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

SUMMARY

Citation

IRENA (2020), A summary of *Reaching zero with renewables: Eliminating CO_2 emissions from industry and transport in line with the 1.5°C climate goal*, International Renewable Energy Agency, Abu Dhabi.

A summary of ISBN 978-92-9260-269-7

Available for download: **www.irena.org/publications**

For further information or to provide feedback, please contact IRENA at **info@irena.org**

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.

Acknowledgements

IRENA appreciates the technical review provided by: Patrick Akerman (Siemens), Pierpaolo Cazzola (International Transport Forum), Emma Skov Christiansen, Renée Van Heusden, Joanna Kolomanska - van Iperen, and Kevin Soubly (World Economic Forum), Johannah Christensen (Global Maritime Forum), Kilian Crone (dena – German Energy Agency), Keith Dawe (Cargill), Guillaume De Smedt (Air Liquide), Alex Keynes and Anaïs Laporte (FTI Consulting), Florie Gonsolin and Marko Mensink (European Chemical Industry), Charlotte Hebebrand (International Fertilizer Association), Volker Hoenig (VDZ), Chris Malins (Cerulogy), Thomas Neuenhahn and Ireneusz Pyc (Siemens Gas and Power), Andrew Purvis (World Steel Association), Deger Saygin (Shura Energy Transition Center), Carol Xiao (ISPT) and Yufeng Yang (Imperial College).

This report also benefited from valuable contributions by IRENA experts: Elisa Asmelash, Francisco Boshell, Gabriel Castellanos, Martina Lyons, Raul Miranda, Gayathri Prakash, Roland Roesch, Emanuele Taibi and Nicholas Wagner.

This report was authored by Paul Durrant, Carlos Ruiz, Padmashree Gehl Sampath, Sean Ratka, Elena Ocenic, Seungwoo Kang and Paul Komor. The study was supervised by Dolf Gielen.

Executive Summary

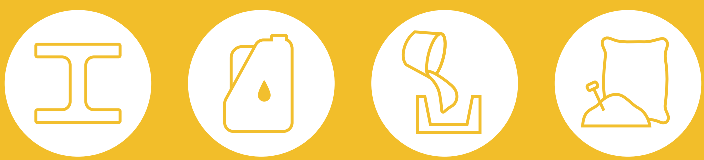
Limiting the rise in average global temperatures to 1.5 degrees Celsius (°C) requires all sectors of the economy to reach zero carbon dioxide (CO_2) emissions early in the second half of this century. Doing so presents significant technical and economic challenges, particularly in some highly energy-intensive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

Energy-intensive industrial sectors



Iron and steel | Chemicals and petrochemicals | Cement and lime | Aluminium

Energy-intensive freight & long-haul transport sectors

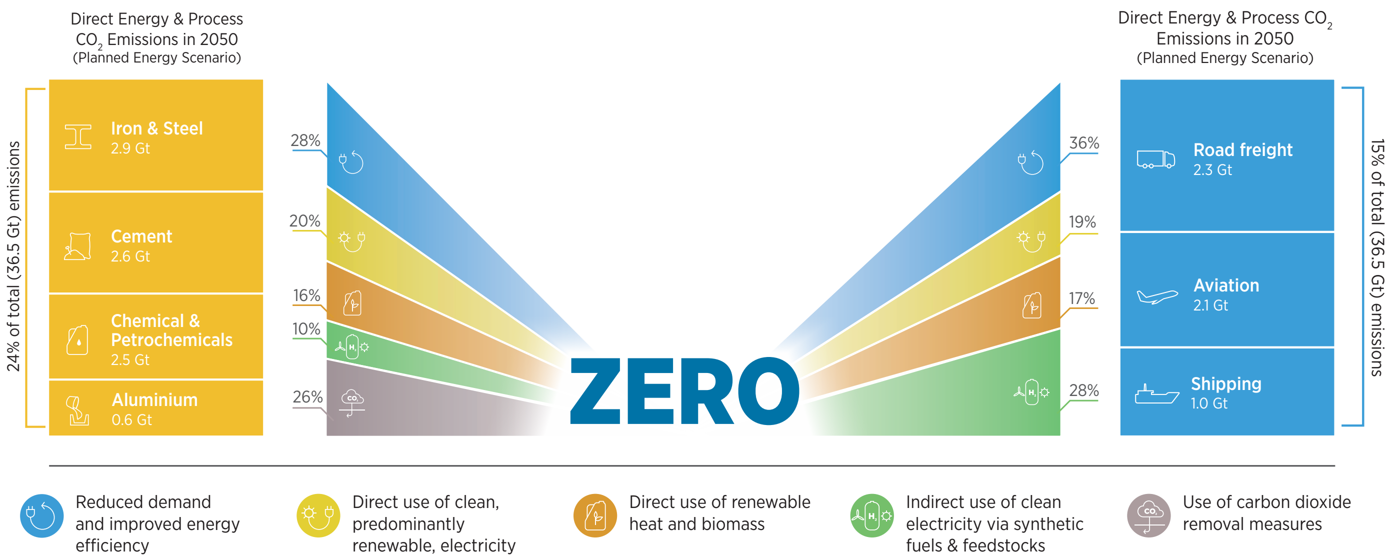
Road freight | Aviation | Shipping

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.

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

Energy-intensive freight & long-haul transport sectors

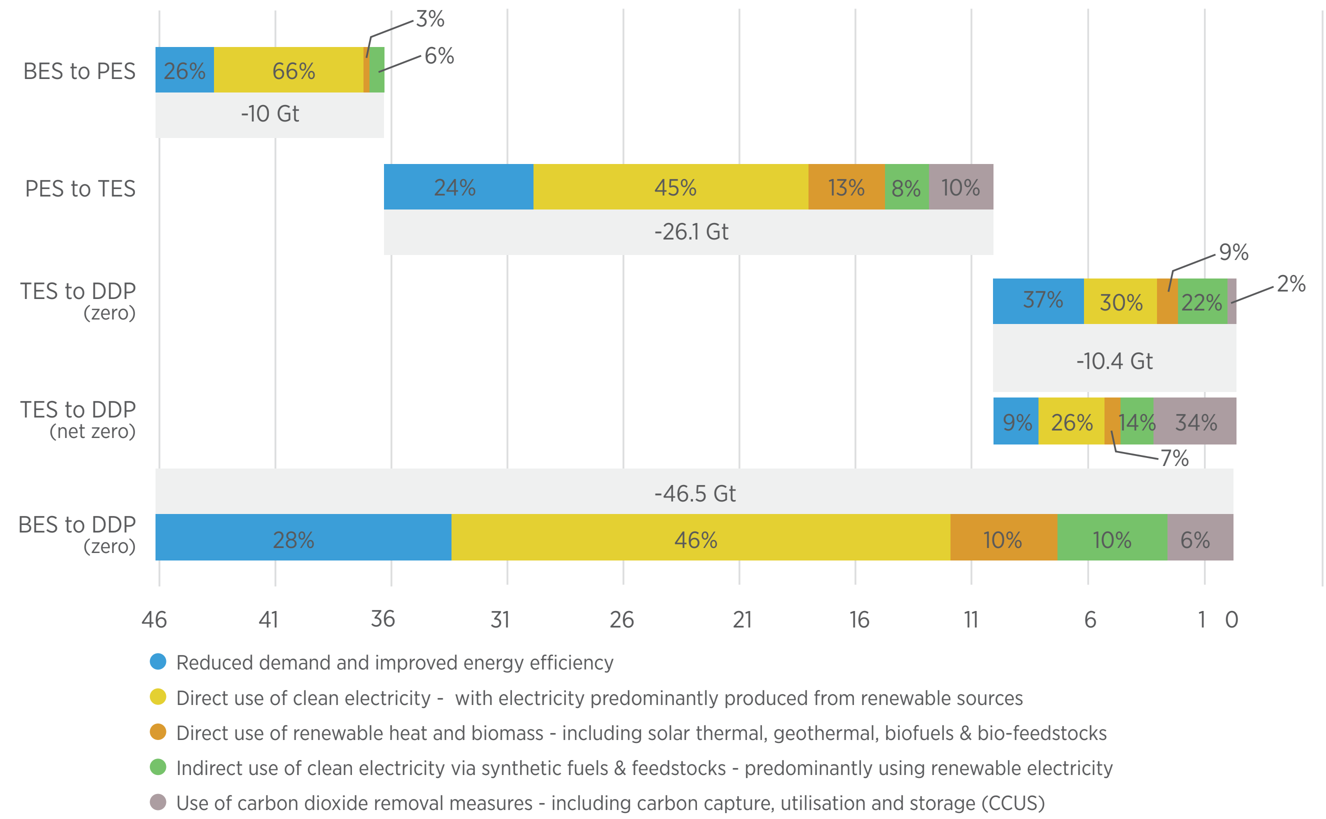
Iron and steel	Chemicals and petrochemicals	Cement and lime	Aluminium	Road freight	Aviation	Shipping
In 2017:	In 2017:	In 2017:	In 2017:	In 2017:	In 2017:	In 2017:
Consumed 32 exajoules (EJ) of energy	Consumed 46.8 EJ of energy	Consumed 15.6 EJ of energy	Consumed 4.5 EJ of energy	Consumed 32.3 EJ of energy	Consumed 13.5 EJ of energy	Consumed 11.3 EJ of energy
Only 4% was from renewables	Only 3% was from renewables	Only 6% was from renewables	16% was from renewables	Only 1.5% was from renewables	A negligible share was from renewables	A negligible share was from renewables
Emitted 3.1 gigatonnes (Gt) of CO_2	Emitted 1.7 Gt of CO_2	Emitted 2.5 Gt of CO_2	Emitted 0.4 Gt of CO_2	Emitted 2.3 Gt of CO_2	Emitted 0.9 Gt of CO_2	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).

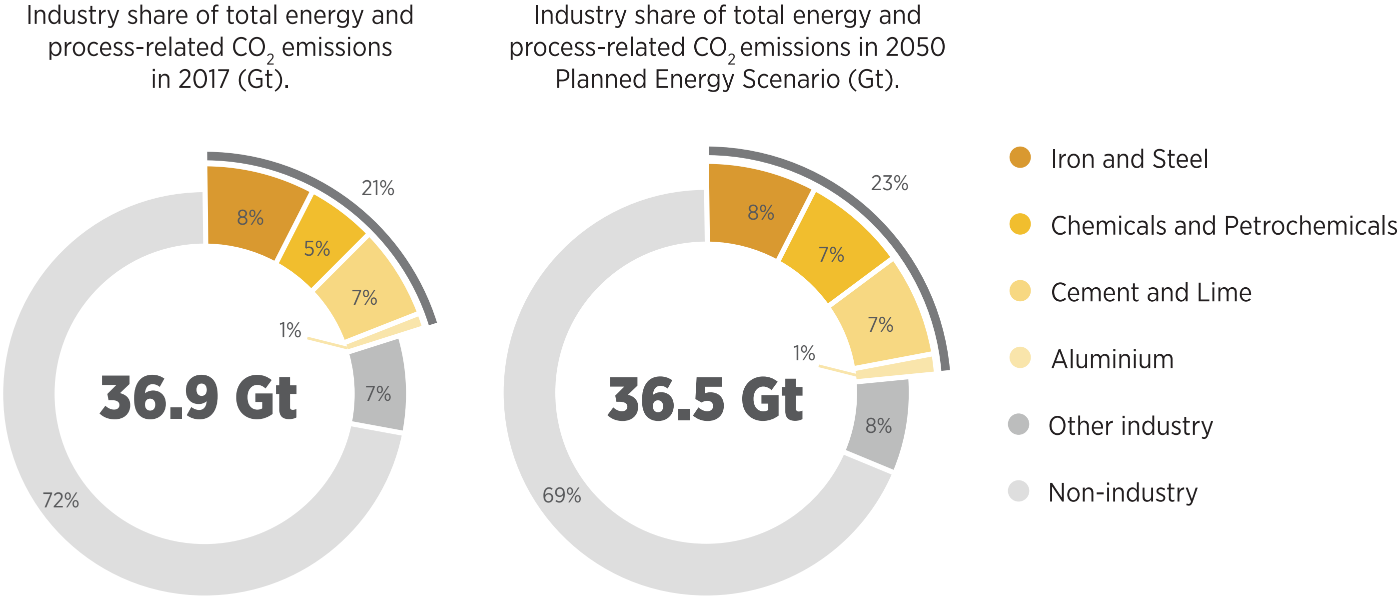
Indirect use of clean electricity via synthetic fuels and feedstocks – predominantly using renewable electricity
Source energy and feedstocks from hydrogen or from fuels or feedstocks produced from hydrogen (synthetic fuels or feedstocks) using CO_2 captured from non-fossil fuel sources. The hydrogen 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.

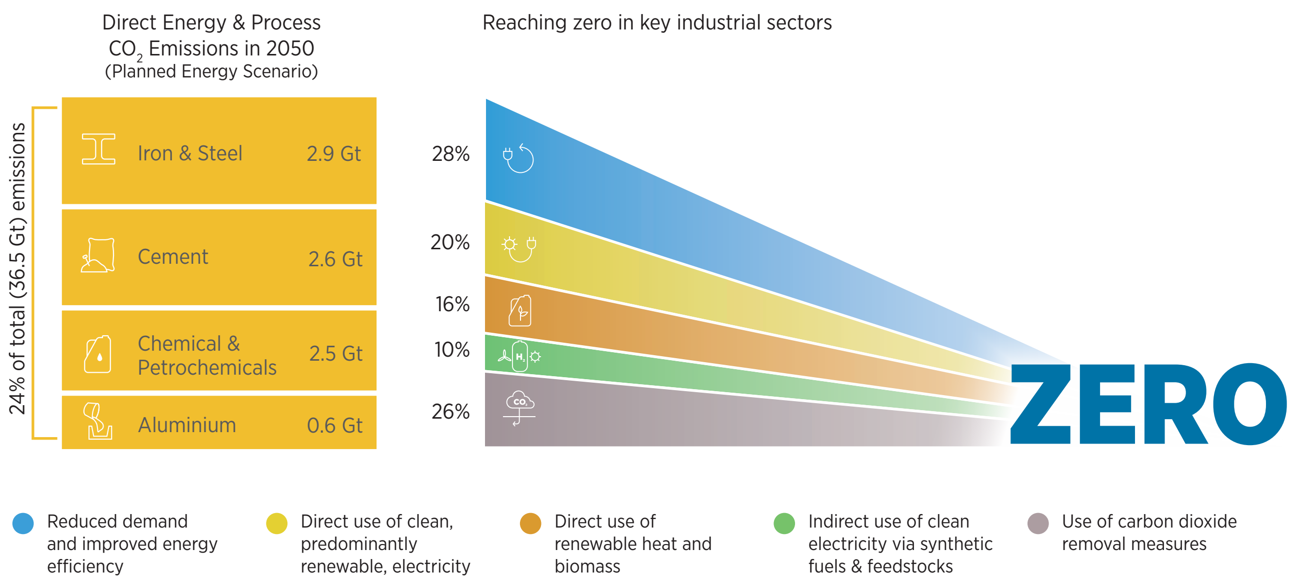
Industry overview



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

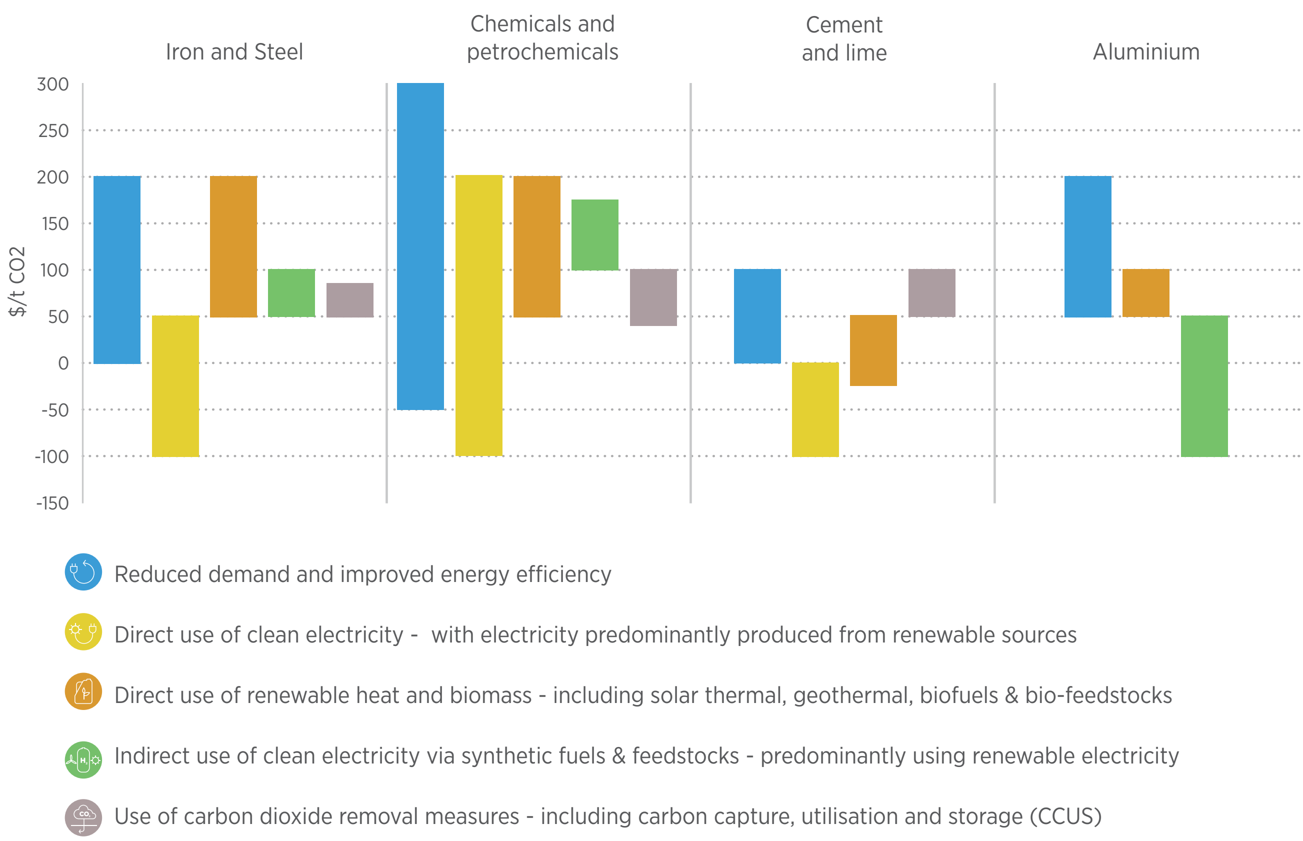


The industrial production of key materials is an essential enabler of modern economies. As countries develop, demand for such material continues to grow. However, that production currently comes with high CO_2 emissions. Industry accounts for around 28% of total global CO_2 emissions, but four industrial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

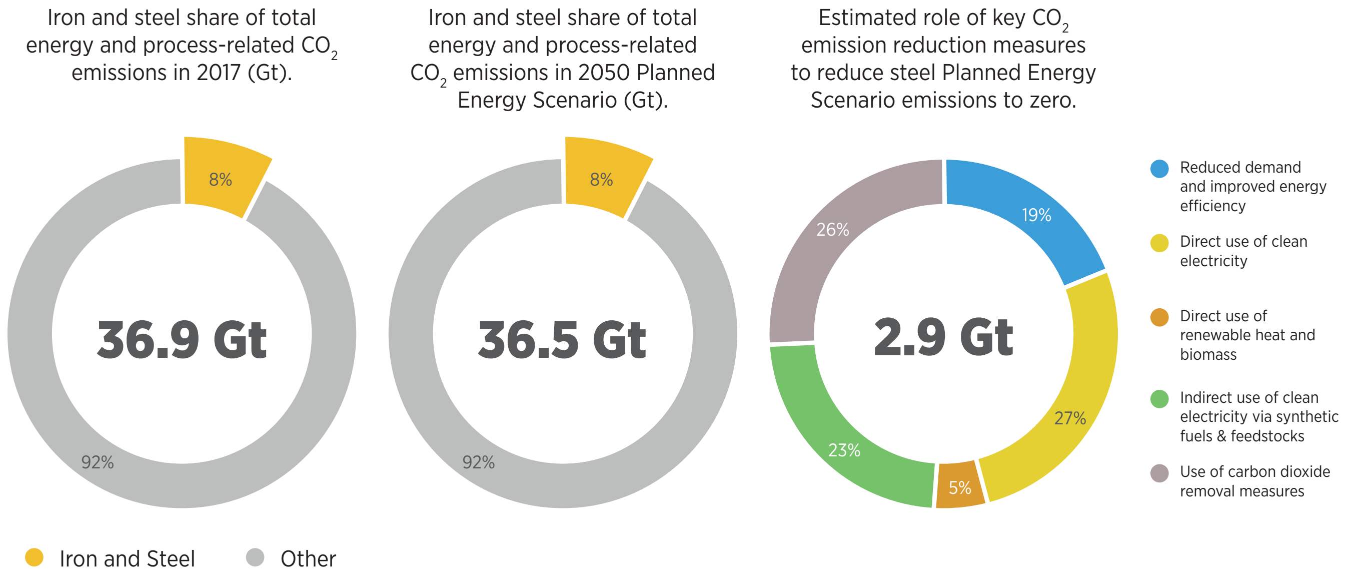
The majority of energy used in industry is currently sourced from fossil fuels. But energy use is not the only source of emissions in the industrial sector; CO_2 emissions must also be eliminated from production processes and from the life cycle of products. Reducing emissions and eventually reaching 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



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.

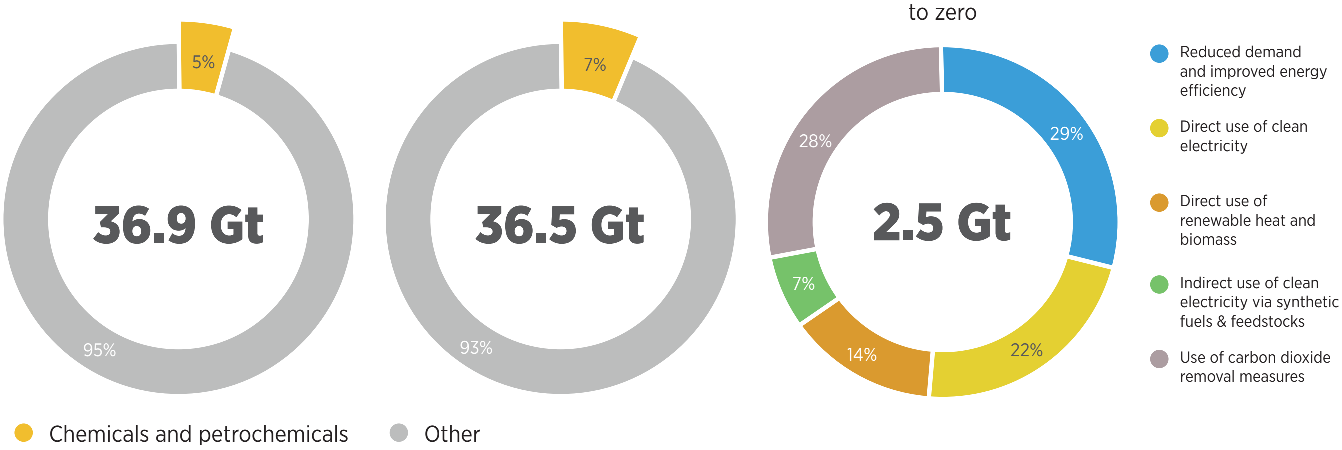
- Ensure that countries with large or expanding iron and steel production can utilise zero-emission-compatible production technologies; emerging economies will account for high shares of future production.

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).

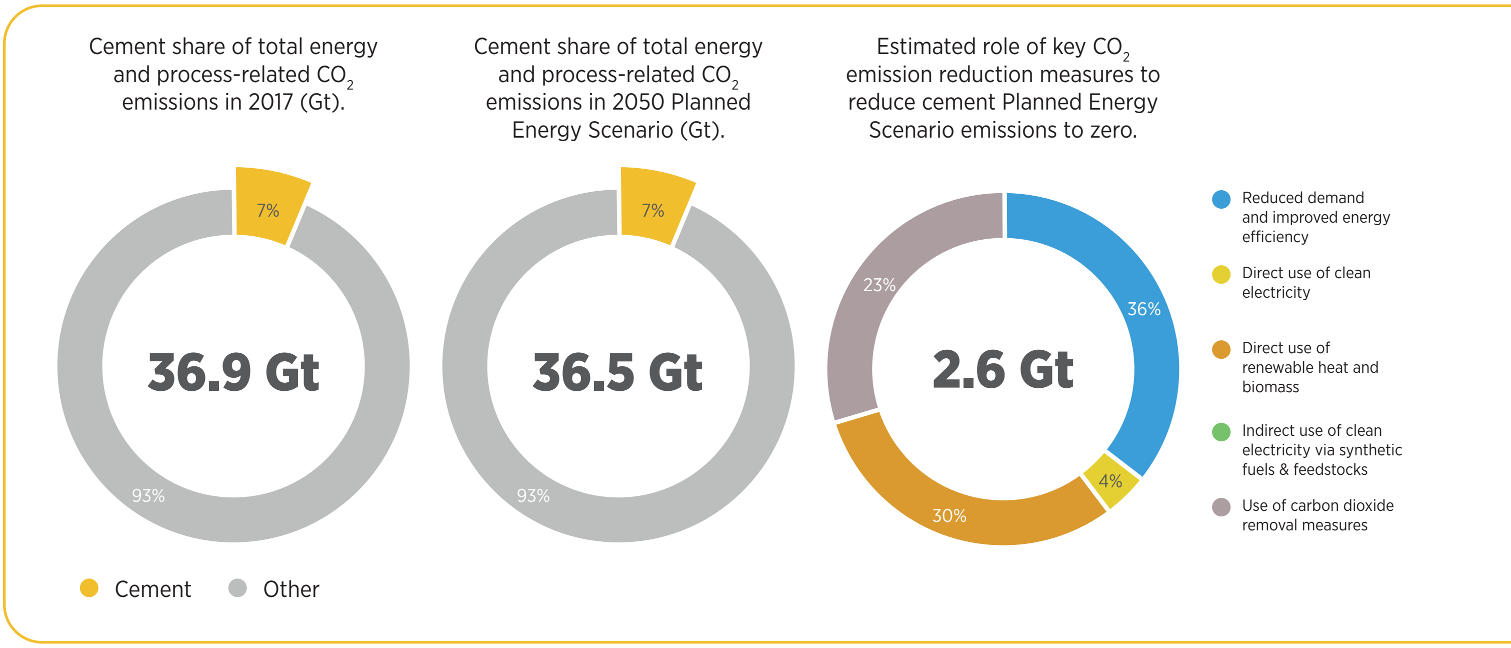
- Create early demand for "green" chemicals and products (mandate if necessary); creating a market can incentivise improvements in process efficiency and costs and reduce the risk of "carbon leakage". Certification of green supply chains may be required.

- 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



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

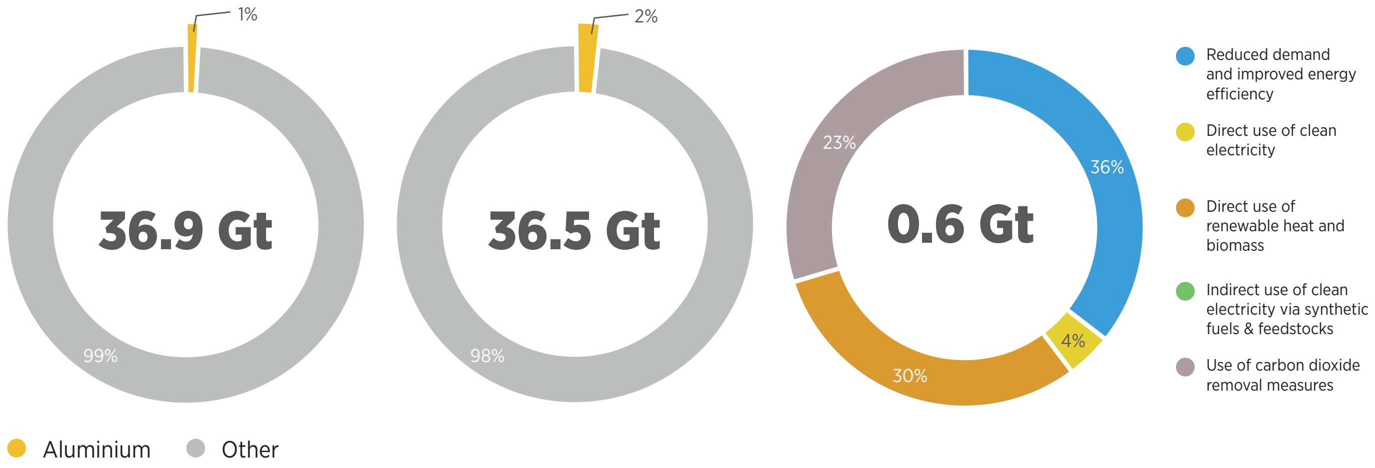
- Explore a portfolio of options to eliminate the sector's emissions through a combination of approaches; offsetting emissions from some plants with carbon removal measures elsewhere will be needed.
- Establish many more demonstration / lighthouse projects to show what can be done and to collate and 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

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

Aluminium 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 aluminium 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.

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

ZERO

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.

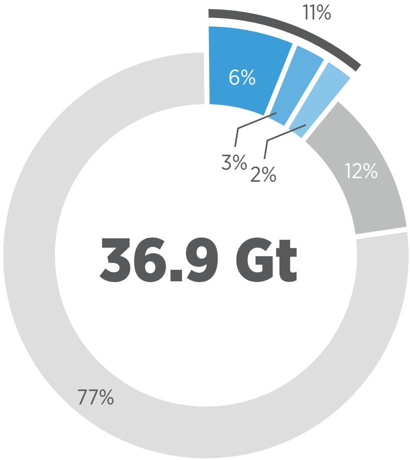
- Establish closer collaboration between companies in the aluminium and power sectors – to ensure that plans are compatible and to exploit synergies, particularly around new business models that create value from flexibility in demand and so help manage the increased deployment of variable renewable energy sources, such as solar and wind.

- Increase public and private activities and cross-border collaboration for RD&D into alternative "inert" anode designs.

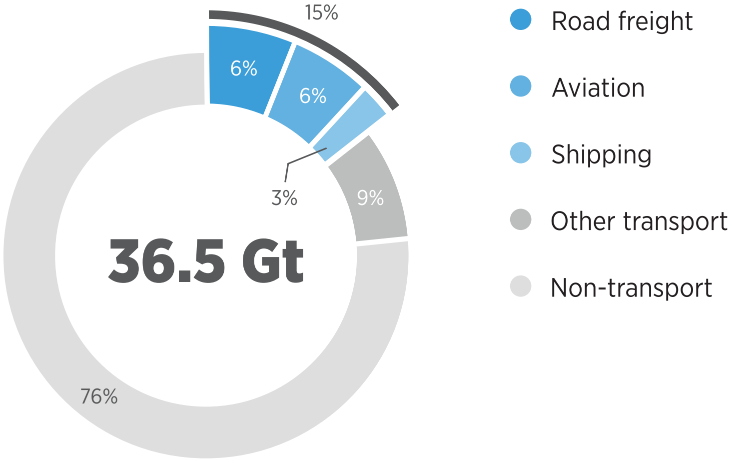
- Explore opportunities to relocate more aluminium production to areas with the potential for low-cost renewable electricity supply; this can reduce costs while delivering emission reductions.

Transport overview

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



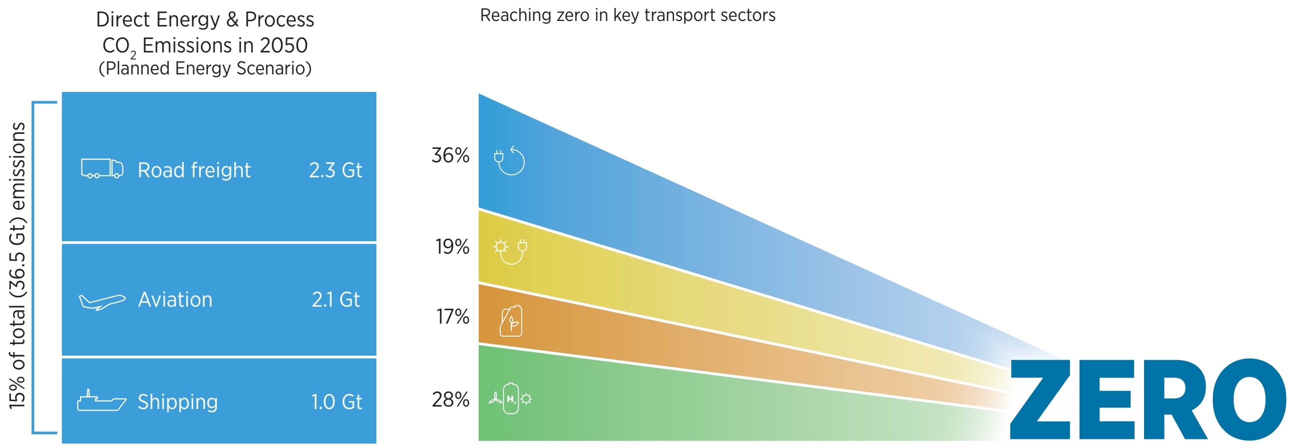
Transport share of total energy and process-related emissions in 2050 Planned Energy Scenario (Gt).



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



*Emissions from energy

- 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

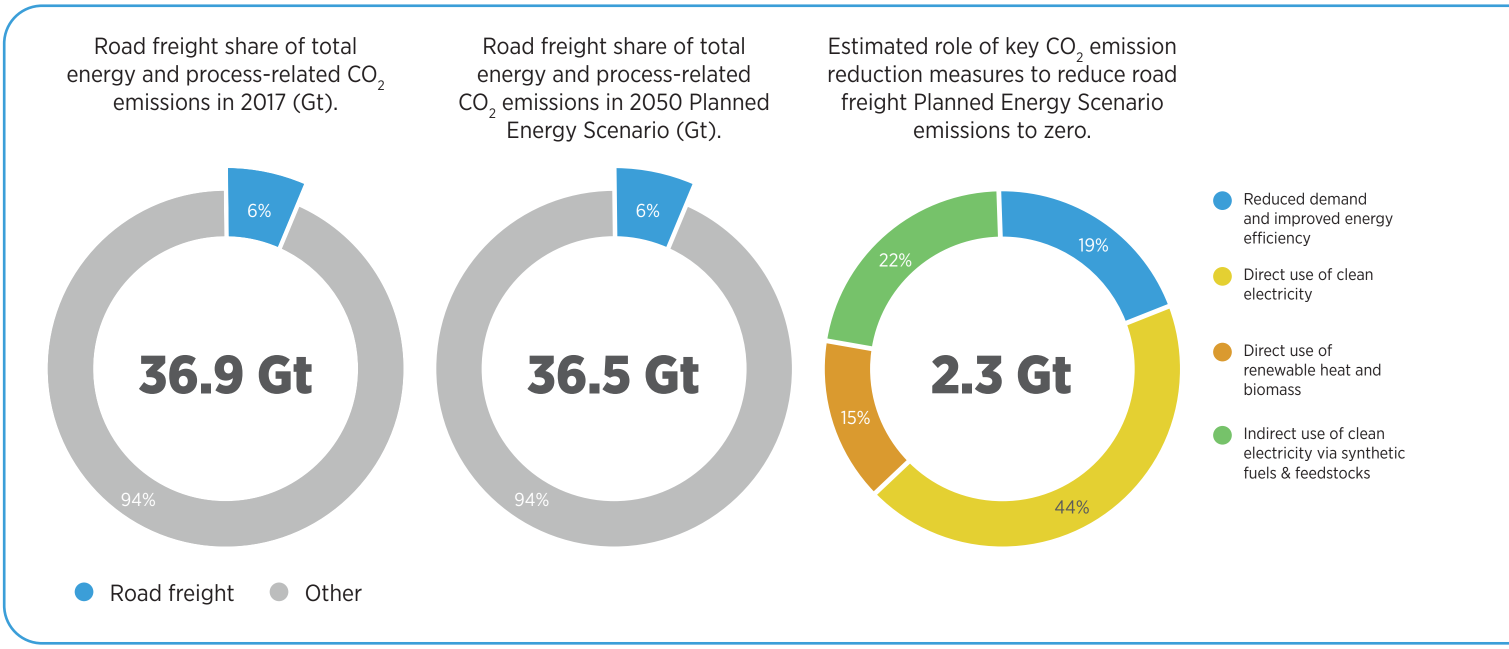
Transport plays a vital role in the world's economy. It facilitates the movement of people and goods across the globe and enables modern life as we know it. This comes at a cost, however, as the transport sector is also a major source of emissions due to its current heavy reliance on fossil fuels. With 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



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

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.

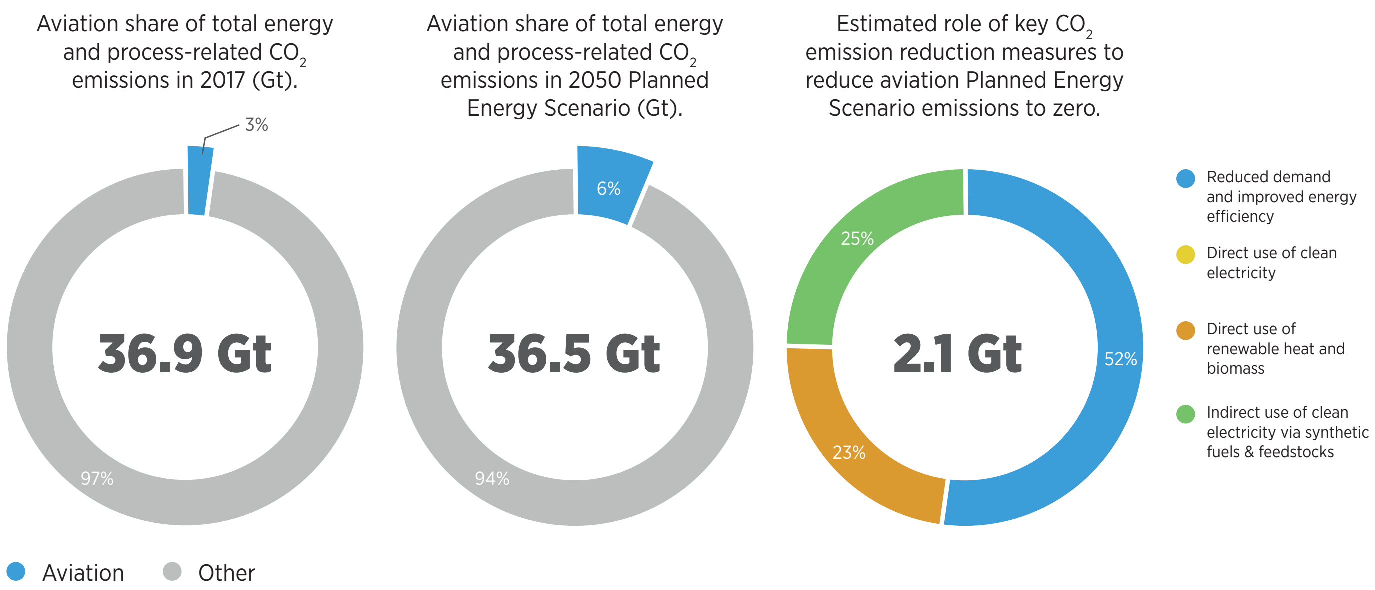
- Establish many more demonstration / lighthouse projects involving small fleets of vehicles, to show what can be done and to collate and share the learning (some low-carbon freight vehicle designs are emerging, but they remain niche).

- 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

ZERO

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.

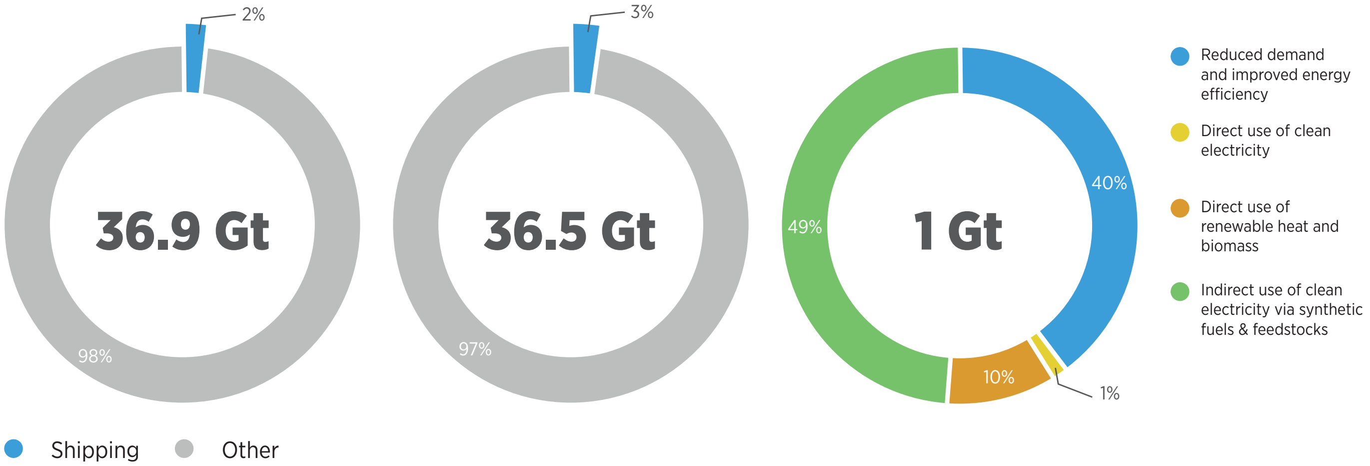
- Exploit cross-sectoral synergies such as the need for expanded sustainable sources of biomass and biofuels, the need for lower-cost green hydrogen and synthetic fuels production, and the associated supply chains' infrastructure.

Shipping

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

Shipping 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 shipping Planned Energy Scenario emissions to zero.



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	**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.

International Renewable Energy Agency