen: A renewable energy perspective (www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective)

Agora-Energiewende's report The future cost of electricity-based synthetic fuels (www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf)

Hydrogen Council studies (https://hydrogencouncil.com/en/category/studies)

International Partnership for Hydrogen and Fuel Cells in the Economy studies (www.iphe.net/resources)

Global Alliance Powerfuels (www.powerfuels.org)

Methanol Institute (www.methanol.org/about-methanol)

Biofuels

Biofuels can offer readily deployable options to substitute for fossil fuel use with minimum retrofitting of infrastructure for the supply chains. Biofuels production can provide pathways for carbon emission mitigation along with other external benefits such as rural development, the invigoration of agro-industry and wood industry, and better waste management. They can also help to build circular economies by using waste streams or end-of-life products as feedstock.

Biofuels use is particularly relevant in road and rail transport, shipping and aviation. Most biofuel is currently used in the road transport sector, the largest consumer of liquid transport fuels. Small quantities are also used in diesel-powered rail transport and aviation. Aviation and shipping are important potential growth markets because they have limited alternative fuel options.

Biofuels may also be used in heat and power generation as a substitute for fossil-based fuels; however, this application is not expected to act as a major driver for the development of advanced biofuels due to the availability of other options for decarbonising heat and power (IRENA, 2016).

Production

Advanced liquid biofuel production

Advanced biofuels are made from a feedstock of non-food and non-feed biomass, including waste materials (such as vegetable oils or animal fats) and energy-specific crops capable of being grown on less-productive and degraded land. They thus have a lower impact on food resources and should have a smaller impact in terms of land use (IRENA, 2019e).

The available conversion pathways for advanced biofuels can generally be categorised in four groups:

Microbial conversion of lignocellulosic biomass[23] to bioethanol or biobutanol –
Conventional bioethanol is produced from sugar and starch materials such as food crops; however, cellulosic bioethanol can be produced from agricultural residues and woody materials which are not suitable for human consumption. The process involves the hydrolysation of lignocellulosic biomass with acid or enzymes to break down the cellulose into sugar.

The development of cellulosic ethanol production has been slow with multiple setbacks, with the first wave of investments from 2005 resulting in many technical and commercial failures both in the US and in Europe. Despite the technical and commercial difficulties, in 2018, worldwide there were 12 refineries with an annual capacity of 10 million litres or more including 2 in Brazil, 3 in China, 5 in Europe and 2 in the US (US EPA, 2018; IRENA, 2019e). In the US, the Environmental Protection Agency (EPA) recorded Renewable Identification Numbers (RINs, tradable credits awarded to domestic biofuel producers) in the cellulosic ethanol category amounting to around 25 million litres from 11 projects in 2018, representing on average 2.2 million litres per project (US EPA, 2019). Based on the modest production levels, most of the 11 projects can be categorised as demonstration projects only, especially when compared with annual global ethanol production which is in the 100 billion litre range.

Transesterification of vegetable oils and animal fats to produce biodiesel –
Fatty acid methyl esters (FAME), commonly known as biodiesels, are produced through the transesterification of sustainably sourced vegetable oils and animal fats. Transesterification involves reacting a glyceride with an alcohol in the presence of a catalyst, resulting in a mixture of fatty acid esters and alcohol.

23 Lignocellulosic biomass refers to agricultural residues (*e.g.*, rice husk and corn stover), forest residues (*e.g.*, woodchips and sawdust) and energy crops (*e.g.*, grass and miscanthus).

While there are around 500 FAME biodiesel plants in the world, of which 224 are in the US (Biodiesel Magazine, 2018) and 190 in Europe (USDA, 2018), only a small share of these can be classified as advanced biofuel, producing biodiesel from entirely non-food and non-feed related raw materials such as cotton seed or jatropha oil. A sizeable number of plants are producing FAME from waste-based fats, used cooking oil or oily wastes from palm oil processing, which have been promoted in Europe under the Renewable Energy Directive with supporting policies until 2020 (listed in Indirect Land Use Change (ILUC) Directive, Annex IX, part B). Used cooking oil and animal fats have, however, alternative uses in the food industry, as an ingredient of animal feed and in oleochemicals production. Using these oils and fats for biofuel therefore causes a substitution effect in these sectors, which may create the need to grow oil seeds as a replacement, thus resulting in a risk of ILUC emissions. Consequently, regulators in Europe and the US have begun to constrain support for biofuels from these feedstocks.

Hydrotreatment of vegetable oils or animal fats to produce drop-in fuels –
This pathway uses similar raw materials to those of FAME, but it produces higher-quality fuels which can be used as drop-in fuels. The sustainably sourced raw materials are subjected to hydroprocessing, rather than transesterification. The resulting hydrotreated vegetable oils (HVO) and hydroprocessed esters and fatty acids (HEFA), also referred to as renewable diesel, can be used to directly replace diesel in engines without the need for modifications. They can also be further processed to produce biojet. Hydroprocessing consists of two stages. The first one is hydrotreatment and the second stage is isomerisation and cracking which brings the biofuel to a quality that equals or surpasses specifications for conventional petroleum fuels.

The scale of HVO/HEFA production plants is more than 10 times higher than that of cellulosic ethanol. Capacities of various refineries range from 20 000 tonnes at Sinopec's plant in China to the typical range of a few hundred thousand tonnes, up to 1 million tonnes annually from Neste Corporation's two refineries in Singapore and the Netherlands. In 2017 there were 15 HVO refineries in the world (Greenea, 2017), with one additional under construction. The total HVO capacity in 2018 was around 5 billion tonnes. In addition, two refineries in Spain co-process HVO so that the resultant conventional fuels have a biocomponent.

While some of today's HVO refineries use virgin palm oil wholly or partly (making them essentially first-generation producers), many of the refineries aim to replace palm oil and are in the process of shifting gradually to completely non-food and non-feed feedstocks. The high demand for HVO presents challenges for expanding supply capacity due to the limited amounts of sustainable waste-based feedstock. This may result in increasing interest in oil crops among HVO producers, such as jatropha (a hardy non-edible plant native to tropical and subtropical areas) or industrial forms of canola (a type of rapeseed). The Finnish company UPM, for instance, is planning a facility of 500 000 tonnes per year, for which one key feedstock option includes cultivation of *Brassica carinata* for winter cropping in Uruguay.

Thermo-chemical processing of biomass for biofuel production –
Thermo-chemical processes, such as pyrolysis and gasification, can convert both food and non-food biomass into fuel products. Pyrolysis involves the decomposition of biomass at high temperature in the absence of oxygen. This process can be used to produce different products such as biocrude, biochar and syngas. Gasification is the partial oxidation of biomass at high temperature to produce syngas.

Thermo-chemical processing remains a relatively marginal part of the biofuel sector at this time. Eight biofuel refineries in the world are applying thermo-chemical processes. Some of these refineries produce biocrude without refining it to transport fuels. Some, however, intend to do that in the future or may send biocrude for co-processing in a petroleum refinery.

The US EPA's registration of RIN D7 (cellulosic diesel) producers includes four facilities, two in the US and two in Canada (US EPA, 2018). In addition, one plant in Canada produces ethanol from post-sorted municipal waste, combining gasification and alcohol synthesis. In Europe, there were three commercial wood-based pyrolysis plants in 2020 (ETIP Bioenergy, 2020).

Biomethane production

Biomethane can be produced via two different pathways, anaerobic digestion and thermal gasification[24]. Most biomethane today is produced through anaerobic digestion. In the gasification process, biomass is reacted at high temperatures with controlled amounts of oxygen or steam to produce syngas. Syngas, which is a mixture of hydrogen, carbon monoxide and CO_2 in varying amounts depending on its production process, then undergoes a methanation process. In the methanation process, hydrogen is reacted with CO_2 to produce methane molecules. Methane produced through this pathway is also called bio-synthetic natural gas (bio-SNG). Biomethane production via gasification is not yet commercially deployed. However, at least two plants are operating. In Austria a demonstration unit for methanation is producing 1 MW, of biomethane, and in Sweden, a demonstration unit has a capacity of 20 MW of biomethane (Heyne *et al.*, 2019). The methanation process is further explained in the Synthetic methane section of this Annex.

In the anaerobic digestion pathway, microorganisms break down organic matter in the absence of oxygen and produce biogas. Biogas consists of 60-70% methane with the remaining 30-40% consisting mostly of CO_2, with small amounts of hydrogen sulphide, water vapour and some hazardous trace compounds. An additional purification or upgrading process is needed to remove these substances and obtain pure biomethane.

In 2019, the World Biogas Association (WBA, 2019) estimated that there were around 700 biogas upgrading plants, with more than 75% of them located in Europe. When considering feedstock availability and existing natural gas infrastructure, some of the countries with the greatest potential to establish a biomethane market in the near term are China, the United States, India, Germany and Brazil.

Germany is the largest producer of biomethane in the world with 220 biomethane plants, or nearly half of the global installations (dena, 2019c). As of 2019, Denmark injects 10% biogas into the natural gas network, and the Danish gas industry aims to reach 100% by 2035 (State of Green, 2017). France reached 2.3 TWh of biomethane injection capacity in 2020 and is targeting a 10% share of biomethane in its gas pipeline by 2030. GRDF (Gaz Réseau Distribution France) in France proposes to exceed the national target of 10% and reach a 30% injection target by 2030, which equates to 90 TWh of renewable gas of which 70 TWh would be biomethane. ENGIE is exploring a scenario of 100% green gas by 2050 in France (biogas plus hydrogen).

The biogas potential in the US was assessed at 18.5 billion cubic metres (m^3) per year, which could transform into roughly 41.2 TWh of electricity. By 2017, the US already had more than 2 100 biogas plants with an installed electricity capacity of 2.4 GW, and there is potential for 11 000 more plants (Scarlat *et al.*, 2018). In 2019, biomethane production capacity in the US exceeded 1.2 billion m^3. In that same year, 31 more projects were in construction with a production capacity close to 350 million m^3 (Mintz and Voss, 2019).

24 Biomethane produced through gasification is also called bio-synthetic natural gas or BioSNG,

China had an estimated 100 000 biogas plants and 43 million residential-scale digesters in 2014 – generating around 15 billion m^3 of biogas, equivalent to 9 billion m^3 of biomethane – and it has plans to build around 3 000 to 4 000 upgrading facilities over the next decade (Canadian Biomass, 2019). China's Medium-and-Long Term Development Plan for Renewable Energy requires the country to reach 80 million household biogas plants, 8 000 large-scale biogas projects with an installed capacity of 3 GW and an annual biogas production of 50 billion m^3 by the end of 2020 (Scarlat *et al.*, 2018).

Challenges and opportunities

Biofuels provide one of the most straightforward solutions to decarbonise end-use sectors in the short term, as they could be deployed immediately and often can be used as drop-in fuels. Biofuels face a number of challenges, however, including guaranteeing their availability and accessibility, ensuring their sustainability and lowering their cost. The question of availability and accessibility is a chicken-and-egg problem. On the one hand the scale of advanced biofuel production is very limited, which makes it relatively costly compared with fossil fuel alternatives. Prices could fall as the production volumes scale up and technology improves; however, there is limited demand for biofuels at their current price point. The question of sustainability is a large and complex consideration but it can in principle be addressed through the exclusive use of advanced biofuels that are produced from feedstocks that do not compete with other land uses, backed up by tight certification and monitoring processes.

Advanced biofuel costs

Production processes such as microbial conversion of lignocellulosic biomass, and pyrolysis to produce biocrude or biomass gasification, are still under active technological development, whereas FAME diesel and HVO/HEFA are mature and in fully commercial operation. The highest expectations are set for microbial conversion and pyrolysis/gasification, because of their ability to use low-quality, low-cost and abundantly available feedstock such as agricultural and forest residues. Technological immaturity, however, translates to high capital costs, which counterbalance the benefits of low feedstock costs[25]. Cellulosic ethanol technology is, however, expected to mature rapidly with an expected learning curve that can bring the specific investment cost below USD 2 per litre by 2030 ((S&T)2 Consultants Inc., 2018). By 2045, production costs of advanced biofuels could be in range of USD 0.57 to USD 0.97 per litre for cellulosic ethanol, USD 0.60 to USD 0.76 per litre for lignocellulosic ethanol via gasification and syngas fermentation, USD 0.86 to USD 1.22 per litre for biodiesel via pyrolysis and USD 0.93 to USD 1.22 per litre for biodiesel via the Fischer-Tropsch process (IRENA, 2016).

Feedstock costs account for a high share of the total production costs of biofuels for most pathways. The cost of feedstock for conventional biofuels represents around 70% to 90% of total production cost. High raw material costs, and low capital costs and non-fuel operational costs, render the biofuel production industry extremely sensitive to changes in feedstock price (IISD, 2013). While the CAPEX of advanced biofuel refineries is higher than that of conventional biofuel refineries for similar output, advanced biofuel feedstock is sought primarily from cellulosic and oily wastes and residues with lower costs. Feedstock costs for cellulosic ethanol production represent 35-50% of the total production cost depending on various geographical factors and supply chain characteristics (Hess *et al.*, 2007). Efforts to reduce production costs should therefore particularly focus on opportunities to reduce the cost of feedstock supply.

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25 The specific investment cost per annual production capacity in litres is USD 4 to 5 per litre for cellulosic ethanol and thermo-chemically produced drop-in fuels, whereas it is between USD 0.7 and USD 1.3 per litre for biodiesel and HVO, and only USD 0.5 to USD 0.6 per litre for conventional ethanol. The cost is expressed as "investment cost per one litre of the plant's annual capacity".

Based on potential improvements in conversion efficiency and capital cost reduction, advanced biofuels production costs could become competitive with fossil fuels if oil prices exceed USD 100 per barrel. At below USD 80 per barrel, advanced biofuels pathways are very unlikely to be able to compete on cost directly with petrol and diesel over the next three decades unless very low or negative cost feedstocks are available. Incentives or regulation will be needed to encourage the uptake of advanced biofuels.

Biomethane costs

The costs of biomethane production via anaerobic digestion (*i.e.*, producing biogas which is then upgraded) include three distinct elements: biogas production costs, biogas cleaning and upgrading costs, and distribution costs. The cost of biomethane is currently high compared to its fossil fuel counterpart. A recent study, by the French Energy Agency ADEME and gas transport utilities, estimated a supply cost of around EUR 80 (USD 87) per MWh for biomethane, EUR 80-120 (USD 87-130) per MWh for hydrogen from renewables and EUR 160-180 (USD 174-196) per MWh for synthetic natural gas (ADEME, 2018).

For comparison, the price of natural gas for European non-household consumers in 2019 was on average USD 35 per MWh[26] (Eurostat, 2020). As one MWh equates to 200 kilograms of CO_2, a cost gap of EUR 40-140 per MWh translates into EUR 200-700 per tonne of CO_2 (Gielen and Bazilian, 2018).

Other studies show how the total cost depends particularly on biogas production costs and show how costs vary within a range of EUR 62-161 per MWh for biomethane from energy crops, EUR 33-135 per MWh from manure and EUR 23-135 per MWh from industrial waste (IRENA, 2018a)[27]. In Germany, biomethane is produced predominantly from maize, and the production cost was in a range of EUR 69-72 per MWh in 2017 (dena, 2019c). A recent case study in Finland shows a slightly higher cost range of EUR 81-190 per MWh from anaerobic digestion biomethane, and of EUR 148-190 per MWh for gasification biomethane (Pääkkönen *et al*., 2019).

26 Assuming EUR 1 = USD 1.09.

27 Assuming methane composition of biomethane = 98%, methane calorific value = 11.06 kWh/m^3, and 2016 exchange rate of EUR 1 = USD 1.11.

More information on this topic can be found in the following publications and platforms:

IRENA's report Boosting biofuels: Sustainable paths to greater energy security
(www.irena.org/publications/2016/Apr/Boosting-Biofuels-Sustainable-Paths-to-Greater-Energy-Security)

IRENA's Innovation outlook: Advanced liquid biofuels
(www.irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels)

IRENA's report Advanced biofuels: What holds them back?
(www.irena.org/publications/2019/Nov/Advanced-biofuels-What-holds-them-back)

UN Food and Agriculture Organization's Global Bioenergy Partnership (GBP)
(www.globalbioenergy.org)

Biofuture Platform (www.biofutureplatform.org)

World Bioenergy Association (https://worldbioenergy.org)

Focus: Greening the gas grids

In the context of completely decarbonising energy consumption, the use of natural gas, even with CCUS, is a transitional solution at best. In the long term, there will be a need to replace natural gas with cleaner alternatives, including the use of biofuels and direct and indirect electrification. Gas infrastructure has a long life, and phasing out the use of gas could potentially cause these assets to become stranded. In the case of gas grids, the idea of repurposing them to transport other clean fuels such as biomethane, synthetic methane and hydrogen is gaining momentum. While there are still uncertainties around the suitability, cost and best pathway to follow, the concept of greening the gas grid by transporting clean fuels offers benefits, including:

- greenhouse gas emission reductions, provided that the natural gas replacements are produced from renewable sources;
- increased system flexibility achieved through the possibility of converting electricity into hydrogen and by making use of gas storage infrastructure and the gas grid itself;
- de-risking emerging clean fuel technologies, for example by removing the uncertainty around hydrogen transport;
- reducing stranded asset risks by making use of existing natural gas infrastructure; and
- providing economic incentives for the development of methane substitutes and hydrogen production.

Three main options are being considered to decarbonise the gas grids: replacing natural gas with drop-in substitutes, blending natural gas with hydrogen and replacing natural gas entirely with hydrogen. These options are explained below.

The first approach consists of replacing natural gas with biomethane or synthetic methane. This approach would reduce the carbon intensity of the gas grid and has the advantage that, since biomethane and synthetic methane are nearly identical in composition to natural gas, the existing gas grid is already capable of transporting these cleaner fuels. A transition to biomethane requires no adjustments to end-use appliances, and the only adaptation would likely have to do with the addition of new connection points and adjusting the grid to the demand.

The feasibility of using natural gas substitutes is likely to depend on the cost of those substitutes, which are currently more expensive than natural gas but are projected to become competitive in the future, depending on their availability and on the rate at which their use can be scaled up. The reduction in carbon intensity will depend on the source of the feedstocks and on the conversion technology used.

The second approach involves blending hydrogen into the natural gas grid. If hydrogen is going to play a significant role as a fuel in the future, it will require adequate transmission and storage infrastructure. Depending on the material they are made of, some existing gas grids are potentially compatible with hydrogen. Hydrogen causes embrittlement issues in carbon steel pipes when in high concentrations and high pressures (Hafsi *et al*., 2018); this is an issue therefore especially for transmission grids. However, when used in limited amounts these issues can be minimised and even avoided. If blended, hydrogen could also be extracted downstream via different processes (*i.e.*, pressure swing adsorption, membrane separation or electro-chemical separation).

The technical limit for blending hydrogen into existing gas grids without major issues or adjustments in transmission, distribution and end-use appliances varies in literature from 10% to 50% (Melaina *et al*., 2013; Qadrdan *et al*., 2015; Penev *et al*., 2016; Maroufmashat and Fowler, 2017). The blending limit will depend on the specific gas grid and needs to be evaluated on a case-by-case basis[28].

28 For example, certain processes which rely on natural gas as feedstock in chemical reactions (*e.g.*, desulphurisation of natural gas, acetylene production) are very sensitive to hydrogen even in blends as small as 1.5%.

TABLE 22: MAXIMUM ALLOWED HYDROGEN CONCENTRATION IN THE GAS GRID FOR SELECTED COUNTRIES

Country	Belgium	France	Germany[29]	Italy	Netherlands	Spain	UK
Allowed hydrogen blend (% molar)	0.1%	6%	2-10%	2-3%	0.02%	5%	0.10%

Source: Dolci *et al.*, 2019

Hydrogen blending in the gas grid is already allowed in some countries, and the different maximum allowable hydrogen blends are shown in Table 22.

The third approach consists of entirely replacing natural gas with hydrogen and completely decarbonising the gas grid. For this approach to work, appliances that work on natural gas would need to be replaced or modified to function with hydrogen. The same would apply to metering infrastructure. Additionally, the transmission or distribution grid might need modifications. Cast iron pipes, often used in older distribution grids, can suffer embrittlement. That, however, is not an issue with plastic pipes (*e.g.*, polyethylene), and therefore newer gas grids built predominantly with plastic pipes would more easily undergo a switch to hydrogen. For transmission pipelines made mostly out of steel, it might be possible to retrofit them with an inner liner made out of plastic or some other hydrogen-resistant material, although this requires more research (Speirs *et al.*, 2017).

Countries with largely developed gas markets, such as some European countries, the UK, Singapore and the US, could find this option attractive to avoid significant stranded assets. Other countries with less-developed natural gas markets could already start investing in building hydrogen compatible gas grids and avoid future retrofits.

Several projects around the world are injecting clean hydrogen into the gas grid. Germany has at least six projects injecting hydrogen into the gas grid in blends that vary from 1% to 10% (EnergieAgentur.NRW, 2016), with a new joint project by the German Association for Gas and Water (DVGW) and Avacon planning to inject up to 20% blends (DVGW, 2019). Turkey plans to make a first hydrogen injection into its gas grid by 2021 (AA, 2020). Other projects include the GRHYD demonstration project, by ENGIE (a French multinational utility) and the French government, which successfully injected hydrogen in blends of up to 20% (I&T, 2019) and demonstrated its feasibility in residential and transport applications (ENGIE, 2016); and the HyDeploy project in the UK, which aims to prove that blending up to 20% hydrogen in gas grids is safe by initially testing it in Keele University's private gas network and then moving to test it in the North East public network (HyDeploy, 2020).

29 A 2% limit applies in Germany if there are compressed natural gas (CNG) tanks connected to the grid. DVGW is developing new technical rules that aim to allow around 20% hydrogen blending. From the end of 2021, up to 20% hydrogen will be added to a natural gas grid section in Saxony-Anhalt.

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