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DECARBONISING HARD-TO-ABATE SECTORS WITH RENEWABLES

PERSPECTIVES FOR THE G7

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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. **www.irena.org**

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FOREWORD

IRENA's World Energy Transitions Outlook presents a comprehensive and cost-effective pathway to limit global average surface temperature rise to 1.5°C above pre-industrial levels by 2050. To achieve this, it is necessary to decarbonise all sectors of the economy by around mid-century. However, there are currently sectors that are hard to decarbonise - namely heavy-duty trucks, shipping, aviation, iron and steel, and chemicals and petrochemicals. These sectors alone represent a quarter of the world's energy consumption and a fifth of total CO_2 emissions. This is likely to increase in the coming decades if they continue to rely on fossil fuels.

Renewables can play a central role in decarbonising these hard-to-abate sectors, and solutions are increasingly available today; yet despite promising progress and increased attention from policy makers, none of the hard-to-abate sectors is on track to reach net-zero emissions by mid-century.

The acceleration of decarbonisation in these hard-to-abate sectors requires decisive action from governments and the private sector, with far-reaching implications for national and international policy, technology and infrastructure planning, global commodity markets, international supply chains, and business models. The G7 can play an influential role in spearheading decarbonisation efforts by adopting the 11 recommendations presented in this report. The Group can also work alongside non-G7 countries by sharing best practices, removing trade barriers, and establishing common standards and definitions for low-carbon commodities.

This report - prepared to inform discussions during meetings among G7 senior officials as well the G7 Ministers' Meeting on Climate, Energy and Environment in Torino City on 29-30 April 2024 – is the result of IRENA's continued support to the G7 and our Members in developing action plans that accelerate the decarbonisation of hard-to-abate sectors in order to achieve the 1.5°C target of the Paris Agreement.

Francesco La Camera

Director-General

International Renewable Energy Agency

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ABBREVIATIONS

AFIR	Alternative Fuels Infrastructure Regulation
ATAG	Air Transport Action Group
BECCS	bioenergy with carbon capture and storage
BECCU	bioenergy with carbon capture and utilisation
BF	blast furnace
BOF	basic oxygen furnace
CBAM	Carbon Border Adjustment Mechanism
CCfD	Carbon Contracts for Difference
CCOD	Carbon Contracts for Difference
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CTE	Committee on Trade and Environment
DAC	direct air capture
DC	direct current
DRI	direct reduced iron
EJ	exajoules
EAF	electric arc furnace
ECEG	European Chemical Employers Group
EU	European Union
EU ETS	European Union Emissions Trading System
EUR	euros
EV	electric vehicle
FAME	fatty acid methyl ester
GHG	greenhouse gas
G7	Group of Seven
gCO_2eq	grammes of CO_2 equivalent
GDP	gross domestic product
GPP	green public procurement
Gt	gigatons
HEFA	hydro-processed esters and fatty acids
HFO	heavy fuel oil
HVCs	high-value chemicals
HVO	hydrotreated vegetable oil
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
ICAO	International Civil Aviation Organisation
ICCA	International Council of Chemicals Associations
ICCT	International Council on Clean Transport
ICE	internal combustion engine
IDDI	Industrial Deep Decarbonisation Initiative
IEA	International Energy Agency
IGO	intergovernmental organisation
IMO	International Maritime Organisation
IRENA	International Renewable Energy Agency
ISO	International Standard Organisation
km	kilometres
kW	kilowatt
kWh	kilowatt hour
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LTAG	long-term aspirational goal
MGO	marine gasoil
Mt	million tonnes

MW	megawatt
OECD	Organisation for Economic Co-operation and Development
PBtL	power and biomass-to-liquid
pkm	passenger kilometre
PV	photovoltaic
SAF	sustainable aviation fuel
tkm	tonne kilometre
TBT	technical barriers to trade
TEN-T	Trans-European Transport Network
TESSD	Trade and Environmental Sustainability Structure Discussions
teu	twenty-foot equivalent unit
TRL	technical readiness level
USD	United States dollar
VLSFO	very low-sulphur fuel oil
WETO	World Energy Transitions Outlook
Wh/kg	watt hours per kilogramme

EXECUTIVE SUMMARY

The Group of Seven (G7) has echoed the call from the International Renewable Energy Agency (IRENA) to accelerate the pace and scale of renewable energy deployment, highlighting its importance not only as an effective means of reducing emissions and enhancing energy security, but also driving economic growth and creating jobs.

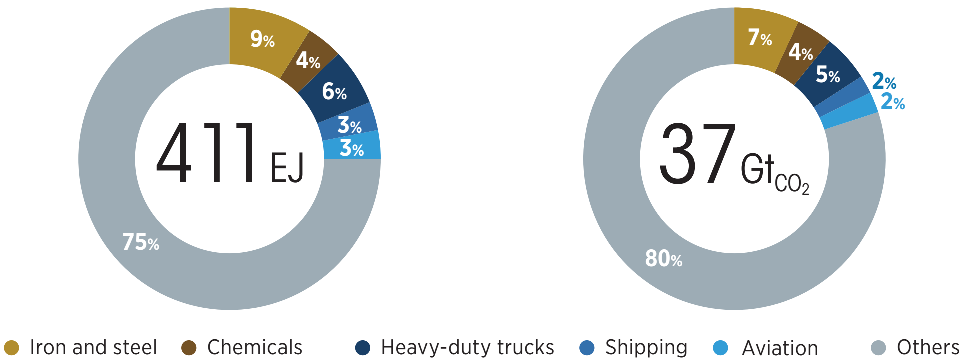
This report aims to provide actionable recommendations that the G7 can follow to accelerate the global efforts to decarbonise select "hard-to-abate" sectors, elaborating on the technological pathways and enabling conditions needed to achieve this goal.

Limiting the global average surface temperature rise to 1.5°C above pre-industrial levels will require all sectors of the economy to decarbonise by 2050. This is a great challenge that will require massive new investments and profound changes in the way energy systems operate.

For some sectors, such as passenger road transport, the path to net-zero emissions is clear, as evidenced by the exponential rise in electric vehicle sales. The pace of transformation in some other sectors, however, is much slower. Some industrial and transport sub-sectors are substantial greenhouse gas (GHG) emitters and are harder to decarbonise due to their physical, technological or market particularities.

This report focuses on five hard-to-abate sectors: road freight transport, shipping, aviation, iron and steel, and chemicals and petrochemicals. These five sectors account for roughly a quarter of the world's energy consumption and are responsible for around a fifth of total CO_2 emissions (Figure S1).

Figure S1 Energy consumption and CO_2 emissions for selected hard-to-abate sectors, 2022

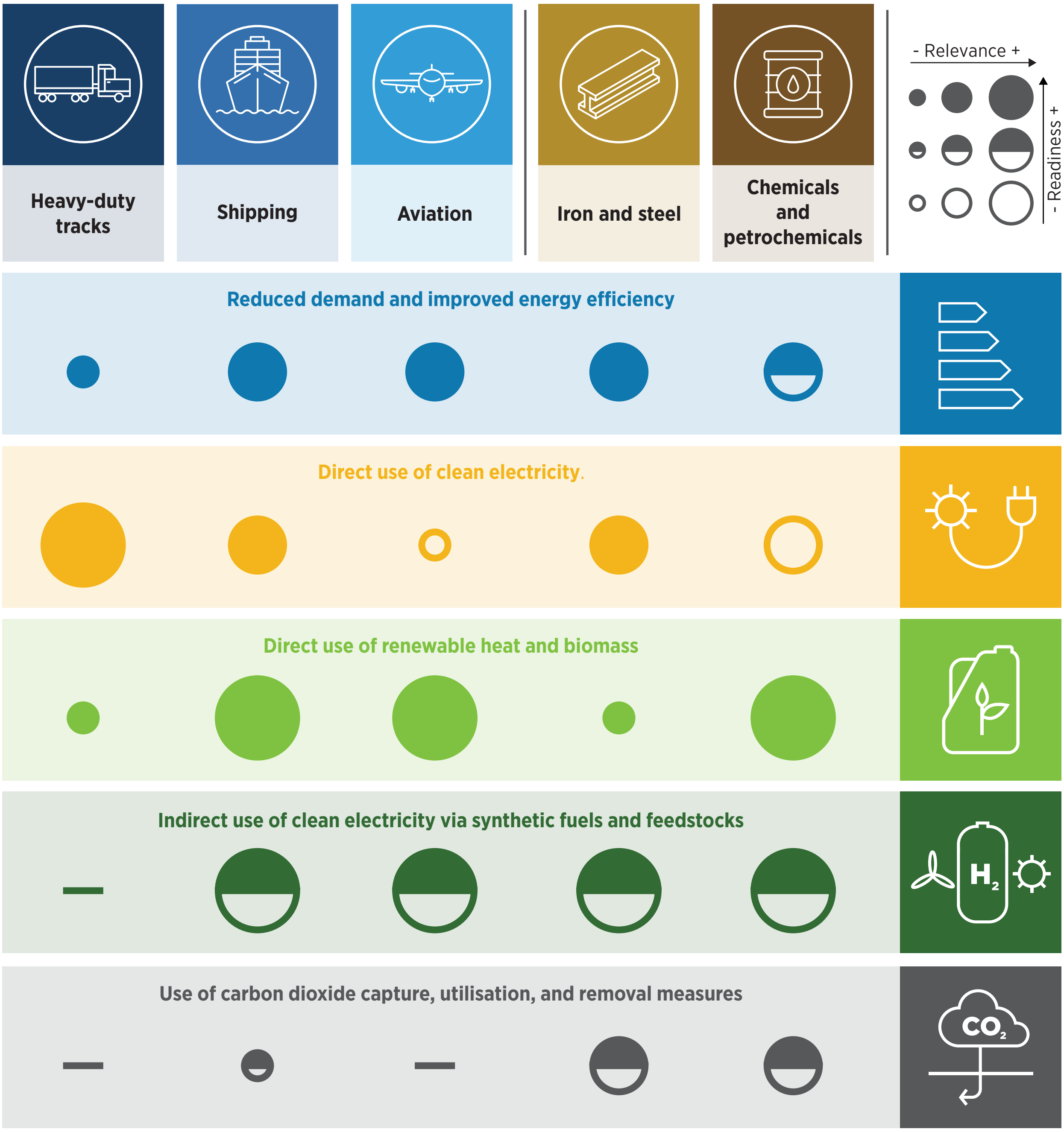


Source: (IEA, 2023a).
Note: EJ = exajoules; Gt = gigatonnes; CO_2 = carbon dioxide.

Renewables can play a central role in the decarbonisation of all hard to abate sectors. The drastic cost reductions that we have observed in recent years make renewable power the cheapest source of carbon-neutral energy worldwide. Furthermore, there is potential for further cost reductions through technological learning and economies of scale.

The full decarbonisation of the hard-to-abate sectors will require a combination of approaches, given the characteristics of each sector. However, most emission reductions will have to be achieved through a combination of five main pathways which rely primarily on renewable energy and energy efficiency as described in Figure S2.

Figure S2 Summary of key technological pathways and readiness assessment for selected sectors



Note: Increasing circle size indicates higher relevance to the decarbonisation efforts of each sector, *i.e.* larger circles indicate higher relevance and smaller circles lesser relevance. Circle filling indicates technology readiness, *i.e.* filled circles indicate a technology is ready for deployment, while empty circles indicate a lack of readiness. The dashes indicate negligible or no relevance.

The transition in hard-to-abate sectors requires fundamental shifts, rather than gradual steps. The window of opportunity for action to counter the global climate threat and meet the 1.5°C target of the Paris Agreeme is closing fast. Meeting the climate agenda requires solutions beyond partial emission reductions. Decision makers should prioritise solutions that are consistent with net-zero emissions, avoid delaying their decarbonisation objectives and the risk of future stranded assets. Most of these solutions rely on renewable energy.

Direct electrification will play an increasing role, with important contributions in multiple applications. Some of these solutions are already mature, or close to technological maturity. These include: the use of electric arc furnaces for steelmaking, which will become more important as the share of recycled steel increases in the coming decades; battery electric trucks, which are at a technological inflection point and becoming increasingly available; heat pumps for low to medium temperature heating in industry; and cold ironing at ports. Some other applications of direct electrification, while having great potential, still need further development. These include: electric crackers to produce primary chemicals; electrolysis of iron ores; and electric or hybrid aircraft and ships for short distances.

Bioenergy and synthetic fuels will play a critical, complementary role to electrification. Scaling up sustainable, low-carbon bioenergy solutions is not only key to the decarbonisation of shipping and aviation. It is also critical in providing feedstocks for chemicals and as a potential carbon source for synthetic fuels. Indirect electrification – *i.e.* via the production of renewable hydrogen – is also set to play an important role in achieving deep emissions reductions in these sectors. It can do this as a reductant in the production of iron in primary steel production, as a form of synthetic fuels for shipping and aviation, and as a feedstock for chemical industries.

These pathways will have to be complemented by continuous energy efficiency improvements, the application of the principles of the circular economy, and behavioural and process changes that reduce demand. Additionally, emissions can be further reduced through the application of CO_2 capture, utilisation and/or removal measures, provided that these technologies achieve the necessary improvements in performance and economics to make them technically scalable and economically viable.

While technology is increasingly available, **in the absence of sufficiently high and widespread carbon pricing, a timely transition in hard-to-abate sectors will almost certainly require paying a premium over the cost of fossil-based systems.** Cost differentials differ widely by sector and application. Despite promising progress and increased attention from policy makers, **none of the hard-to-abate sectors is on a trajectory compatible with reaching net-zero emissions by mid-century.**

Several enabling conditions need to be put in place to accelerate the decarbonisation of hard-to-abate sectors. These will require decisive action by governments, as well as by the private sector. They also have fundamental implications in terms of national and international policy and regulatory environments, technology and infrastructure planning, global commodity markets, international supply chains and business models.

To achieve this, this report provides the following recommendations for the G7:

On creating an enabling policy environment

1. **Establish sector-specific decarbonisation targets:** G7 countries can support the transition by establishing long-term, sector-specific, national objectives with clear intermediate milestones. Beyond national policies, G7 members can work with other countries, within and beyond the G7, towards further international convergence in the decarbonisation objectives for key traded commodities such as steel, ammonia, and methanol, as well as aviation and shipping fuels.

2. **Take further steps towards creating a level playing field for green technologies.** G7 countries can accelerate the adoption of green technologies in hard-to-abate sectors by implementing national carbon pricing policies that internalise the full value of the negative environmental externalities of fossil energy. Aligning energy taxes with decarbonisation objectives – for example, by reducing relative taxation of electricity *vis a vis* that of fossil fuels – can also play an important role by driving the electrification of heat and transport applications. Furthermore, G7 countries can work with other countries, within and beyond the G7, towards further convergence in international carbon pricing – for example, through sector-specific international agreements.

On fast-tracking infrastructure deployment and technology adoption

3. **Accelerate the deployment of renewable power supply in alignment with COP 28's pledge:** G7 countries can support the transition in hard-to-abate sectors by scaling up deployment of renewable power supply in line with the COP28 pledge of tripling renewable capacity by 2030. This will require additional efforts, including a substantial scaling up of investments and updating of policies and regulations. Electrification of hard-to-abate- sectors may also result in opportunities to optimise investments in power systems, as well as their deployment, and operation. A holistic approach to define the location of new renewable generation facilities could lead to reduced costs for the energy transition by minimising storage needs and the need to transport electricity and other energy carriers produced with electricity.

4. **Scale up sustainable bioenergy production and sustainable carbon sourcing:** G7 countries can support the transition in hard-to-abate sectors by working within and beyond the G7 to scale up global sustainable biomass supply chains. This can be achieved with policies that provide incentives for the production and/or use of bioenergy, coupled with strict sustainability governance procedures and regulations.

5. **Kick-start deployment of production capacity for green hydrogen derivatives:** G7 countries can accelerate the transition in hard-to-abate sectors by supporting the first wave of commercial-scale plants to produce low carbon commodities using green hydrogen – such as ammonia, methanol and iron.

6. **Enhance planning to accelerate the deployment of critical infrastructure:** G7 countries can support the transition in hard-to-abate sectors by strengthening cross-sector planning and international co-ordination in energy, industry, trade, transport, and the environment. They can also support the transition by accelerating permitting and deployment of critical energy infrastructure. Among others, this includes power grids – paired with smart electrification strategies – bioenergy conversion plants, hydrogen networks, and fuel terminals in ports and airports.

7. **Drive the adoption of innovative technologies to avoid lock-in:** G7 countries can accelerate the global transition in hard-to-abate sectors by prioritising and promoting the deployment of technologies that are consistent with net-zero emissions. G7 members can also work with non-G7 countries towards the widespread adoption of such new solutions, particularly in developing nations. This can be done through *inter alia* technology co-operation programmes, the exchange of best practices, and many other methods to avoid lock-in.

On driving markets and financial flows

8. **Create initial markets for low carbon commodities:** G7 countries can support the transition in hard-to-abate sectors by establishing green public procurement programmes or mandates for low carbon commodities. G7 members can also work within and outside the G7 to accelerate international convergence in definitions, standards, thresholds, and certification procedures to enable the international trade of such low carbon commodities.

9. **Bridge the finance gap:** G7 countries can drive an increase in global investment flows towards hard-to-abate sectors by working together with the private sector and financial institutions in de-risking projects within and outside the G7. Government support for project bankability can be implemented through several mechanisms, such as via the provision of guarantees, concessional loans, and blended finance, among other instruments.

On developing a skilled workforce

10. **Support the development of a skilled workforce:** G7 countries can play a significant role in developing the skills needed for the transition in hard-to-abate sectors. Potential measures include exchanging information on innovative technologies and best practices and providing financial support to specialised educational programs and trainings.

On leveraging international co-operation

11. **Foster international co-operation:** G7 countries can work together with developing countries towards mutually beneficial partnerships to decarbonise supply chains for industrial commodities. This can be done through co-operative long-term investment planning that results in a lower cost of decarbonisation for all.

1. INTRODUCTION

1.1 Objectives and structure of this report

The Group of Seven (G7) has echoed the call from the International Renewable Energy Agency (IRENA) to accelerate the pace and scale of renewable energy deployment.[1] This highlights the importance of renewables not only as effective means of reducing emissions and enhancing energy security, but also of driving economic growth and creating jobs.

In 2023, the G7 stated that they would "accelerate the deployment of renewable energies such as solar, onshore/offshore wind, hydropower, geothermal, sustainable biomass, biomethane and tidal using modern technologies, as well as invest in the development and deployment of next-generation technologies, and develop secure, sustainable and resilient supply chains" (G7 Ministers of Climate, Energy and the Environment, 2023).

The 2024 G7 Presidency requested IRENA's advice on how the G7 could contribute to accelerating global energy transitions.

While the energy transition will involve the decarbonisation of the power, transport, and heating and cooling sectors, there are elements of the energy system that are more complex and costlier to decarbonise. This is due to technological limitations, economic and geopolitical concerns and these sectors' extensive demand for energy. We refer to these sectors as "hard to abate". This report elaborates on the technological pathways and systemic innovations needed to decarbonise five of these sectors: heavy-duty trucks, shipping, aviation, iron and steel, and chemicals and petrochemicals. This report aims to provide actionable recommendations that the G7 can follow to accelerate global efforts to decarbonise these sectors.

This first chapter includes a short introduction to the decarbonisation challenge, particularly in the context of the five hard-to-abate sectors addressed in this study, while also looking at the five decarbonisation pathways that could help reduce emissions to net-zero.

Chapter 2 delves deeper into the status, challenges, and proposed solutions for the decarbonisation of each of the five hard-to-abate sectors mentioned above. Chapter 3.1 draws conclusions providing a more general perspective on decarbonisation, highlighting cross-cutting issues and commonalities in terms of challenges, enabling conditions and solutions for the different sectors. Finally, Chapter 3.2 makes recommendations about how the G7 can support the successful decarbonisation of these sectors.

[1] *See: www.irena.org/News/pressreleases/2023/Apr/G7-Communique-Echoes-IRENAs-Call-for-Rapid-Deployment-of-Renewables*

To complement this work, IRENA prepared two other studies for the 2024 G7 Presidency. The first of these outlines the implications for the G7 of the pledge to triple renewable power by 2030 made at COP28. This study then offers recommendations on how to materialise those ambitions. The second study focuses on energy transitions that are inclusive and maximise local value in the African region. It does this by outlining the key infrastructure investment opportunities and critical enabling conditions available for the African continent to enhance its role as a global partner in the energy transition.

1.2 Decarbonising hard-to-abate sectors

Limiting the global average surface temperature rise to 1.5°C above pre-industrial levels will require all sectors of the economy to decarbonise by 2050. This is a great challenge that will require massive new investments and profound changes in the way energy systems operate.

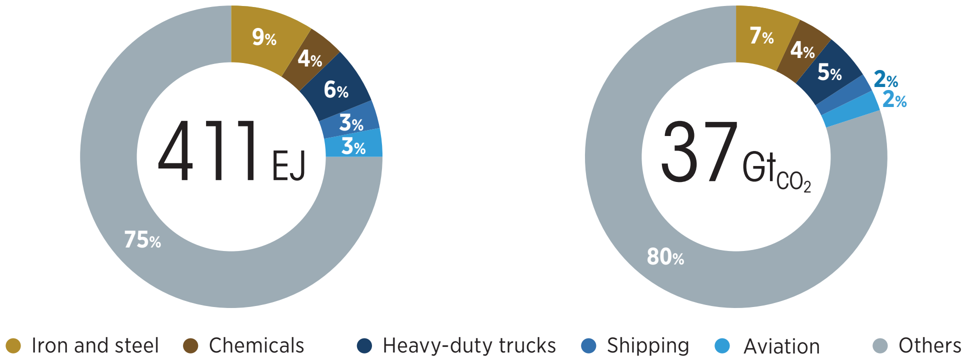
For some sectors, such as electricity supply, the path to net-zero emissions is clear. Most technologies for this sector are mature and commercially available, and the transformation is accelerating. Renewable technology costs have also dropped drastically over the last couple of decades, resulting in unprecedented deployment rates. In 2023, 87% of new electricity capacity additions globally were renewable – up from 53% in 2013 (IRENA, 2024a).

Something similar is happening with passenger road transport, where battery electric vehicle (EV) adoption is rising exponentially. Some 13.6 million electric passenger cars were sold in 2023 alone – roughly 15% of total global automobile sales and a 425% increase since 2020 (ACEA, 2024; Carey, 2024; EV-Volumes, 2023).

The pace of transformation in some other sectors, however, is much slower. Some industrial and transport sub-sectors are substantial GHG emitters and are harder to decarbonise due to their physical, technological or market particularities.

This report focuses on five hard-to-abate sectors: road freight transport, shipping, aviation, iron and steel, and chemicals and petrochemicals. These five sectors account for roughly a quarter of the world's energy consumption and are responsible for around a fifth of total CO_2 emissions (Figure 1).

Figure 1 Energy consumption, CO_2 emissions, activity metrics for selected hard-to-abate sectors, 2022



2022	Heavy-duty tracks	Shipping	Aviation	Iron and steel	Chemicals and petrochemicals
Activity	30 trillion tkm	110 trillion tkm	6 trillion pkm 220 billion tkm	1.8 billion tonnes	719 million tonnes
Energy consumption [EJ/year]	26.8	11.2	11	35	16
CO_2 emissions [Gt]	1.8	0.86	0.8	2.8	1.3

Source: (ICAO, 2023a; IEA, 2023a, 2023b; UNCTAD, 2022).
Note: EJ = exajoules; Gt = gigatonnes; tkm = tonne kilometre; pkm = passenger kilometre.

The steps that need to be taken to decarbonise these sectors have long been debated. Progress on the implementation of these steps, however, has so far been very slow. In recent years though, two important factors have changed. The first is the unprecedented social and political momentum now pushing for an acceleration in decarbonisation. The second is the technological maturity and increasing competitiveness of renewable power and other enabling technologies, potentially bringing the solutions closer to reality for some of the decarbonisation challenges in these sectors.

IRENA's perspective on achieving net-zero CO_2 emissions (IRENA, 2020), recognises that while each sector is different and will require different approaches, most emission reductions will have to be achieved through a combination of five main pathways which rely primarily on renewable energy and energy efficiency. (Figure 2).

Figure 2 Main technology pathways for the decarbonisation of industry and transport

Reduced demand and improved energy efficiency

Reducing the demand and intensity for energy and materials through a range of actions. These include energy efficiency, behavioural and process changes, industry relocation and the application of the principles of the circular economy.

Direct use of clean electricity

Replacing technologies and processes that rely on fossil fuels with alternatives powered directly by clean electricity. This not only displaces fossil fuel use, but also increases the efficiency of these processes.

Direct use of renewable heat and biomass

Satisfying heat requirements with renewable heat from solar thermal, geothermal or bioenergy technologies, and directly replacing fossil fuels with biofuels where direct electrification is not possible.

Indirect use of clean electricity via synthetic fuels and feedstocks

Sourcing energy and feedstocks from hydrogen and its derivatives, produced using clean electricity and sustainably sourced carbon, obtained from non-fossil fuel sources.

Implementation of CO_2 capture, utilisation, and removal measures

CO_2 emissions from processes where emissions cannot be fully eliminated can be captured and stored permanently, or used in ways in which it will not be released later. To avoid net CO_2 additions to the atmosphere, the carbon utilisation pathway needs renewable sources of carbon or the application of a closed loop where the CO_2 resulting from combustion is recycled back into fuels.

The window of opportunity for meaningful action to counter the global climate threat is closing fast. The climate agenda requires solutions beyond partial emission reductions. Decision makers should prioritise solutions that are consistent with net-zero emissions, and avoid delaying their decarbonisation objectives and the risk of future stranded assets. Most of these solutions rely on renewable energy.

The following chapter takes a deeper look into each of the five hard-to-abate sectors mentioned above, analysing their status and challenges. It then shows how the five technological pathways also outlined above can be applied towards the full decarbonisation of those sectors.

2. CHALLENGES, SOLUTIONS, AND PROGRESS TOWARDS DECARBONISATION OF THE SELECTED SECTORS

2.1 Heavy-duty trucks

Heavy-duty trucks[2] play a crucial role in the global economy. Since 2010, the volume of goods transported by this mode of transport has increased by over 30%, a similar increase to that of global gross domestic product (GDP)[3] (IEA, 2023a; World Bank, 2024). As a result of this strong correlation between road freight activity and economic growth, heavy-duty road truck activity is expected to more than double by mid-century (ITF, 2023; IEA, 2023a; MPP, 2022). Fast deployment of zero-emissions trucks[4] is therefore essential if dependence on fossil fuels is to be reduced and air quality improved, benefiting the climate and society.

Emissions and energy use

Heavy-duty trucks represent only about 9% of global vehicle stock (IDTechEX, 2019), yet they are responsible for almost a quarter of all transport-related CO_2 emissions. In 2022, this figure translated to around 5% of global CO_2 emissions, or, in absolute terms, around 1.8 Gt of CO_2 (IEA, 2023a). Put another way, emissions from heavy-duty trucks are larger than those from the international aviation and shipping sectors combined.

Today, heavy-duty trucks rely almost exclusively on diesel, petrol and natural gas. Biofuels account for less than 5% of total consumption in the sector (IEA, 2023a).

In the last few years, the sector has made some progress towards decarbonisation. The emissions intensity of new trucks has decreased by around 14% since 2019,[5] partly due to efficiency measures, operational improvements, and an increase in biofuels in the fuel mix (WEF, 2023).

[2] Heavy-duty trucks include medium trucks (3.5 tonnes to 15 tonnes) and heavy trucks (above 15 tonnes).

[3] At constant, 2015 US dollars (USD), global GDP increased from USD 65 trillion in 2010 to close to USD 90 trillion in 2022 (World Bank, 2024).

[4] In this report, zero emission trucks refers to trucks with zero tailpipe emissions.

[5] The emission intensity for new trucks dropped from 109.3 grammes of CO_2 equivalent (gCO_2eq)/tkm to 94.4 gCO_2eq/tkm between 2019 and 2022 (WEF, 2023).

Decarbonisation pathways

Global heavy-duty truck activity is expected to more than double by 2050. With continuous reliance on diesel and limited action taken, by then, heavy-duty trucks alone could account for over 75% of all road freight-related CO_2 emissions and emit between 2.3 Gt and 3 Gt of CO_2 (MPP, 2022; IEA, 2023a).

In the short- to medium-term, the carbon footprint of the sector can be reduced by introducing stringent efficiency standards for trucks. Beyond efficiency, a modal shift from road- to rail-based freight can further reduce the energy intensity of the transport sector. However, modal shifts typically require substantial investments in infrastructure that can take years or even decades to materialise. In the long term, a combination of renewables-based options - such as the use of biofuels, adoption of electric trucks, and the use of renewable hydrogen and synthetic fuels - is required to reach net-zero emissions in the sector.

From those renewables-based options, significant progress has been observed in terms of electric trucks owing to several factors. These include: their superior efficiency;[6] expected earlier market availability at scale; and benefits from synergies with technological advances in battery electric cars, which are already being deployed in large volumes.

The costs and performance improvements of batteries have also greatly improved the economic case for EVs in recent years.

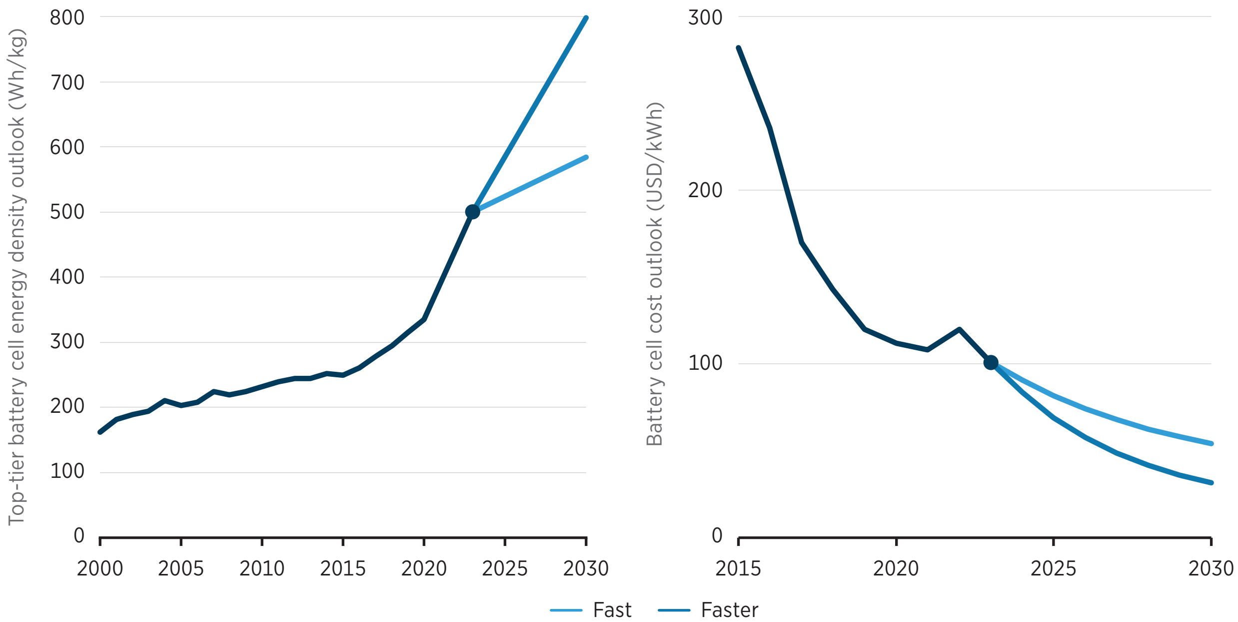
From 2010 to 2023, the weighted average price of lithium-ion battery packs declined 89%, to USD 139 per kilowatt hour (kWh) (BNEF, 2023a). Over the same period, the cost of lithium-ion battery cells dropped to around USD 100/kWh, while in 2023, the energy density of some newly commercialised batteries crossed the 500 watt-hours per kilogramme (Wh/kg) mark (RMI, 2023). As a result, the scope of application of batteries is quickly expanding to a broader set of road vehicle segments and types of services. Accordingly, electric trucks are gaining attention and emerging as the most promising technological solution for decarbonising the heavy-duty segment. Electric trucks have the potential to be cost-competitive in the absence of subsidies and are becoming increasingly available for wider adoption.

Yet, even if there is a rapid adoption of electric trucks, a large fleet of internal combustion engine (ICE) vehicles will unavoidably be in operation for the next two to three decades. For these, emission reductions can also be achieved in the short- to medium-term by using sustainably sourced biomass-based diesel substitutes.[7] However, in the longer run, the use of sustainably sourced biomass needs to be prioritised in those sectors where there is a limited scope for electrification and other low-carbon alternatives.

[6] *Electric powertrains in electric vehicles typically operate at energy efficiencies above 90%, while internal combustion engines in vehicles typically convert less than a third of the energy in the fuel into useful mechanical energy (Martin Weiss et al., 2020).*

[7] *Fatty acid methyl esters (FAME) are produced via the esterification of vegetable oils and fats and are also known as biodiesels. Hydrotreated vegetable oil (HVO), also known as hydro-processed esters and fatty acids (HEFA), is commonly referred to as renewable diesel (IRENA, 2020).*

Figure 3 Evolution and projections to 2030 for battery cell energy density (left) and costs (right)



Source: (Walter *et al.*, 2023).

There are also ongoing efforts to explore the use of hydrogen trucks. However, the economics and technical characteristics[8] of these vehicles lag far behind those of electric trucks. Moreover, the use of green hydrogen should be prioritised in sectors where it adds the most value to decarbonisation efforts, *i.e.* where direct electrification with renewable power is not an option. Such applications include the production of key industrial commodities such as ammonia, steel and the production of synthetic fuels for long haul aviation and shipping. In these, green hydrogen can be a complementary solution to sustainable biofuels.

[8] *For example, about three times more renewable electricity supply is needed to power a hydrogen truck as compared to a battery electric truck.*

Figure 4 Summary of decarbonisation pathways and infrastructure needs for heavy-duty trucks

The carbon footprint of the sector can be reduced by introducing stringent efficiency and emissions standards for trucks. Beyond efficiency, in cases where there is large demand of freight services – such as major transport corridors – and adequate infrastructure provision, a modal shift from road-based freight to rail can further reduce the energy intensity of the transport sector.

Battery electric trucks are set to be the leading pathway for decarbonising road freight transport. Compared to other low-carbon alternatives, electric trucks are highly efficient, soon to be cost-competitive, and increasingly available now for wider adoption. Faster deployment of charging infrastructure is essential.

Emission reductions can also be achieved in the short- to medium-term using biomass-based diesel substitutes, such as biodiesels and renewable diesel. This is particularly relevant for the fleet of ICE vehicles which will unavoidably be in operation for the next two to three decades.

There are ongoing efforts to explore the use of hydrogen trucks, but their economics and technical characteristics lag far behind those of electric trucks.

Key infrastructure needs for heavy-duty trucks

- Fast charging infrastructure for e-trucks in rest areas and slow charging in depots
- Expansion and reinforcement of distribution grids
- Digital infrastructure for smart charging
- Stationary storage close to charging stations to reduce peak loads

Tracking Progress

Road freight decarbonisation is approaching a turning point, driven by technological progress and growing regulatory and market pressures. It is also set to advance more rapidly than anticipated. In recent years there has been rapid growth in zero-emission vehicle models entering the market. The Zero-Emission Technology Inventory (ZETI) database[9] shows that there are currently 116 heavy-duty truck models existing and announced. Of these, 99 are battery electric and the remaining 17 are fuel cell-based.

In terms of performance, since 2020, the average ranges for zero-emission trucks have increased by 11%. The availability of vehicles with a range of 500 miles (805 km) indicates promising capabilities for longer hauls (Global Drive to Zero, n.d.).

In terms of vehicle sales, electric medium- and heavy-duty trucks accounted for 1.2% of global truck sales in 2022, with over 60 000 units sold. China was the main market, accounting for 85% of global sales (IEA, 2023c). In 2023, a total of 2 600 zero-emission heavy-duty trucks were sold in the European Union (EU). This figure is over three times the total sold in 2022 (820), indicating strong growth in market demand (ICCT, 2024a).

Despite this progress, however, the current pace of adoption of electric trucks is less than what is needed to achieve climate targets. Under IRENA's 1.5°C Scenario, EVs should account for nearly two-thirds of the heavy-duty vehicle stock by 2050 (IRENA, 2023a). This implies that electric heavy-duty trucks have to become widely available and sold in significant volumes in most jurisdictions around the world within this decade. The major challenges, including higher upfront costs, insufficient charging infrastructure, an imbalance in taxation of electricity vis-a-vis fossil fuels, and only incipient supply chains to meet the fast demand growth of electric trucks, need to be addressed.

Different charging models for heavy-duty electric vehicles are being explored and pilot prototypes are emerging. Electric trucks have been relying on off-shift charging for most of their energy, typically done at private or semi-private charging depots and usually overnight. There is a global push to implement fast or ultra-fast charging options, however, as a necessary step in making regional and long-haul operations technically and economically viable. Notable examples include a joint venture by Daimler, Volvo, and Traton Group, which aims to roll out a large-scale public charging network for heavy-duty trucks and coaches in Europe. This would have at least 1 700 fast and ultra-fast charging points (Milence, 2022). Tesla plans to build electric semi-truck charging stations between California and Texas to reach 70% battery capacity, in alignment with the US mandatory 30-minute break for truck drivers after 8 hours of driving (Electrek, 2023). Forum Mobility, a service provider, plans to deploy over 1 000 direct current (DC) fast chargers for heavy-duty electric trucks at the San Pedro and Oakland ports (Forum Mobility, n.d.).

Alternatives to charging stations, such as electric road systems,[10] are currently being demonstrated, although only a few countries, such as Sweden, are advancing with specific plans.

As in the electric passenger vehicle segment, a variety of charging standards are also currently under development and are soon to be adopted. In 2022, the industry association CharIN introduced the Megawatt-level Charging Standard. This has a maximum power rating of 3.75 megawatts (MW) and is scheduled for adoption in 2024, primarily in Europe and North America (CHARIN, 2022). Elsewhere, in September 2023, China established the "ChaoJi" charging standard, which has a maximum power of 1.2 MW. Commercialisation of chargers with power levels rated in the megawatts calls for significant investment, however, as stations with such high requirements will incur significant installation, grid connection and upgrade costs.

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[9] *See: https://globaldrivetozero.org/tools/zeti-data-explorer/*

[10] *This is infrastructure that allows for charging while driving and is currently under consideration in Sweden for electrifying long-haul trucking.*

Advanced power system planning, and grid management measures are emerging to accommodate charging needs, along with the raising market share. Alternative solutions, such as installing stationary storage, integrating local renewable capacity via the creation of clean energy corridors, and using smart charging, can help reduce infrastructure costs related to grid connection. They can also reduce electricity procurement costs. Smart charging measures have already been adopted in the United Kingdom (which mandated compliance with its Open Charge Point Protocol in 2022), Belgium and Luxembourg (IRENA, 2023b).

On the policy side, governments at different levels have set sales targets and started implementing incentives to encourage the use of zero-emission trucks. Under the global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles, 27 countries around the world have pledged that zero-emission medium- and heavy-duty vehicles will represent 30% of their new truck sales by 2030, and 100% by 2040, at the latest (IEA, 2023c). In California, the Advanced Clean Truck policy requires manufacturers to reach a sales goal of 40% zero-emission trucks by 2035. Since 2023, the US Inflation Reduction Act has provided tax credits of up to USD 40 000 per vehicle for the purchase of zero emission heavy-duty electric trucks. The aim of this is to bring the cost per mile of these vehicles down to par with traditional diesel trucks (US Government, 2023).

Stricter regulations and stringent standards are being formulated in various jurisdictions. In Europe, new CO_2 emissions standards have been introduced that set a 45% emissions reduction target for heavy-duty vehicles by 2030, compared to 2019 levels, increasing to 90% by 2040 (EC, 2023a). In the United States, the GHG for Heavy-Duty Vehicles - Phase 3 standards for 2027 also aim to bring significant reductions in pollutant emissions from trucks (US EPA, 2023). Other major economies such as China, Canada, India, and Japan also apply standards to heavy-duty vehicles (The Climate Change Authority, 2023). In parallel, to increase demand for zero-emission trucks, some governments have started committing to a 100% phase-out of ICE medium- and heavy-duty trucks in the long term. Indeed, according to the International Council on Clean Transport (ICCT) tracking progress tool, eight governments have set ambitious ICE truck phase-out targets, aiming for at least 40% of all sales for electric trucks by 2050 (ICCT, 2024b).

Policies specifically targeting the rollout of charging infrastructure, grid extensions and modernisation are also starting to emerge. Europe is well advanced on this front, with the EU Alternative Fuels Infrastructure Regulation (AFIR). This aims to install electric recharging stations for heavy-duty vehicles every 60 km along the Trans-European Transport Network (TEN-T) core, with complete network coverage by 2030 (EC, 2023b). The stations will have a minimum output of 350 kW. This regulation could provide sufficient public charging infrastructure for the EU to reduce CO_2 emissions from new heavy-duty vehicles by 65% – substantially more than the official 45% reduction target across the EU (T&E, 2023).

The United States, meanwhile, is advancing with the National Electric Vehicle Infrastructure Formula Program. This has allocated funding of USD 885 million for 2023 to support the installation of charging stations along 122 000 km of highways (US DOE, n.d.). In addition, the country recently unveiled its first-ever national strategy to accelerate the charging infrastructure for freight trucks (US DOE, 2024). In addition, California plans to build a clean highway corridor, called The West Coast Clean Transit Corridor, with charging facilities from San Diego to British Columbia for heavy- and medium-duty trucks (IRENA, 2023b).

The road freight industry is increasingly considering zero-emission trucks as a viable option for decarbonising their fleets. More than 3 600 companies worldwide have committed to science-based targets, with some actively seeking zero-emission trucks and willing to pay a premium for them (MCFM, 2022). Several original equipment manufacturers are leading the way by establishing ambitious goals to produce battery-electric trucks. For instance, Daimler Truck expects up to 60% of its European sales to come from EVs by 2030, while Traton and Volvo aim to achieve a 50% market share within the same timeframe (Soulopoulos, 2023). A few well-known private companies, such as Maersk, Sysco, Holcim, Schneider National and Rio Tinto, have ordered thousands of heavy-duty electric trucks from Daimler, Volvo, Scania, and others. Industry initiatives such as Road Freight Zero and Smart Freight Centre's Fleet Electrification Coalition are actively working on aggregating demand for electric trucks, tackling challenges relating to charging infrastructure and identifying and developing innovative financing solutions for zero-emission trucks.[11]

Innovative business models are also emerging to accelerate the adoption of electric trucks. For instance, Scania has introduced a pay-per-use model that provides transport companies with access to electric truck solutions. This model makes it easier for carriers to switch to electric trucks, eliminating upfront costs and potential residual value concerns (Scania, 2023).

[11] *See: www.weforum.org/projects/decarbonizing-road-freight-initiative/ and www.smartfreightcentre.org/en/projects/ongoing-projects/fleet-electrification-coalition/.*

2.2 Shipping

Maritime transport is vital to the world's economy, enabling international trade and commerce, and facilitating the movement of goods and resources across the world. In 2022, international seaborne trade reached 11 billion tonnes, or over 80% of global trade by volume, mainly dominated by dry bulk, oil shipments and containerised trade (UNCTAD, 2023).

About a third of seaborne trade involves the transportation of fossil energy products (Jones *et al.,* 2022). This means that maritime transport is not only a consumer of energy, but also a means for its transport. The decarbonisation of power systems, road transport and heat production with renewable electricity will result in steep demand reductions for fossil energy products and consequently, for the shipping of these energy commodities. Yet the sector will still play an important role in unlocking and accelerating the decarbonisation of other transport and industrial sectors, helping satisfy the resulting demand for green fuels and chemicals instead.

Ships are long-lived assets, with the vessels deployed in the next few years largely shaping the fleet and fuel mix that will occur two-to-three decades from now. This highlights the need for the transition to renewable-energy-powered vessels to happen as soon as possible, or the world risks missing 2050 net-zero targets.

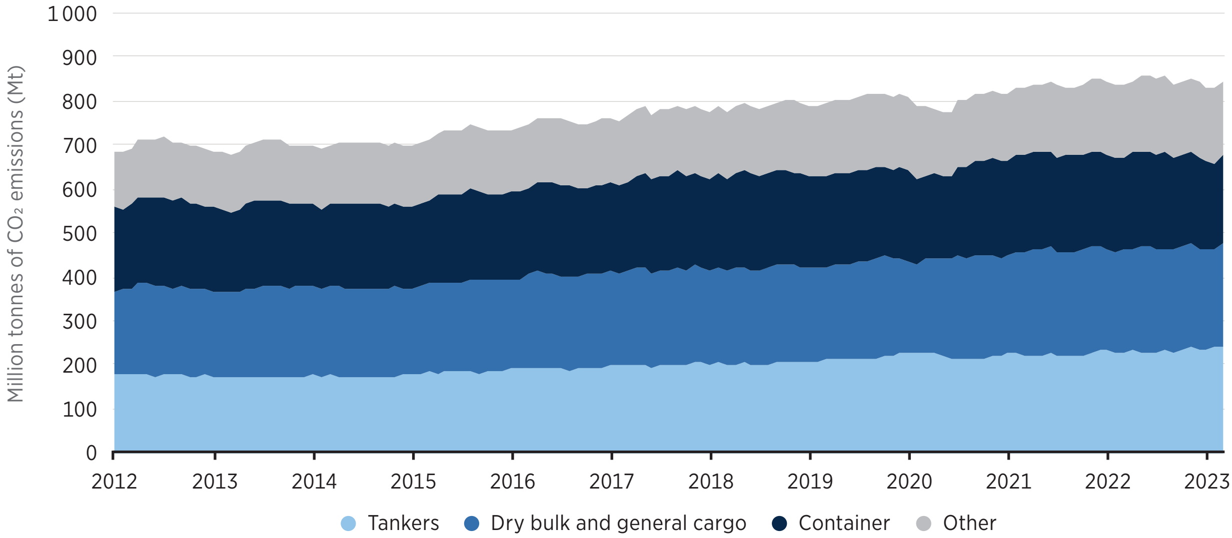
Emissions and energy use

Maritime transport is amongst the least carbon-intensive transport modes, in terms of emissions per passenger kilometre (pkm) and per tonne kilometre (tkm) (European Environment Agency, 2023). However, the sector is still a major polluter given the sheer magnitude of its activity. In 2022, energy consumption in the shipping sector reached 11.2 EJ. At 3% of total global energy consumption, this also equates to 10% of all transport-related energy consumption, worldwide (IEA, 2023a).

Maritime trade activity has roughly doubled in the last 20 years, going from 55 trillion tkm in 2002 to 110 trillion tkm in 2022 (UNCTAD, 2022). According to the projections used by the International Maritime Organisation (IMO) in their 2020 GHG study, this activity is expected to increase by between 40% and 100% by 2050 (IMO, 2021a). The lower end of this range corresponds to scenarios with steep reductions in oil and coal demand due to the energy transition. This increase could also change depending on the future evolution of demand for natural gas.

In 2022, the sector's CO_2 emissions amounted to over 0.8 Gt (Figure 4). This is equivalent to between 2% and 3% of total global CO_2 emissions, or roughly 10% of transport-related emissions (IEA, 2023a). Roughly 80% of these emissions come from international shipping (IMO, 2021a).

Figure 5 CO_2 emissions by main vessel types, 2012-2023



Source: (UNCTAD, 2023).

Note: The "Other" group includes vehicle and roll-on/roll-off ships, passenger ships, offshore ships and service and miscellaneous ships.

The shipping sector is heavily dependent on inexpensive, low-grade fossil fuels such as heavy fuel oil (HFO) and marine diesel oil. In 2020, the IMO introduced a global regulation aimed at significantly curbing sulphur oxide emissions (IMO, 2021b). This directive prompted a rapid and widespread change within the sector towards adopting very low sulphur fuel oil (VLSFO), or the installation of onboard scrubbers to curb these emissions. This showcased the ability of the sector to rapidly adapt and implement policy-driven changes.

There are a number of net-zero compatible alternatives for conventional marine fuels, such as sustainably produced low-carbon biofuels, green e-fuels, or hybrid, power and biomass-to-liquid (PBtL) fuels.[12] However, these all come at a considerable cost premium. Depending on the spot price of conventional marine fuels, these alternatives can be up to twice the price for biofuels and three-to-four times, or even higher, for e-fuels (IRENA, 2021a; Ship & Bunker, 2024). Alternative fuel cost reductions will therefore be needed to turn shipping away from its fossil fuel dependency.

Most trade activity is undertaken by container ships, bulk carriers and fuel and chemical tankers. While these types of vessels account for only about 20% of the global fleet, they are responsible for 80%-85% of the GHG emissions associated with the shipping sector (IMO, 2021a; UNCTAD, 2023). This means that targeted interventions can have outsized implications, in terms of emissions reductions.

[11] *PBtL processes combine biomass-to-liquid (BtL) and power-to-liquid (PtL) processes to achieve higher carbon conversion efficiencies and lower production costs.*

Decarbonisation pathways

Maritime transport-related emissions have steadily increased over the last decade and are expected to reach 130% of their 2008 levels by 2050, if no action is taken (UNCTAD, 2023). This highlights the urgency of moving away from the sector's current fossil fuel dependency – something that could be achieved through the application of several decarbonisation pathways.

IRENA's 1.5°C scenario estimates that roughly 17% of the emissions reductions necessary by 2050 could come from changes in global trade dynamics triggered by the energy transition. These changes would come mainly in the form of an overall reduction in global fossil fuel use. This would be caused by the decarbonisation of other sectors as they strive to become carbon neutral. This would, in turn, cause a reduction in fuel tanker activity and consequently a reduction in the sector's energy demand (IRENA, 2023a).

Another important driver for decarbonisation would be the adoption of energy-efficient technologies and operational measures. These would include high-efficiency propellers, wind-assisted propulsion, waste heat recovery systems and speed optimisation. In terms of emissions reductions, energy efficiency improvements can have an immediate impact and could potentially contribute 20% of the CO_2 reductions the sector requires by 2050, according to IRENA's 1.5°C scenario (IRENA, 2023a). Savings from energy efficient technologies, beyond those mandated by the IMO's Energy Efficiency Design Index Phase 3, are estimated to be in the order of 25% for container vessels, 18% for bulk carriers, 18% for tankers and 26% for liquefied natural gas (LNG) carriers (MAN ES, 2023).

Energy savings alone will not be enough to take shipping all the way to net-zero emissions. The remaining emissions will need to be abated through the adoption of renewable-based alternatives. These include electric propulsion, biofuels and e-fuels that displace the use of conventional fossil-based marine fuels. According to IRENA's 1.5°C scenario, these could contribute over 60% of the necessary emissions reductions (IRENA, 2023a).

Direct electrification can also play an important role in the decarbonisation of vessels working short and inland routes (*i.e.* ferries and coastal and river transports). Today's battery technologies could already enable the electrification of vessels on such routes, as well as small cruise ships and ro-ro ships. In addition, electrification of new ships with routes of up to 1000 km has been made possible by recent battery technology improvements. The two, 700 twenty-foot equivalent unit (teu) container ships built by COSCO Shipping Lines in 2023 are a good example of this (COSCO, 2023; IDTechEx, 2023).

Further improvements in battery technologies, paired with potential cost reductions, could see electrification become an increasingly relevant option for a wider set of use cases. Furthermore, the importance of the role of cold ironing[13] as a part of port electrification efforts cannot be overstated. Some vessel types, such as tankers and bulk carriers, spend considerable time at berth and consequently, a considerable proportion of their emissions – over 20% – occur while they are in port (IMO, 2021a).

Sustainably produced, low-carbon biofuels, such as biodiesel, renewable diesel,[14] bio-LNG and bio-methanol can be effective short- to medium-term options for shipping. Biofuels boast high technological readiness, allowing them to be immediately harnessed as blends or drop-in fuels, requiring little to no changes in terms of operation and infrastructure. However, it is crucial to acknowledge that the rapid scale-up of sustainable biomass sourcing requires careful consideration of its potential negative impacts, including land-use change and life-cycle GHG emissions. This necessitates strict controls along the entire supply chain, robust certification mechanisms and substantial policy interventions in the agriculture sector.

Overall, three main barriers have limited the potential of biofuels in shipping: economics, sustainability and availability concerns. Yet, despite these challenges, biofuels are a key decarbonisation option for the sector, not only as a fuel, but potentially as a source of biogenic carbon for e-fuel production. Biofuels are the cheapest non-fossil fuel alternative, while sustainability concerns can be addressed through good practices (IRENA, 2022).

In addition, the availability of sufficient sustainable biomass is not a hard constraint on biofuels playing an important role in decarbonising the shipping sector. IRENA suggests that the global technical potential for sustainable advanced biofuels is at least 114 EJ (IRENA, 2016), roughly 11 times the energy demand for shipping. Current biofuel production globally is only around 4.5 EJ, mostly food and feed crop-based (90%) and used mainly for road transport (OECD/FAO, 2023). As road transport is trending fast towards electrification, there is an opportunity to switch automotive biofuel production towards the production of biofuels for other sectors, such as shipping and aviation.

In the medium- to long-term, e-fuels produced from green hydrogen – in the form of e-methanol, e-ammonia, and e-methane – could also play a significant role in the sector's decarbonisation. These fuels bring advantages. These include the fact that they can be produced with zero-carbon renewable power, and they have their potential to satisfy demand is virtually unlimited, given direct air carbon capture technologies. These fuels also come with limitations, however, and should not be perceived as "silver bullets" in sector decarbonisation.

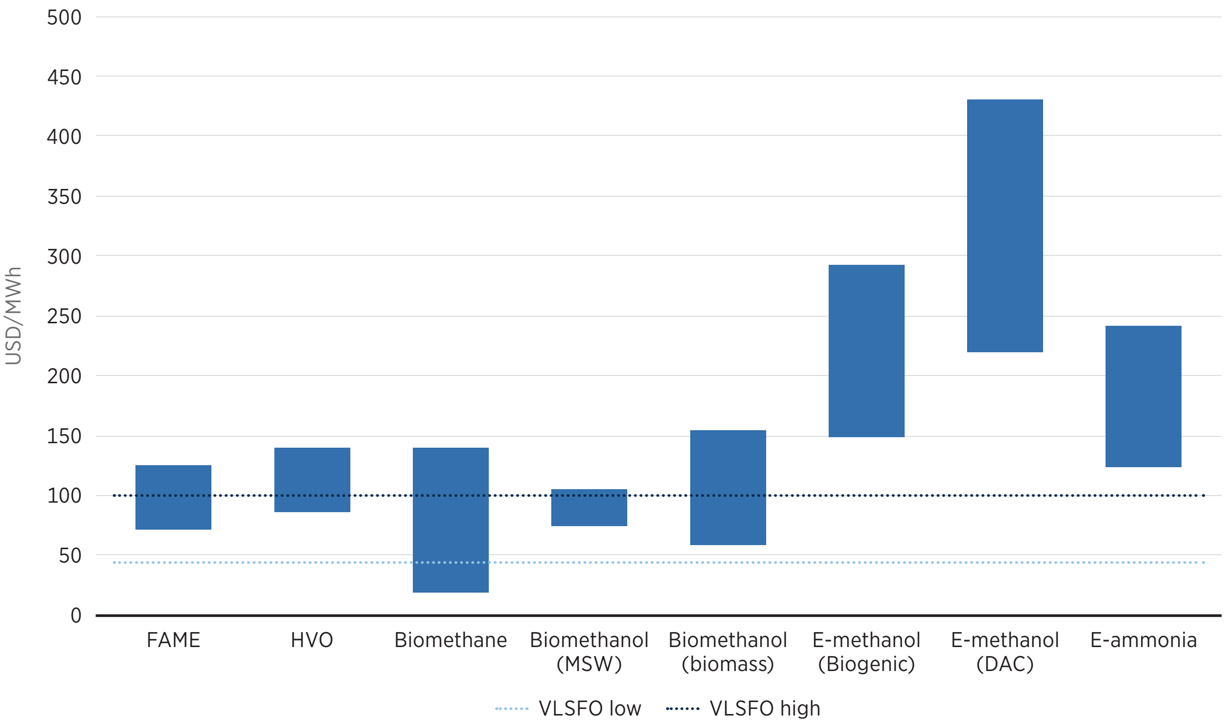
[13] *Cold ironing refers to the process of providing shoreside electrical power to a ship at berth while its main and auxiliary engines are turned off.*

[14] *Biodiesel and renewable diesel are different fuels. Biodiesel is chemically distinct from regular diesel and can only be currently used in blends without engine modifications. Renewable diesel is chemically identical to regular diesel and can be used as a drop-in fuel without any need for modification.*

One of the main challenges for e-methanol (CH_3OH) and e-methane (CH_4) as synthetic fuels, is that they need carbon for their synthesis. This means that for these e-fuels to be truly green, the carbon needs to come from sustainable sources, *i.e.* from biogenic sources, or captured directly from the atmosphere. Fossil-sourced carbon would make these fuels unsustainable and incompatible with net-zero goals. Potentially, they would also have even greater lifecycle emissions than conventional marine fuels (MAN ES, 2023). Indeed, the cheap and sustainable sourcing of carbon should be a key consideration when discussing e-fuels, as it could become a bottleneck in their deployment and an important component of their cost. To achieve cost efficiency, cheap sources of biogenic or atmospheric carbon and green hydrogen would likely have to be near each other to prevent the high costs of transporting either one for the manufacture of e-fuels. Biogenic sources are currently the cheapest source of carbon, while the alternative is direct air carbon capture, whose prospects for cost reduction are uncertain.

E-ammonia (NH_3), on the other hand, has the advantage that it does not require a carbon source, so it can be produced in any location as long as there is a cheap supply of low-carbon energy. However, the main challenges for ammonia as a marine fuel come from its toxicity and the operational challenges it presents. Ammonia engine technologies are also still only under development. The use of ammonia as a marine fuel will require robust operational and safety standards and creates the need for new capacities and skills that can guarantee its safe handling, even though there are already standards for its handling in the chemical industry.

Figure 6 Cost comparison of renewable marine fuels



Source: (IRENA, 2018, 2021a; IRENA and AEA, 2022; IRENA and Methanol Institute, 2021; Ship & Bunker, 2024).

Note: Renewable fuel costs are production costs. VLSFO shows the highest and lowest spot prices registered between March 2021 and March 2024.

Finally, an important aspect to consider when discussing e-fuels is their efficiency. E-fuels require significantly more primary energy, compared to other alternatives such as direct electrification and some biofuels. The use of e-fuels should therefore preferably be limited to cases where more efficient alternatives are unfeasible. As all alternative fuel options have their own sets of challenges, a combination of renewable-based options will likely be needed to fully decarbonise the sector.

Figure 7 Summary of decarbonisation pathways and infrastructure needs for shipping

The **active adoption of energy efficient technologies and operational measures will be critical to reduce energy demand and CO_2 emissions in the short term**. Such technologies and measures include shore power, improved route planning, high efficiency propellers, wind assisted propulsion, waste heat recovery systems and speed optimisation, among others. **Further reductions are expected to come from changes in global trade dynamics,** as other sectors transition to net-zero.

Electrification of ports could lead to short term emissions reductions through, *e.g.* cold ironing. Additionally, **electric vessels such as ferries and coastal and river transports could play an important role in decarbonising short and inland routes.**

Sustainably produced biofuels are short to medium-term options for shipping.
The high technological readiness of liquid biofuels produced from second-generation feedstock, as well as bio-LNG and bio-liquefied petroleum gas (LPG), allows them to be harnessed as drop-in fuels, requiring little-to-no changes in operation and infrastructure.

In the medium- to long-term, green hydrogen-based fuels (e-fuels), such as green methanol, ammonia and methane, could play a significant role in the sector's decarbonisation.
Ammonia does not require a carbon source, so it can be produced in any location with cheap renewable power supply. In contrast, due to its toxicity, it has important operational challenges. Methanol does not have the operational challenges of ammonia, but it requires a renewable carbon source, which makes the scalability of production more challenging.

Key infrastructure needs for shipping

- Reinforcement of port connections to transmission and distribution grids
- Shore-to-ship power infrastructure
- Electric charging facilities for electric vessels
- Transport, storage and bunkering equipment for sustainable shipping fuels (*e.g.* bio/e-methanol and e-ammonia)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Tracking progress

The transition towards net-zero shipping is gaining momentum and important players in the sector, both public and private, have already taken steps in the right direction. Most notable among these is the IMO, which is responsible for regulating international shipping and which recently revised its Strategy on Reduction of GHG Emissions from Ships. The revised strategy aims for a reduction in GHG emissions from ships of at least 20% (striving for 30%) by 2030, with the goal of achieving net-zero emissions by around 2050. In addition to this, the IMO has established energy efficiency indexes that require emissions reductions for both newly built and existing ships.

This is an important step since policy can be an important – if not the most important – driver in the decarbonisation of the sector. The IMO's initiative is expected to be complemented by a basket of measures, too, with these including a marine fuel standard and a GHG pricing mechanism, expected to enter into force by 2027 (IMO, 2023).

Also notable is the EU's FuelEU Maritime Initiative, which aims to provide legal certainty for ship operators and fuel producers and help kick-start the large-scale production of sustainable maritime fuels. It will do this by introducing energy intensity reduction mandates, incentives for renewable fuels of non-biological origin and an obligation to use onshore power supplies, among other provisions (European Council, 2023).

At the same time, **the importance of carbon pricing cannot be overstated. Net-zero fuel alternatives currently come at a considerable cost premium**, with carbon pricing a key policy option in narrowing the cost gap and/or funding the deployment of clean infrastructure.

For reference, over the last couple of years, the cost of alternative fuels has been between two to six times higher than the cost of HFO (DNV, 2024a). A good example of the potential impact of carbon pricing in closing this gap is the inclusion of shipping in the EU Emission Trading System (EU ETS). Over the coming years, this scheme will make vessels sailing in European waters pay for an increasingly larger share of their emissions. When comparing biodiesel and marine gas oil (MGO) prices between 2022-2023, if the additional CO_2 emissions cost for MGO featured in the EU ETS had been operational, biodiesel would have been cost competitive with its fossil counterpart (Argus, 2023).

Similarly, policies offering financial incentive schemes for e-fuel production and direct air capture, such as the Inflation Reduction Act in the United States, can play an important role in de-risking first movers and creating initial demand for renewable fuels (DOE, 2023).

The private sector is also taking steps, with several shipping companies establishing their own net-zero targets, and several initiatives emerging, such as the Getting to Zero Coalition.[15] This has gathered 160 companies within the maritime, energy, infrastructure and finance sectors, supported by key governments and intergovernmental organisations (IGOs).

[15] *See: www.globalmaritimeforum.org/getting-to-zero-coalition*

The timely deployment of the necessary technology and infrastructure at ports (*i.e.* grid infrastructure for electrification and sustainable fuel terminals), on ships and in fuel manufacturing is also important in enabling the adoption and mainstreaming of renewables-based fuels and in avoiding delays in the transition. The sector is currently experiencing a growth in orders for LNG- and methanol-powered vessels (DNV, 2024a) and is also looking at ammonia as a solution for the future. These fuels all have different infrastructural needs, a fact that will have to be considered when evaluating decarbonisation strategies.

The deployment of new LNG-powered vessels offers limited benefits in terms of emissions reductions compared with the current fuel mix and creates a risk of fossil technologies becoming locked-in. While LNG ships are theoretically compatible with bio-LNG or renewable e-methane, the scalability and the cost reduction potential of these options is limited.

Methanol engines are a mature and proven technology and ship orders are growing, particularly in the container ship segment. In October 2023, A.P. Moller-Maersk launched the first container ship powered by green methanol, the *Laura Maersk* (Maersk, 2023a). It is expected that as many as 170 methanol-compatible ships will be on the water in the next five years (DNV, 2024a). **Ammonia engines, on the other hand, still need some development.** Currently they are at technology readiness level 4 (TRL4) – technology validated in a laboratory – although they are expected to reach TRL9 – technology proven operationally – by 2025. They could therefore play a more relevant role in the medium-term, as ammonia is a carbon-free e-fuel, unlike methanol (MAN ES, 2023).

The decarbonisation of the sector through renewable fuels will depend on the ability to scale up renewable fuel supply (biofuels and green e-fuels) rapidly and sustainably. This must also be done without overlooking the need for sustainable and affordable sources of carbon that are biogenic or come from direct air carbon capture, while also being available at the right locations.

There are also steps being taken in terms of building up the supply and demand for alternative fuels. This requires considerable investment in developing fuel manufacturing projects and deploying the necessary infrastructure. The uptake of e-fuels in shipping, for example, necessarily implies an important increase in renewable power supply to produce green hydrogen as a feedstock. According to IRENA's World Energy Transitions Outlook (WETO), decarbonising shipping would require close to 60 megatonnes (Mt) of green hydrogen/year, roughly equivalent to two-thirds of today's total hydrogen supply. This would require roughly 600 gigawatts (GW) of electrolyser capacity and 1.2 terawatts (TW) of renewable capacity (IRENA, 2023a). This would be roughly equivalent to the total global installed hydropower electrical capacity in 2022 (IRENA, 2024b).

Attracting investments in new technologies can be challenging. Projects face bankability challenges due to uncertainties in demand, the higher costs of alternative fuels, and the sector being highly competitive, internationally. **Efforts from governments and multilateral financial institutions are needed to level the playing field as well as to finance the deployment of the necessary technology and infrastructure.**

The co-operation of private actors along the supply chain can also play a role in de-risking investments. A good example of this is the off-take agreement signed in 2023 between A.P. Moller-Maersk and Chinese developer Goldwing for the provision of 500 000 tonnes per year of green methanol (Maersk, 2023b). Such "vertically integrated" agreements ensure a stable demand for the fuel producer, facilitating the financing of the fuel supply projects, while also giving security to the shipping company by guaranteeing the required supply volumes of green fuel at predictable prices.

Renewable fuels are still in their early stages of adoption and their handling and operation will likely require a completely new set of skills and procedures. These will also have to be adopted at a global scale – for example, in ammonia bunkering operations. In this regard, the sector would benefit from co-operating and building synergies with other sectors such as aviation, which has similar decarbonisation pathways and shares some of the same challenges. The chemical sector, too, has decades of experience in the handling of some of the chemicals that are now being used as fuels.

Collaborative efforts such as green corridors can also help demonstrate the feasibility of new technologies and accelerate their scaling up. There are multiple examples of collaborative initiatives, such as the Clean Energy Marine Hubs by Clean Energy Ministerial (CEM, 2023), or the recently signed agreement between the United Kingdom and the United States for the establishment of a green shipping corridor (DfT, 2023). This is one of over 50 green shipping corridors that have so far been announced worldwide (DNV, 2024b).

2.3 Aviation

Aviation plays a vital role in connecting people, enabling global business, facilitating international trade and tourism, and providing a means of rapid transportation. The sector is a driver of economic growth, shortening travel times and increasing global interconnectedness.

One of the main challenges faced by aviation, however, is in both providing its social and economic benefits while also increasing its environmental responsibility. As one of the most carbon-intensive transport modes, aviation is a significant contributor to global GHG emissions and climate change. It is worth noting that the sector is also responsible for non-CO_2 emissions, *i.e.* other gases and aerosol particles which affect the atmospheric composition and affect cloudiness, adding to the impact of the sector's CO_2 emissions (Lee, 2018).

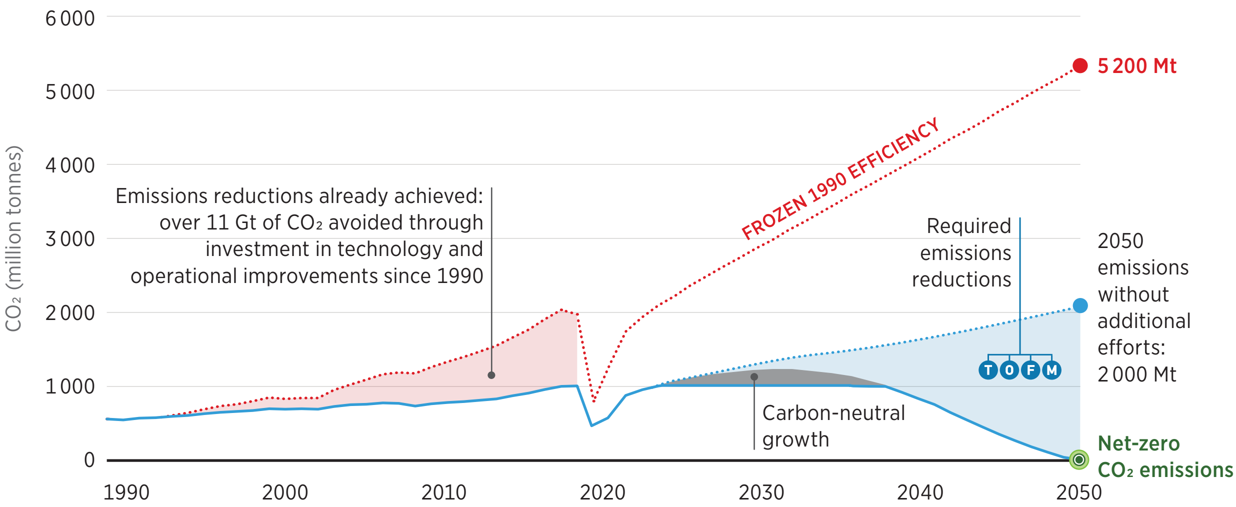
In recent decades, demand for aviation services has steadily grown and could double by 2050, compared to 2022 levels (Graver, 2022; IATA, 2023). Therefore, there is a need to rapidly deploy decarbonisation solutions.

Emissions and energy use

In 2022, the energy consumption of the global aviation sector reached 11 EJ. This equates to 10% of the world's transport-related energy consumption and 3% of total global energy consumption (IEA, 2023a). This energy demand was met nearly exclusively by fossil fuels. Only 450 million litres of sustainable aviation fuels (SAF) were consumed that year, equivalent to 0.1% of global aviation fuel consumption (IATA, 2022).

Dependency on fossil fuels results in aviation contributing significantly to the world's CO_2 emissions and climate change. CO_2 emissions from aviation in 2022 reached 0.8 Gt, equivalent to between 2% and 3% of global emissions and 10% of all transport related emissions (IEA, 2023a). Growth in aviation emissions has been also continuous, but it has been partially offset by substantial efficiency improvements. As shown in Figure 8 below, these improvements have resulted in as much as 11 Gt of CO_2 in emissions reductions since 1990 (ATAG, 2021). In addition to carbon emissions, aviation also contributes to global warming through the formation of contrails.

Figure 8 Historical and projected CO_2 emissions of the aviation sector, 1990 2050



Source: (ATAG, 2021).

Due to the mass and volume limitations of aircraft, aviation depends on highly energy-dense fuels. There are sustainable fuel alternatives, but these come with a cost premium. The limited choice of usable fuels and the immaturity of alternative aircraft technologies, such as electric or hydrogen-powered aircraft, therefore limit the decarbonisation pathways available to the sector.

Decarbonisation pathways

One pathway is the continued deployment of technological and operational energy efficiency improvement measures. Indeed, while the aviation sector has made significant progress in deploying increasingly efficient airframes and engines, there is still potential for further improvement. The International Civil Aviation Organisation (ICAO) long-term aspirational goal aims for a 2% increase in fuel efficiency annually until 2050. This is higher than the average historically observed and other projected improvements of just 1.5% per year (ICAO, 2022).

According to IRENA's 1.5°C scenario, demand reduction and energy efficiency improvement are an important part of the sector's decarbonisation efforts. These measures could account for roughly half of the sector's emission reductions by 2050[16] (IRENA, 2023a). Further reductions could come from modal shifts in short-distance air travel – for example, replacing short flights with trains, which are much less carbon intensive (European Environment Agency, 2023).

Undoubtedly the most technologically straightforward pathway to decarbonise the sector, however, is the use of advanced biofuels, namely biojet, given the maturity of the technology. Biojet can be used as a drop-in fuel on existing and future aircraft, making it a practical and immediately implementable option. Long-term bioenergy potential is not a constraint for the transition of the sector, either. IRENA suggests that the global technical potential for sustainable advanced biofuels is at least 114 EJ (IRENA, 2016), or roughly eight times the energy demand for aviation. Current global biofuel production is only around 4.5 EJ, however, and is mostly food and feed crop-based (90%) and used mainly for road transport (OECD/FAO, 2023).

The main challenge with biofuel is first, its higher cost compared to conventional jet fuel, and second, the need to scale up its supply sustainably. Indeed, the rapid scale-up of sustainable biomass is complex and cannot be achieved without careful consideration of its potential negative impacts, particularly in terms of land use change and life cycle GHG emissions. This needs strict controls along the entire supply chain, robust certification mechanisms and substantial policy interventions in the agriculture sector. At the same time, the increasing electrification of road transport could allow redirecting biofuel production capacity towards other sectors, such as aviation and shipping.

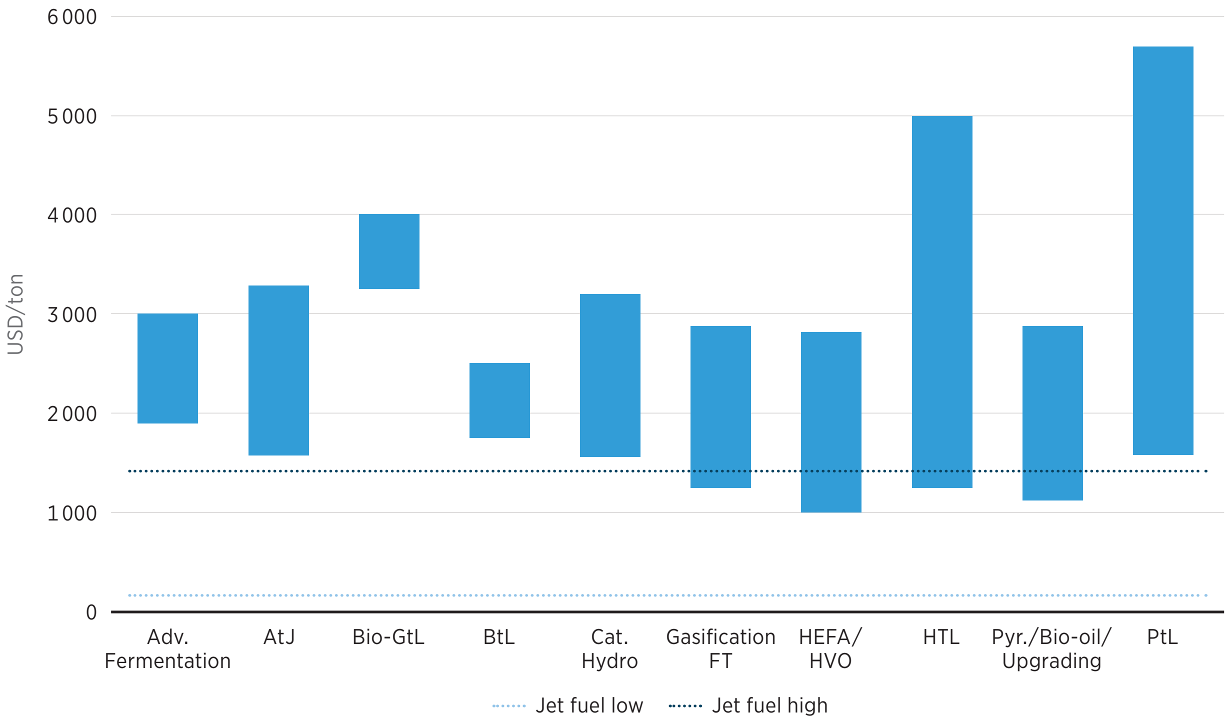
Another option is the adoption of synthetic fuels produced from green hydrogen – that produced from electrolysed water using renewable electricity. This can then be combined with a renewable source of carbon to produce a hydrocarbon fuel. The two options being currently considered are green hydrogen and e-kerosene. Yet, while hydrogen could eliminate exhaust emissions from aviation, hydrogen aircraft technology for large passenger or cargo transport does not exist yet. This technology is also not expected to reach commercial maturity within a timeframe compatible with making a material impact on carbon neutrality by mid-century. A fundamental issue revolves around the low volumetric energy density of hydrogen, which would require a fundamental redesign of airframes as well as operational procedures and safety standards. Furthermore, there is no hydrogen refuelling infrastructure in place.

[16] *IRENA's 1.5°C scenario does not aim for net-zero in aviation alone, but rather across all energy systems. Therefore, emissions in aviation are not eliminated in this scenario, with residual emissions being offset by negative emissions in other sectors.*

E-kerosene, on the other hand, is chemically identical to its fossil counterpart and could be used in existing aircraft. The use of e-kerosene opens the door for deep emissions reductions. However, the fact that the e-kerosene molecule contains carbon adds a layer of complexity. For e-kerosene to be an effective decarbonisation solution, it would have to be low-carbon and this carbon would need to come from a sustainable source, *i.e.* from biogenic sources such as bioenergy with carbon capture or captured directly from the atmosphere. The need to build a sustainable supply chain for carbon is a major challenge, particularly given that to achieve cost efficiency, cheap renewable electricity for hydrogen production and a sustainable (and scalable) carbon source would need to be available.

Biofuels and e-fuels could account for the remaining half of the necessary CO_2 reductions needed by 2050, as per IRENA's 1.5°C scenario.

Figure 9 Production cost comparison of sustainable aviation fuels



Source: (IRENA, 2021b; WEF, 2020).

Note: Jet fuel shows the highest and lowest prices registered between January 2020 and March 2024. Adv. = advanced; AtJ = alcohol-to-jet; GtL = Gas-to-liquid; BtL = biomass to liquids; FT = Fischer Tropsch; Cat. Hydro. = Catalytic hydrothermolysis; HTL = Hydrothermal liquefaction; Pyr. = pyrolysis; PtL = Power-to-liquid.

Finally, electric propulsion is another technology pathway that should be considered for aviation. In the past, this has had limited potential as a decarbonisation solution due to the limited energy density of commercially available batteries. However, there has been remarkable progress in battery technologies over the last few years. Breakthroughs in energy density, with some batteries reaching 500 Wh/kg, could open the door to their application in electric or hybrid small aircraft and short-haul flights (CATL, 2023).

Electric propulsion also offers potential advantages over jet engines in areas such as higher efficiency, lower mechanical complexity and maintenance costs. Yet, this pathway is not without its challenges. These include the need to develop and certify new aircraft concepts, in addition to the need for further research and development in battery technologies. This is necessary to make them viable for flight as well as ground operations. These challenges also limit the decarbonisation potential of this technological pathway, given that new aircraft concepts can take as long as a decade to be developed and certified (FAA, 2023).

Figure 10 Summary of decarbonisation pathways and infrastructure needs for aviation

The continued improvement of energy efficiency measures and technologies is critical. Improved aerodynamics, weight reduction and the integration of more efficient engines, for example, can reduce energy demand and thus CO_2 emissions. **Further reductions could come from a modal shift in short distance travel**, likely to rail transport.

Sustainable, low-carbon biofuels are the most technologically straightforward pathway to decarbonise aviation. Biojet can be used as a drop-in fuel on existing and future aircraft. Their scale-up will require major policy developments to ensure sustainability.

Synthetic fuels can also play a significant role in the decarbonisation of aviation. This can be achieved in the medium term through **e-kerosene** and in the long term, possibly by **green hydrogen**. E-kerosene requires a renewable carbon source, which makes the scalability of fuel production more challenging.

Direct electrification, in the form of electric or hybrid electric aircraft could play an important role in reducing aviation emissions for short-haul aviation in the medium- to long-term.

Key infrastructure needs for aviation

- Adaptations in fuel supply infrastructure to integrate SAF.
- Reinforcement of airport connections to transmission and distribution grids
- Charging infrastructure for ground operation vehicles and electric aircraft
- In the long-term, should hydrogen-powered aircraft become a reality, hydrogen transport, storage and fuelling infrastructure would be needed.

Tracking progress

The aviation sector's energy transition is lagging, as evidenced by the negligible, 0.1% share taken by SAF in its fuel consumption (IATA, 2022). Despite this, there are increasing signals within the sector of a willingness to work towards climate neutrality. According to the ICAO, by the first quarter of 2024 there were 30 facilities producing sustainable aviation fuels worldwide, with a potential total output capacity of 8.5 billion litres of SAF per year (ICAO, 2024).

Policies will be critical to build momentum and trigger action towards the decarbonisation of the sector. In this regard, the ICAO and its members have taken steps in the right direction. These include: the development of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016; the adoption of a long-term aspirational goal (LTAG) for international aviation in 2022, which aims at net-zero carbon emissions by 2050; and the adoption of the ICAO Global Framework for Sustainable Aviation Fuels, Lower Carbon Aviation Fuels and other Aviation Cleaner Energies (ICAO, 2023b).

The private sector has also seen some commitments made. These include the Air Transport Action Group (ATAG), which includes representatives of major aviation industry associations and of the largest aircraft and engine makers. ATAG has made a commitment to reach net zero by 2050 (ATAG, 2023).

Currently, the industry mostly relies on carbon offsetting as a mechanism to contribute towards global climate goals. However, offsets do not actually decarbonise the sector's operations and in most cases they do not even deliver net emissions reductions (Probst *et al.,* 2023).

Renewable fuel alternatives currently come at a considerable cost premium. Carbon pricing policies, such as the EU ETS, can play a central role in accelerating the adoption of such alternatives, however, by narrowing the cost gap with fossil fuels and incentivising the deployment of clean infrastructure. Yet, while aviation emissions have been included in the EU ETS since 2012, the scheme only covers intra-European flights.[17] In 2022, the EU also agreed to phase out free allowances by 2026, which was a major shortcoming in the original rules governing aviation in the EU ETS and which will see obligated parties pay more (EC, 2022).

Together with carbon pricing, policies such as ReFuelEU[18] can also accelerate adoption – not only by enforcing the initial uptake of sustainable aviation fuels, but also by sending a longer-term signal to the market regarding the volume of fuels that will be needed. ReFuelEU mandates a gradual increase in the minimum share of SAF in fuel supply and obliges airports to guarantee the necessary SAF infrastructure. With such signals, investors in fuel production assets can have more certainty about the demand they can expect from aviation.

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[17] From 1 January 2024, it also covers non-domestic flights to and from outermost regions of the Union that were previously exempted (EC, 2023c).

[18] See: www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/

Financial incentives can also help accelerate the scale-up of biofuels and e-fuels, de-risking first movers and levelling the competitive playing field. A good example of these is the Inflation Reduction Act[19] in the United States, which offers tax credits for SAF production and for low-carbon hydrogen production.

Large investments will be needed to develop the SAF supply chain. The sector is already experiencing some movement in this regard, with some of the largest players in the sector – including aircraft manufacturers and airlines – making investments and partnerships in SAF production. Examples of this include the memorandum of understanding signed between Air France-KLM and Total Energies for the provision of 800 000 tonnes of SAF over a 10-year period. This is more than three times the amount of SAF the whole industry consumed in 2022 (Total Energies, 2022). Other players, such as Airbus, have created partnerships with fuel manufacturers to foster sustainable aviation fuel production (Airbus, 2023).

Overall, as of 2023 forty-five e-kerosene projects and twenty pilot projects had been identified in Europe. However, none had yet reached a financial decision stage (T&E, 2024). Indeed, despite various announcements and statements indicating a commitment to decarbonisation within the sector, actual deployment of SAF remains limited.

Some airlines offer their clients the possibility of offsetting their emissions, and more recently, to pay for the use of SAF. These measures, however, depend on the customer's willingness to pay and do not require any climate commitment from the airlines; they simply transfer the environmental responsibility to the customer. Furthermore, airline pricing models can be a disincentive for emission reductions. Direct flights, for example, generally emit less CO_2 than connecting flights (Debbage and Debbage, 2019), but it is sometimes cheaper to take a connecting flight than a direct flight. **A combination of increased ambition, real commitments and structural changes across the sector could, nonetheless, really accelerate the transition.**

2.4 Iron and steel

Steel is an indispensable material in our modern world. It is widely used in infrastructure, buildings, transportation vehicles, home appliances, medical equipment and in many other areas that support society and its well-being. Steel's strength, durability, versatility, and recyclability make it suitable for this vast array of applications.

Demand for steel closely follows the development of an economy, particularly in the early stages of industrialisation. Furthermore, steel plays a vital role in the energy transition, as it is used in several renewable technologies, such as EVs, wind turbines, and solar photovoltaic (PV) structures (IRENA, 2023c).

[19] *See: www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/#:~:text=The%20Inflation%20Reduction%20Act%20specifies,mode%20or%20condition%2C%20low%20or*

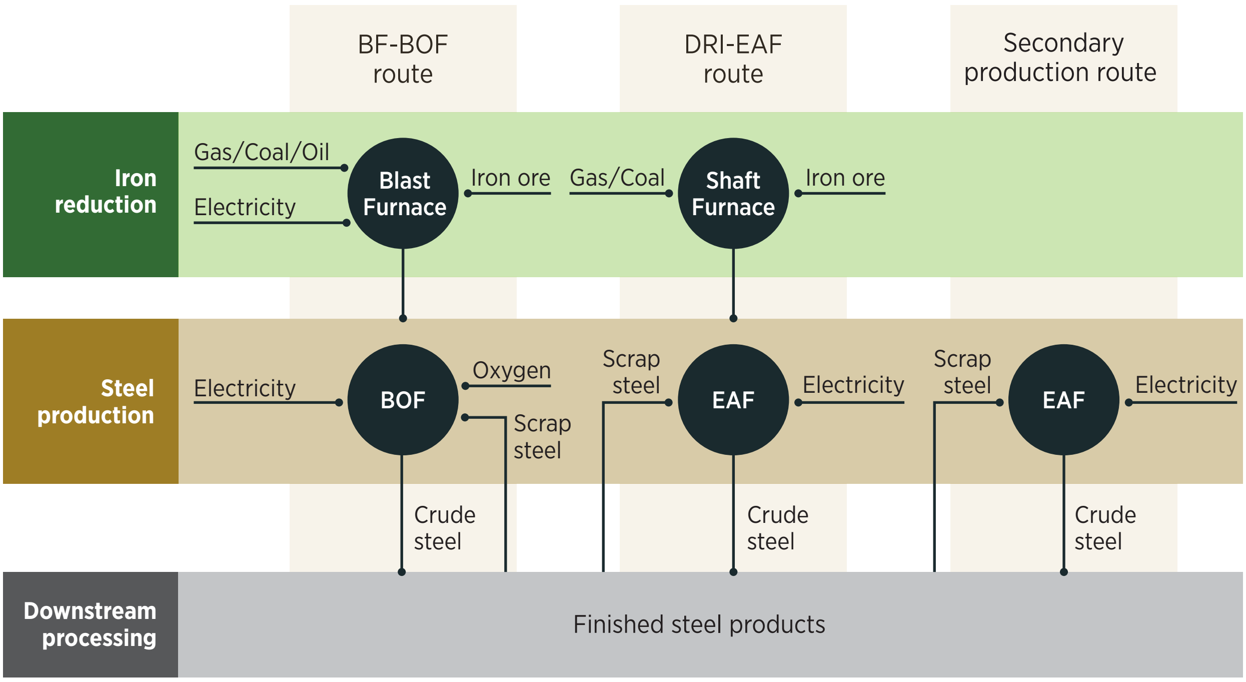
Emissions and energy use

Steel production has been increasing consistently over time. In absolute terms, the production of steel rose almost tenfold from 190 million tonnes in 1950 to almost 1.85 billion tonnes in 2023 (IRENA, 2023c; WSA, 2024). This significant rise in steel production has also led to an increase in CO_2 emissions from the sector. Currently, the production of steel is carbon intensive, relying primarily on fossil fuels, both for energy and as reductants in the processing of iron ore. For every tonne of steel produced in 2022, approximately 1.4 tonnes of CO_2 were emitted into the atmosphere. That same year, the iron and steel sector alone was responsible for about 8% of global energy and process-related CO_2 emissions. In absolute terms, this was equivalent to 2.8 Gt of direct CO_2 emissions (IEA, 2023a).

Steel can be produced via primary or secondary routes (Figure 11). Primary steel production involves two steps: ironmaking, where iron ore is reduced to pig iron in a blast furnace (BF), or sponge iron is produced via direct reduction;[20] and steelmaking, where the iron is processed in a basic oxygen furnace (BOF) or an electric arc furnace (EAF), depending on the type of iron input.

In secondary steel production, steel scrap is reclaimed and re-melted in an EAF, without the need for a new iron ore reduction process.

Figure 11 Traditional pathways for steel production



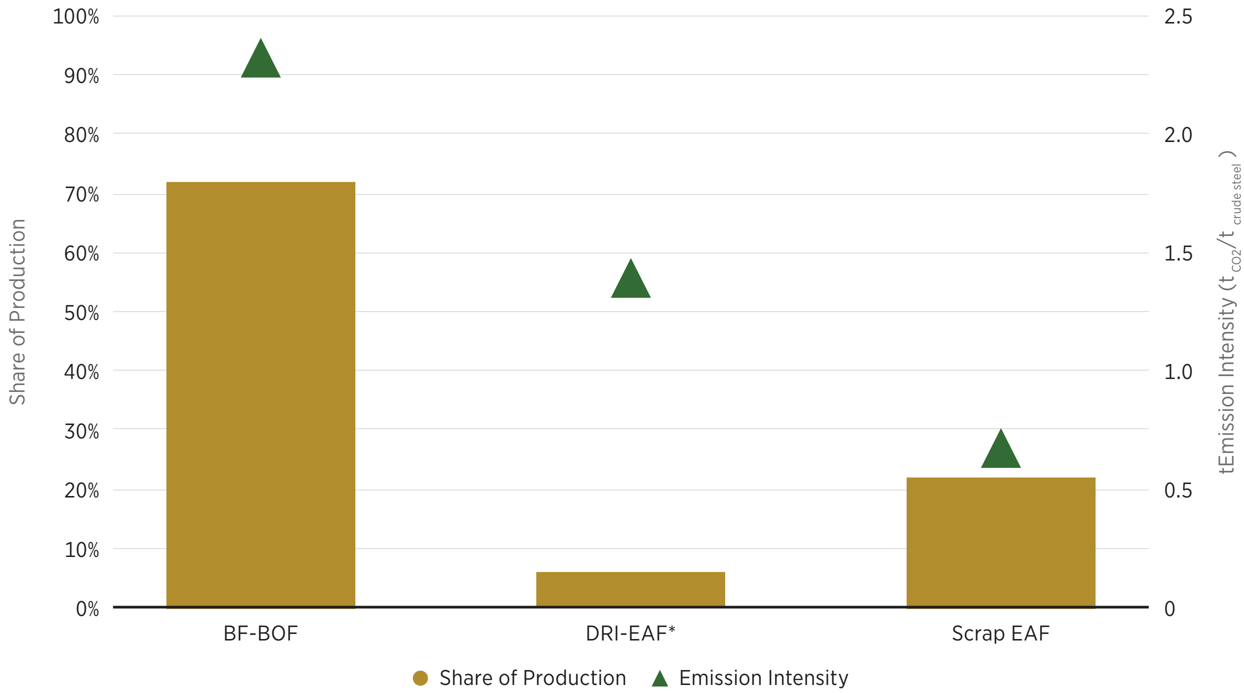
Source: (IRENA, 2023d).
Note: BF = blast furnace; BOF = basic oxygen furnace; DRI = direct reduced iron; EAF = electric arc furnace.

[20] *Direct reduction refers to the group of processes for making iron from iron ore in solid state. This is done without exceeding the melting temperature of iron by using carbon monoxide and hydrogen derived from natural gas or coal, so no blast furnace is needed (IRENA, 2020).*

The BF-BOF is currently the predominant production route, accounting for about 72% of global steel production (Figure 12). This route is also the most energy and emission-intensive, as it relies on coal, coke and other coke products as the primary reductant agent and energy source.

On the other hand, secondary steel production based on scrap, which accounts today for about 22% of total production, is the least energy and emission-intensive production route, as it mostly relies on electricity. The DRI-EAF route is more energy and emission-intensive than the scrap-based route, due to its reliance on natural gas for iron reduction. It is worth noting that while scrap-EAF only accounts for 22% of all production, recycled scrap accounts for roughly 30% of the total metallic raw material inputs for global steel production (IEA, 2020; WSA, 2023a, 2023b).

Figure 12 Share of production routes and their estimated emissions intensities



Source: (IEA, 2020; WSA, 2023a, 2023b).
Note: DRI-EAF is natural gas-based and DRI-EAF production values are estimated.

Decarbonisation pathways

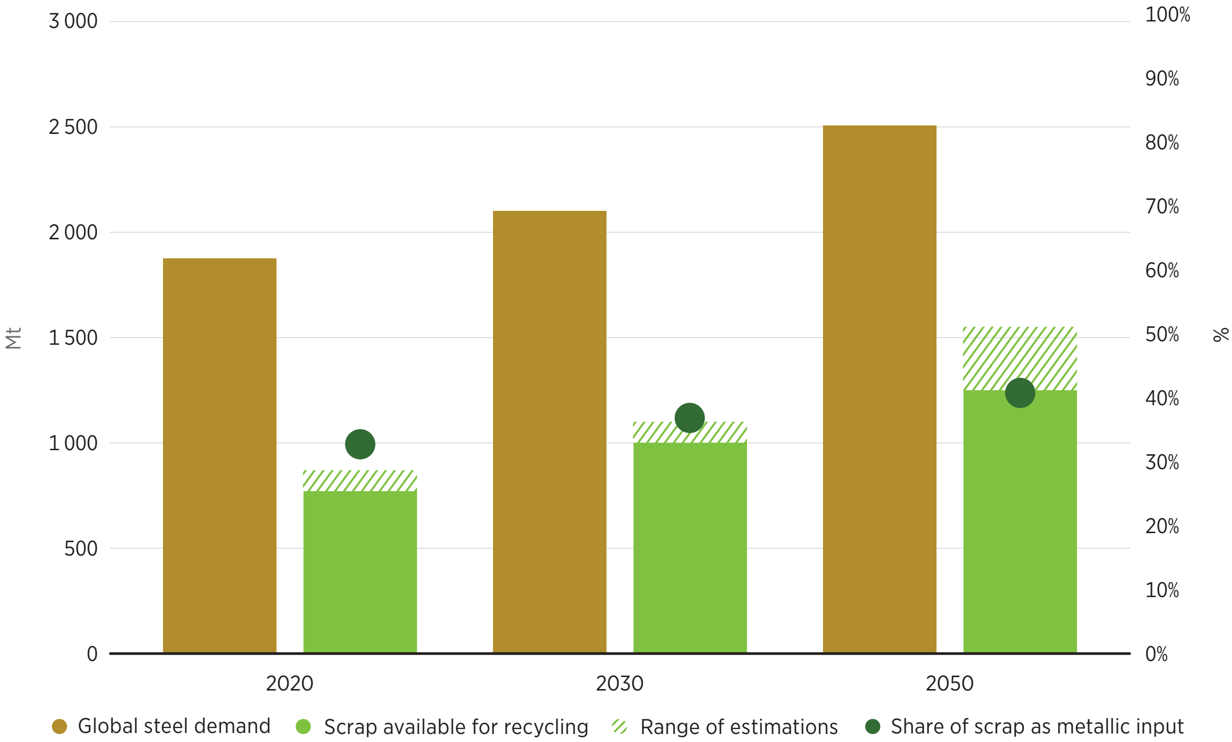
Largely driven by the growth of emerging economies, demand for steel is expected to rise from about 1850 million tonnes (Mt) per year today to about 2 500 Mt per year by 2050. It is therefore paramount to transition away from current fossil fuel-dependant production routes towards renewable-based production pathways (IRENA, 2023c). IRENA's 1.5°C scenario highlights the need for a combination of strategies to decarbonise the iron and steel sector, including: increased scrap recycling; process efficiency; material efficiency; and renewable-based primary steel production, mainly using green hydrogen (IRENA, 2023a).

Direct electrification using renewable electricity is set to play a key role in decarbonising the sector. It will do this by increasing the share of steel produced through the secondary route mentioned above. When powered by renewable electricity, steel can be produced via the EAF method with near-zero emissions. At the same time, scrap availability is expected to increase along with historic steel production levels and many steel products reaching their end-of-life. Globally, steel scrap availability is therefore expected to increase from between 770 Mt per year and 870 Mt per year currently to between 1 250 Mt per year and 1 550 Mt per year by 2050 (Figure 13).

Scrap-EAF production already accounts for 32% of the total steel decarbonisation projects announced (BNEF, 2024a). The process of collecting and sorting can be expensive and time-consuming, however, and may limit the use of scrap. In addition, impurities in steel scrap, such as copper and tin, can limit its usability for certain applications. These contaminants can come from previous-use cases and improper scrap management practices (IRENA, 2023c).

In the future, direct electrification could also play a role in the decarbonisation of primary steel production. It could do this by using high- or low-temperature electrolysis to reduce iron ore. However, these technologies are still in their early stages. The Boston Metal Group is one of the companies pursuing this route, aiming to have a commercial plant deployed by 2026. Another initiative, the SIDERWIN consortium has demonstrated the feasibility of iron production via electrolysis at 110°C (IRENA, 2023c).

Figure 13 Global steel demand and scrap availability, 2020-2050



Source: (IRENA, 2023d).

Material efficiency[21] strategies can have a substantial impact in reducing global steel demand. According to IRENA's 1.5°C Scenario, the adoption of such measures could reduce global steel demand by 7% by 2030 and 15% by 2050 (IRENA, 2023a). Apart from reducing direct material demand, these strategies can also bring various systemic environmental and economic benefits beyond the steel sector.[22] Some challenges exist in the widespread adoption of such strategies, however. These include: the need for technical changes happening over several years; regulatory restrictions that may limit the use of alternative materials; the need for additional investments in new manufacturing technologies and processes; and the need for specially skilled labour with technical expertise to adapt to new, evolving measures (IRENA, 2023c).

Yet, owing to the increasing availability of scrap and the demand reductions that can come from the widespread adoption of material efficiency measures, by 2050, as much as half of global steel demand could be satisfied through secondary steel production based on scrap. However, to completely decarbonise the sector, **the remaining half of global steel production, which relies on the primary route, would also have to transition away from fossil fuels towards renewable-based alternatives.**

One promising approach is the use of hydrogen-based direct iron reduction (DRI).[23] This can reduce emissions by around 95%, as showcased by the world's first batch of renewable-based primary steel, delivered by the HYBRIT plant in Sweden in 2021 (Reuters, 2021). Hydrogen-based DRI is close to commercial maturity and becoming widely accepted as an alternative technology within the industry, with over 57 projects, or 40%, of the project pipeline announced by 2023 (BNEF, 2024a). By 2030, 62 Mt of steel per year from Hydrogen-based DRI could materialise (BNEF, 2024a).

While the cost differential between conventional and green crude steel produced via hydrogen-based DRI is substantial, the cost impact on some higher added-value end products can be relatively low. For instance, an increase of 40% to 70% in the per tonne cost of steel translates into less than a 1% increase in an average passenger car's overall cost, while the cost increase for buildings is around 2% (Sandbag Climate Campaign ASBL, 2024).

The widescale adoption of hydrogen-based steel faces several challenges, however. These include: a requirement for high-grade iron ore; access to sufficient volumes of low-cost renewable electricity;[24] a dependable supply of green hydrogen and associated infrastructure; and geographical location for hydrogen production and storage facilities (IRENA, 2023c).

[21] Material efficiency refers to decreasing the amount of a material needed to produce a product and maximising its value. For steel, this could include producing lighter steel products and structures, refurbishing and reusing steel products, and redesigning products with alternative materials when justified, based on life cycle analysis.

[22] For example, the use of high-strength steel in vehicles can make them lighter, reducing their fuel consumption and emissions, while helping them maintain service efficiency. This is particularly true for EVs, which have smaller carbon footprints (IRENA, 2023c).

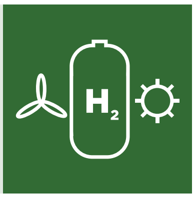
[23] DRI is the chemical removal (reduction) of oxygen from iron ore in its solid form.

[24] Producing 1 Mt/year of hydrogen requires around 10 GW of electrolyser capacity and 20 GW of renewable power for electricity (IRENA, 2023c).

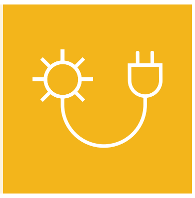
Figure 14 Summary of decarbonisation pathways and infrastructure needs for iron and steel

A key role will be played by increased use of scrap to produce recycled steel, along with material efficiency measures. These both reduce the need for primary steel production. There is also untapped potential for enhancing process efficiency through retrofits, process control, process intensification, heat recovery, and other initiatives.

Hydrogen-based reduction of iron ore represents a promising, low-emission technological pathway. Indirect use of clean electricity, in the form of hydrogen, can decarbonise primary steel production.

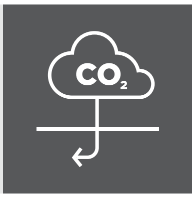


Using renewable electricity for scrap recycling will be a key driver to reduce emissions from secondary production. Direct use of electricity to reduce iron ore, akin to processes used today to produce aluminium, could play in important role in the future. Using renewable electricity can significantly reduce emissions.



Direct use of renewable heat and biomass for furnace heaters and other downstream steel production can contribute to a reduction in residual emissions from low-carbon steel production.

CO_2 capture, utilisation and storage (CCUS) measures can be retrofitted to existing traditional fossil-fuel-based steel production.



Key infrastructure needs for iron and steel

- Reinforced electricity grids and/or onsite renewable power generation
- On-site production or transportation infrastructure for green hydrogen
- Deployment of carbon capture and storage capacity

Tracking progress

As the political momentum towards addressing climate change grows, key industrial sectors like iron and steel are receiving increased attention. By the end of 2021, more than 90% of the world's steel capacity and production came from countries committed to achieving net-zero emissions by mid-century (OECD, 2022a). Along with commitments to reduce CO_2 emissions, several developments in regulations also support the industry's initial steps in the transition to net-zero. These include existing and emerging carbon pricing mechanisms, such as the emissions trading systems in the EU, South Korea, China and other emerging economies, such as India. These also include the Carbon Border Adjustment Mechanism (CBAM) in Europe and the Inflation Reduction Act in the United States.

Recently, Germany launched a 4 billion euro (EUR) Carbon Contracts for Difference (CCfD) first bidding to encourage heavy industries to switch to low-carbon processes (Hydrogen Insight, 2024).

Public procurement accounts for about a quarter of global steel demand (BNEF, 2024a). Currently, there are only few green public procurement (GPP) schemes that include steel products. Indeed, California is the only jurisdiction with a mandatory GPP that considers steel emissions (BNEF, 2024a). The Buy Clean Initiative[25] in the United States will also include steel in the near term, however, and has proposed emissions thresholds. Elsewhere, the Industrial Deep Decarbonisation Initiative (IDDI) announced a "Green Public Procurement pledge" at COP 27. As part of this pledge, at COP28, Austria, Canada, Germany, Japan, the United Arab Emirates, the United Kingdom, and the United States have committed to low-emission procurement within a set time frame to achieve net-zero emissions in all public construction projects (IDDI and UNIDO, 2023). Via its green government strategy, Canada also aims at reducing the embodied carbon of structural materials used in major public construction projects by 30%, starting in 2025. A goal of net-zero emissions by 2050 in all Canadian government-owned and leased real property has also been set, and in the procurement of goods and services (Government of Canada, 2024).

Several global steel players are taking steps to decarbonise their steel production and forming partnerships to pool demand for green steel. As of January 2023, steel producers representing about 38% of global capacity had established net-zero targets. As of October 2023, approximately 73 offtake agreements for low-carbon primary steel had been signed, with the automotive sector and consumer goods and equipment manufacturers leading the way (BNEF, 2024a). Some notable examples include Volvo Trucks' purchase of SSAB AB's first batch of fossil-free steel and Mercedes Benz's agreement with H2 Green Steel. The company H2 Green Steel has recently secured debt financing for EUR 4.2 billion to build the world's largest green steel plant in Boden, Sweden (H2 Green Steel, 2024). While these developments are promising, the volume of these private sector commitments still represents a negligible share of today's overall steel demand.

In the private sector, there are initiatives that promote near-zero emissions products and drive a positive trajectory towards net-zero emissions. For example, the First Movers Coalition has over 120 commitments to purchase near-zero emission goods and services by 2030,[26] while the SteelZero Initiative includes 40 businesses committed to buy and use 100% net-zero steel by 2050[27] or earlier. Similarly, the Sustainable Steel Buyers Platform[28] of the Rocky Mountain Institute aims to enable corporations to participate in the joint purchase of low-carbon steel in North America. Meanwhile, IRENA's Alliance for Industry Decarbonisation (AFID)[29] initiative aims to facilitate dialogue at an industry level and increase co-operation to help companies develop solid decarbonisation strategies and implementation plans, aligned with their countries' net-zero and decarbonisation commitments.

[25] *See: www.sustainability.gov/buyclean/*

[26] *See: www.weforum.org/press/2024/01/wef24-first-movers-coalition-commitments/*

[27] *See: www.theclimategroup.org/about-steelzero-*

[28] *See: https://rmi.org/sustainable-steel-buyers-platforms-request-for-information/*

[29] *See: www.allianceforindustrydecarbonization.org/*

There are ongoing efforts to establish unified definitions, standards, certification schemes and emission accounting mechanisms. These can provide certainty for those governments and companies looking to purchase and trade steel with certain environmental attributes.

There are two main components to the development of steel standards: an emissions accounting methodology, and normative thresholds that define low-emission steel. On the former, at COP 28, the IDDI released a white paper suggesting a shared set of principles for consistent GHG accounting. Similarly, the First Movers Coalition, Wirtschaftsvereinigung Stahl and SSAB AB have their own standards and methodologies. These are in addition to the approaches used by organisations such as the International Standard Organisation (ISO) and the World Steel Association.

Several companies have begun labelling and branding products based on their own definitions of low carbon steel. China's Baosteel "Beyond ECO" standard, Arcelor Mittal's low-carbon emissions global standard and SSAB's steel standard are a few examples available in the market (IEA, IRENA and UNCCHLC, 2023; Ali Hasanbeigi and Adam Sibal, 2023).

Lack of harmonisation across several emission measurement approaches and definitions of zero emission steel, however, is a bottleneck in the transition to green steel products. If unaddressed, this could lead to negative economic consequences, such as increased transaction costs, confusion for steel buyers and potential greenwashing. "The Steel Standards Principles" launched during COP28 aim to establish universally recognised and compatible emissions measurement methodologies for the iron and steel industry.[30]

Financial institutions have also started applying sustainability criteria to investments in iron and steel production assets. As an example, the Sustainable STEEL principles,[31] launched by a consortium of lenders, help banks align their steel lending portfolios with 1.5°C climate targets. The latest figures show that half of the sustainable STEEL signatories achieved alignment with well below 2°C and a third of them aligned with 1.5°C. Similarly, the Climate Bonds Initiative has recently launched criteria for iron and steel production. This will guide banks and investors when investing in the sector's sustainable activities and incentivise the development of regulations.

There are ongoing discussions to progress towards an international level-playing field for the trade of steel. The Organisation for Economic Co-operation and Development (OECD) Steel Committee has been a platform for steel trade co-operation for years and has now expanded the scope of discussions to include decarbonisation issues. The Climate Club,[32] launched at COP28, is a new intergovernmental forum for exchange on industry decarbonisation and seeks increased collective action across diverse geographies.

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[30] *See: www.industrialenergyaccelerator.org/general/driving-consistency-in-the-greenhouse-gas-accounting-system/*

[31] *See: https://steelprinciples.org/*

[32] *See: https://climate-club.org/*

2.5 Chemicals and petrochemicals

Chemicals are crucial to our daily lives, in use in many industries, technologies and household products. Most emissions from the sector stem from a small number of these chemicals, particularly ammonia, methanol and steam cracking products (ethylene, propylene, butadiene and aromatics).

Ammonia is a crucial commodity used mostly (about 85%) in the production of synthetic nitrogen fertiliser. It is therefore also critical to global food security. Methanol is an essential building block in the production of a wide array of compounds, including, among others, solvents, resins and pharmaceuticals. "High-value chemicals" (HVCs), such as olefins (principally ethylene, propylene and butadiene) and aromatics (including benzene, toluene and xylenes) are essential building blocks for a variety of products across several industries. These include plastics, synthetic organic fibres like nylon, and other polymers (IRENA, 2020).

Emissions and energy use

The production of ammonia, methanol and HVCs – also known as primary chemicals – has been increasing over the last few decades. This production currently relies almost entirely on fossil fuels and feedstocks.

Over the last decade, ammonia production has grown modestly, however, at an average annual growth rate of 1% (IEA, 2024). In 2022, approximately 187 Mt of ammonia was produced globally and primarily sourced from natural gas (72%) and coal (26%) (BNEF, 2024b). In the case of methanol, production has almost doubled over the last decade, growing at an average annual rate of 6.5% (IEA, 2024). In 2022, around 106 Mt of methanol was produced globally, while currently, over half of production is in China (Methanol Institute, 2024a). In terms of fuel mix, around 65% of global methanol comes from natural gas, 35% from coal and 0.2% from renewable sources (IRENA *et al.*, 2021).

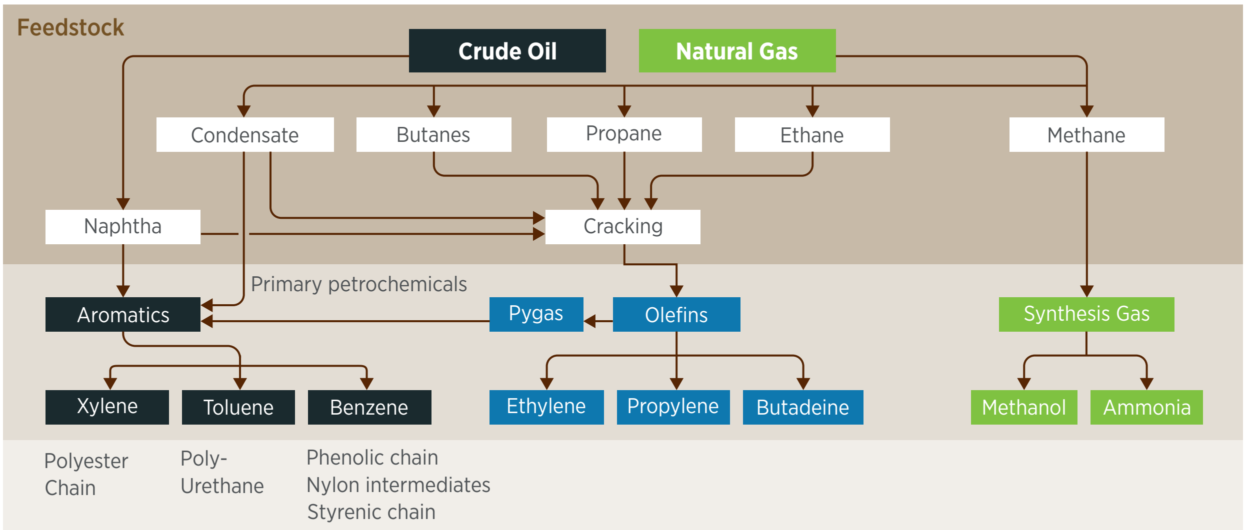
Demand for HVCs has been increasing steadily over the past decade, with an average annual growth rate of 3% (IEA, 2024). In particular, the production of plastics has almost doubled since the beginning of this century and reached around 400 Mt at the end of 2022 (OECD, 2022b; Plastics Europe, 2023). Today, 90% of plastic products are still made from fossil feedstocks. In 2022, bio-based plastics constituted 0.5% of total plastics production, a figure equivalent to 2.3 Mt, in absolute terms. Globally, around 9% of global plastics production comes from the recycling of plastic waste (Plastics Europe, 2023).

In 2022, production of these primary chemicals was responsible for approximately 936 Mt of direct CO_2 emissions, or about 72% of the total chemicals and petrochemicals sector's CO_2 emissions (IEA, 2023a). Ammonia production is responsible for the largest share of total direct CO_2 emissions from primary chemicals production (45%), followed by methanol (28%), with the remainder coming from the production of HVCs (IEA, 2024).

At the same time, while the primary chemical sector is the largest industrial energy consumer, it is only the third largest CO_2 emitter. The sector has roughly equal amounts of emissions from energy used in production processes and from feedstock use. This means that some hydrocarbon stocks are contained both in products in use and those that make their way to controlled and uncontrolled waste disposal systems globally (IRENA, 2020).

Under IRENA's Planned Energy Scenario with limited interventions and actions, the sector's CO_2 emissions could more than triple, from 1.3 Gt in 2022 to 4.7 Gt in 2050 (IEA, 2023a; IRENA, 2023a). At present, most post-consumer plastic is landfilled, incinerated or mismanaged, with only 9% being recycled globally (OECD, 2022b). Low recycling and energy recovery rates increase energy use and CO_2 emissions. In addition, poor waste management practices contribute to air and water pollution that impacts local ecologies. This highlights the urgent need to transform the sector from a climate and sustainability perspective.

Figure 15 Overview of feedstocks and petrochemical products



Source: (IRENA, 2020).

Decarbonisation pathways

The sector's emissions derive from energy used in production processes as well as energy carriers used as feedstock for chemicals. Both sources need to be eliminated, if the sector's emissions are to be reduced to zero. To achieve this, a combination of decarbonisation pathways is necessary. These routes include: reducing demand by increasing re-use and recycling of products; reducing energy consumption by improving the energy efficiency of processes; adopting renewables-based alternatives to fossil fuel feedstocks; and switching to renewable-based electricity and the use of CCUS technologies, including bioenergy with carbon capture and storage (BECCS) (IRENA, 2020).

Some technological pathways are already commercially available and can be scaled up in the coming decades. These include energy efficiency improvements; substituting fossil fuels with bio-based feedstocks for some chemicals; electrification of multiple heating processes; and renewable hydrogen.

Globally, since 2010, the chemical and petrochemical sector's energy intensity has improved at a steady average annual rate of between 0.5% and 1%. Despite these efficiency gains, however, the sector's energy demand has been growing by around 3% per year (IRENA, 2020). Under IRENA's 1.5°C scenario, an annual energy efficiency improvement of 3% for production processes will be necessary over the next three decades (IRENA, 2023a).

Applying the principles of the circular economy in the industry has several economic, social, and environmental benefits. Circular economy measures generally include: increasing re-use; mechanical and chemical recycling; material substitution; and using sustainable feedstocks to reduce demand.

Globally, the production of plastics is expected to more than double by 2050, to 986 Mt per year (IRENA, 2023a). Meanwhile, re-use and recycling of petrochemical products is still limited and insufficient. At present, mechanical recycling is dominant, with less than 0.1% chemically recycled (Plastics Europe, 2023). This is mainly because the economics of chemical recycling are not yet favourable. Indeed, impurities or expensive sorting requirements may make the process economically unfeasible (IRENA, 2020).

The substitution of renewable ammonia for conventional ammonia can make a major contribution to decarbonising the chemical sector. Today, ammonia is mostly produced via the Haber-Bosch process, with natural gas the dominant fuel and feedstock. Renewable ammonia can be produced from green hydrogen. This hydrogen is converted into ammonia in a synthesis process using nitrogen separated from air. While the technology is commercially available, production costs for renewable ammonia are significantly higher than fossil-based ammonia. The production cost of natural gas-based ammonia and coal-based ammonia is currently between USD 110/t and USD 340/t. Renewable ammonia production costs for new plants are currently estimated to be between USD 720/t and USD 1400/t. This will potentially decrease to between USD 310/t and USD 610/t by 2050 (IRENA *et al.*, 2022).

Renewable methanol can be derived from biogenic feedstocks (biomethanol) or synthesised[33] from green hydrogen and carbon dioxide (e-methanol). Biomethanol can be produced via gasification or anaerobic digestion processes. A wide array of biomass feedstocks can potentially be used. These include agricultural and forestry waste, landfill biogas, sewage, municipal solid waste (MSW), and black liquor from the pulp and paper industry. The production costs of biomethanol are expected to remain higher than for fossil-based methanol, however, within an estimated range between USD 327/t and USD 1013/t, depending on the costs of the feedstock (IRENA *et al.*, 2021).

E-methanol can be synthesised from green hydrogen and a sustainable source of carbon. This can be CO_2 from BECCS or direct air capture (DAC). The estimated production costs for e-methanol are higher than those of biomethanol and fossil-based methanol, within a broad range of between USD 800/t and USD 2400/t, depending on the costs of hydrogen and the costs of sourcing sustainable carbon. With anticipated decreases in renewable power generation costs, the cost of e-methanol could potentially decrease to levels between USD 250/t and USD 630/t by 2050 (IRENA *et al.,* 2021).

The use of sustainably sourced biomass to replace fossil fuels and feedstocks is an option for decarbonising the production of high value chemicals. As an example, life-cycle emissions could be significantly reduced in the plastics sector if bio-based plastics were substituted for fossil fuel-based plastics. Plastics preferably need to be both bio-based and biodegradable. Yet, the high cost of bioplastics acts as a major barrier to their uptake. In addition, the technology readiness level is relatively low and further innovation and pilot deployments are needed to build knowledge, confidence and economies of scale (IRENA, 2020).

Bio-based alternatives to primary petrochemicals include bioethanol, bio-ethylene and bio-aromatics. For example, ethylene can be readily produced from bioethanol. The production of bio-based ethylene has been carried out on a commercial scale for some years now – although volumes are relatively small, at less than 1% of total global ethylene production. Increased efforts are needed to scale up production and drive down costs, as these are currently higher than fossil fuel ethylene (IRENA, 2020).

Using synthetic hydrocarbons for feedstocks and renewables for energy supply is another option for the decarbonisation of high value chemicals. Hydrogen can be produced from renewables-powered electrolysis and synthesised with a sustainable carbon source in the presence of a catalyst to produce hydrocarbon feedstocks which could substitute for primary petrochemicals.

A major bottleneck for the widespread use of synthetic hydrocarbons, however, is the cost-effective sourcing of sustainable carbon (*i.e.* that not captured from fossil fuels). Presently, obtaining clean CO_2 from either biomass or DAC is expensive and significantly raises overall production costs. These will need to fall substantially for this approach to be a competitive alternative to the use of biomass feedstocks (IRENA, 2020).

Across the sector, direct electrification can play a role in decarbonising heat processes. E-crackers, which are electric alternatives to the traditional steam cracker process used to produce HVCs, are currently being tested in several pilot plants. Shell and Dow have installed an experimental electric-powered heat steam cracker furnace unit at the Energy Transition Campus in Amsterdam, testing it as a replacement for gas-fired steam cracker furnaces. The unit has the potential to scale up by 2025 (Shell, 2022).

In addition, at a test facility in Germany, BASF, SABIC and Linde have commenced construction of the world's first demonstration plant for large-scale electrically heated steam cracker furnaces. This aims for a 90% reduction in CO_2 emissions compared to conventional technology (BASF, 2022). For low and medium temperatures, heat pumps can be deployed. Research efforts are currently underway to increase the temperature range to a maximum of 200°C (IRENA, 2023b).

[33] *Several different processes can be employed to produce synthetic hydrocarbons, including thermochemical and electro-chemical processes. The Fischer-Tropsch and methanol syntheses are prime examples (IRENA, 2020).*

Figure 16 Summary of decarbonisation pathways and infrastructure needs for chemicals and petrochemicals

Adopting circular economy principles is an essential starting point to reduce the scale of the challenge. It is also critical to managing other environmental concerns, such as the impact of plastic waste.

Emerging technologies could contribute to decarbonising multiple heating processes in the sector. These processes include e-crackers, high-temperature heat pumps, electric resistance furnaces and induction furnaces able to reach temperatures between 200°C and 1 000°C.

Using biomass for chemical feedstocks is a decarbonisation option for the sector. Primary petrochemicals can be replaced by bio-based chemicals, or fossil fuel-derived polymers (particularly plastics) can be replaced by alternatives produced from biomass.

The substitution of renewable ammonia for conventional ammonia can make a major contribution to decarbonising the chemical sector. Using synthetic hydrocarbons for other chemicals, produced from green hydrogen and clean CO_2 sources, is being explored and could play a role in the long term. However, the large cost gap with conventional alternatives and the sourcing of clean CO_2 are issues that need to be addressed.

Use of carbon dioxide capture, utilisation, and removal measures. Capturing CO_2 emissions from processes where emissions cannot be fully eliminated, storing it permanently or utilising it in ways in which it will not be released later.

Key infrastructure needs for chemicals and petrochemicals

- Expansion of renewable power generation capacity
- Deployment of electrolyser capacity
- Stationary electricity storage to ensure stable and reliable operation
- Deployment of carbon capture and storage capacity
- Biomass feedstock logistics and supply chain

Tracking progress

Several governments have established decarbonisation targets, strategies and policies that apply to their domestic industries. However, only few of contain targets and policies aimed specifically at the chemicals sector. This leaves substantial room for progress on this front.

Notable examples of such efforts include: France's 31% emissions reduction by 2030 target for its chemicals industry; the EU Chemicals Strategy for Sustainability, which promotes the sustainability of critical chemicals; Japan's efforts on improving circularity in the chemicals sector, such as the Resource Circularity Strategy and the Act on Promotion of Resource Circulation for Plastics, which form part of Japan's Green Transformation (GX); or the United Kingdom's decarbonisation and energy efficiency roadmap for the chemicals sector (BEIZ, 2017; CNI, 2021; ECHA, 2022; REI, 2024).

The private sector has also begun efforts towards establishing decarbonisation targets. Over 70% of the top 100 chemical producers globally have set the target of achieving carbon neutrality by 2050, while some have also established interim targets (Michel *et al.*, 2023).

A few examples of private sector action include BASF's plans to reduce Scope 1 and 2 emissions by 25% by 2025, compared to 2018; Dow Chemical's aim for a 15% reduction by 2030, or a 30% reduction compared to 2005; or LyondellBasell Industries, which set a 42% reduction target by 2030, compared to 2020. All three companies aim for carbon neutrality by 2050 in terms of Scope 1 and 2 emissions (Michel *et al.*, 2023). The Alliance for Industry Decarbonisation (AFID) has also adopted its Decarbonisation Commitment. Members of AFID have individual reduction plans that when combined aim to reduce direct and indirect GHG emissions by 51%. They also aim to increase their installed renewable energy capacity from 84 GW to 187 GW between 2023 and 2030 (IRENA, 2023d).

Supporting policies in the form of subsidies and grants for low carbon ammonia and methanol are starting to emerge. This is happening in the broader context of support for the scale up of the hydrogen industry. Some prime examples include: the recent EU Innovation Fund's Research and Development (R&D) grant of more than EUR 1.8 billion to produce green hydrogen, ammonia and methanol, or for scaling up electrolyser and fuel cell manufacturing (Hydrogen Insight, 2023); federal tax credits for clean hydrogen production in the United States under the Inflation Reduction Act; India's subsidies for renewable ammonia production, which recently saw the announcement of a first competitive bidding round targeting demand of 550 000 t per year (AEA, 2024).

The number of renewable ammonia and methanol projects announced is growing. Globally, there are around 131 renewable methanol production projects expected to be operational by 2028. These will have a total projected capacity of 19.5 Mt (Methanol Institute, 2024b). There is also a substantial pipeline of renewable ammonia plants. These have a collective expected capacity of 15Mt per year likely to be operational within this decade and over 71 Mt per year before 2040 (IRENA *et al.*, 2022). While some of these initiatives are fully funded and in the construction phase, a significant portion have yet to secure financial closure, however. Nevertheless, the anticipated growth in renewable ammonia capacity is expected to persist, as industrial projects at the demonstration stage progress from multi-megawatt to gigawatt levels, while additional large-scale ventures are unveiled.

There is growing international action to tackle plastic pollution. As of 2022, close to 100 nations had implemented bans and levies on plastic packaging and single-use items. Yet, although the number of countries around the world banning single use plastics is growing, enforcement is still an issue in some parts of the world (Braun, 2024).

3. ACCELERATING THE TRANSFORMATION

3.1 Key considerations in the decarbonisation of hard-to-abate sectors.

The technologies to decarbonise hard-to-abate sectors have seen significant progress in recent years and are today largely available. Innovation is narrowing the scope of what has been traditionally understood as hard-to-abate sectors.

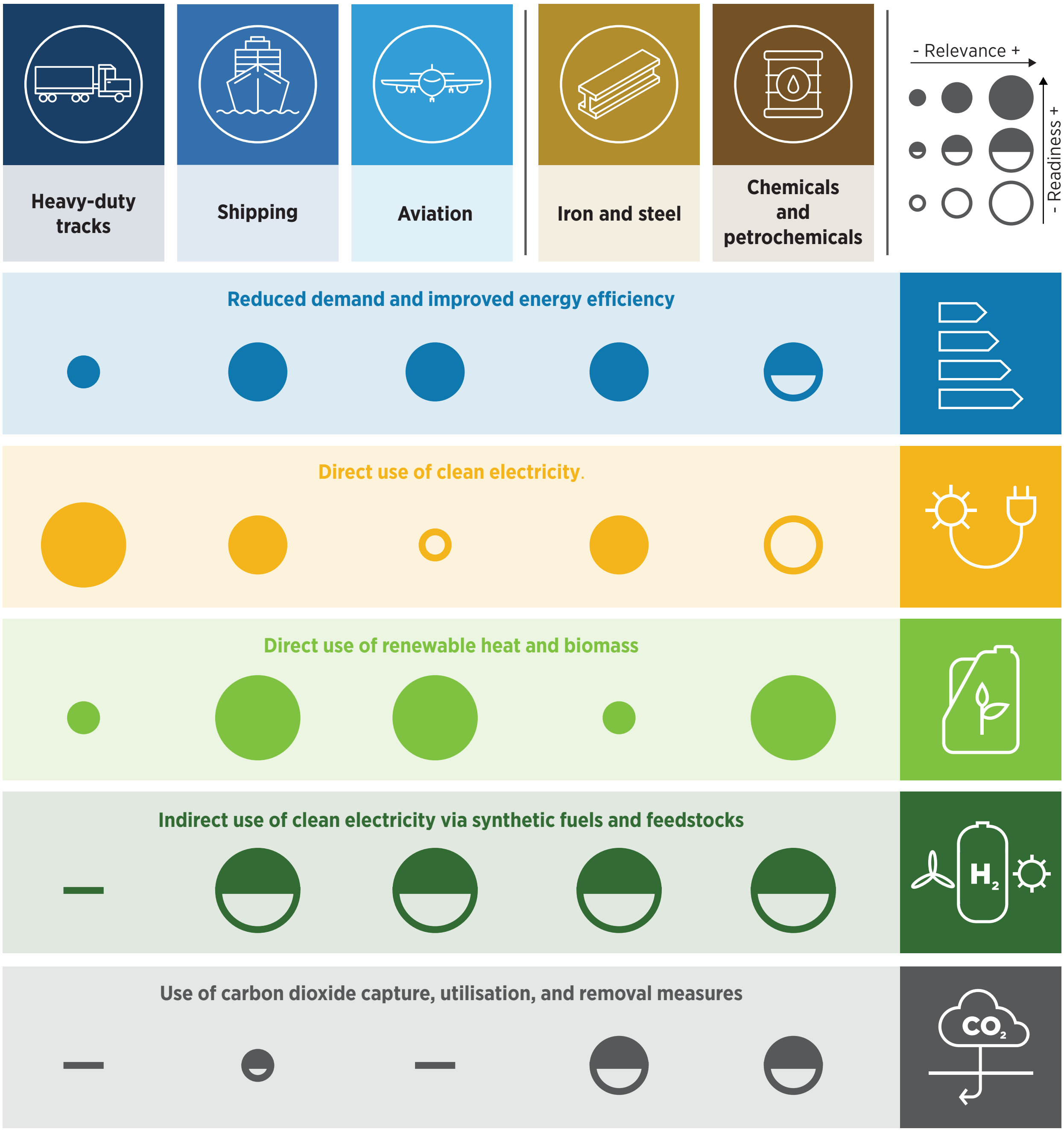
In the transport sector, solutions exist to decarbonise the bulk of heavy road freight, shipping and aviation. Battery producers have improved performance and reduced costs to a point that makes electric trucks technologically feasible even for demanding long-haul applications. Biofuels are a mature technological solution that can be scaled up to meet a substantial part of the needs of aviation and shipping. As the road sector transitions at an accelerated pace towards battery EVs, large amounts of biomass feedstock dedicated today to produce biofuels for cars and trucks will become available to produce SAF and shipping fuels.

In the industrial sector, we have also seen substantial progress in recent years. Hydrogen-based DRI production has been proven at precommercial scale and the first commercial scale plants are being built, or are at the advanced project stage, with a substantial pipeline of low carbon steel production – around 62 Mt per year by 2030 – so far announced (BNEF, 2024a). E-crackers, an electric alternative to the traditional steam cracker process in the production of HVCs, are being tested at a precommercial scale.

Renewables can play a central role in the decarbonisation of all hard-to-abate sectors. The drastic cost reductions that we have observed in recent years make renewable power the cheapest source of carbon-neutral energy worldwide. Furthermore, there is potential for further cost reductions through technological learning and economies of scale. Hard-to-abate sectors can be decarbonised with renewables using several solutions, including: direct electrification; the use of bio-based fuels and feedstocks; and so-called "indirect electrification" *i.e.* the production of synthetic fuels using renewable energy and sustainable carbon sources.

The transition in hard-to-abate sectors will require a combination of technological solutions. Figure 16 shows a simplified mapping of the five sectors analysed in this paper against the five main decarbonisation pathways.

Figure 17 Summary of key technological pathways and readiness assessment of selected sectors



Note: Increasing circle size indicates higher relevance to the decarbonisation efforts of each sector, *i.e.* larger circles indicate higher relevance and smaller circles lesser relevance. Circle filling indicates technology readiness, *i.e.* filled circles indicate a technology is ready for deployment, while empty circles indicate a lack of readiness. The dashes indicate negligible or no relevance.

Direct electrification will play an increasing role, with important contributions in multiple applications. Some of these solutions are already mature, or close to technological maturity. These include: use of electric arc furnaces for steelmaking, which will become more important as the share of recycled steel increases in the coming decades; battery electric trucks, which are at a technological inflection point and becoming increasingly available; heat pumps for low to medium temperature heating in industry; and cold ironing at ports. Some other applications of direct electrification, while having great potential, still need further development. These include: electric crackers to produce primary chemicals; electrolysis of iron ores; and electric or hybrid aircraft and ships for short distances.

Bioenergy and synthetic fuels will play a critical, complementary role to electrification. Scaling up sustainable, low-carbon bioenergy solutions is not only key to the decarbonisation of shipping and aviation. It is also critical in providing feedstocks for chemicals and as a potential carbon source for synthetic fuels. Indirect electrification – *i.e.* via the production of renewable hydrogen – is also set to play an important role in achieving deep emissions reductions in these sectors. It can do this as a reductant in the production of iron in primary steel production, as a form of synthetic fuels for shipping and aviation, and as a feedstock for chemical industries.

These pathways will have to be complemented by continuous energy efficiency improvements, the application of the principles of the circular economy, and behavioural and process changes that reduce demand. Additionally, emissions can be further reduced through the application of CO_2 capture, utilisation and/or removal measures, provided that these technologies achieve the necessary improvements in performance and economics to make them technically scalable and economically viable.

While technology is increasingly available, in the absence of sufficiently high and widespread carbon pricing, a timely transition in hard-to-abate sectors will almost certainly require paying a premium over the cost of fossil-based systems. Cost differentials differ widely by sector and application. Battery electric trucks, for example, have a feasible pathway to reach cost parity and even become cheaper to operate than fossil counterparts in the short- to medium-term. The adoption of biofuels for shipping and aviation and bio-feedstocks for chemical commodity production will likely continue to come at moderate cost-premiums. Synthetic fuels and feedstocks will likely result in relatively high premiums for the foreseeable future, although such cost-premiums could be partially reduced by technology improvements.

Unprecedented social and political momentum, together with the increasing competitiveness of renewables and other enabling technologies, has resulted in **increased action towards the decarbonisation of hard-to-abate sectors**.

In the public sector, initiatives like the Breakthrough Agenda, Mission Innovation and the recently created Climate Club aim to catalyse transformative actions towards a low-carbon future in some hard-to-abate sectors. Along with these efforts, significant policies are setting ambitious targets and offering incentives to drive decarbonisation across industry and transport. These policies include the Inflation Reduction Act in the United States and the Net-zero Industry Act, or the Fit for 55 Package – which include RefuelEU Aviation and FuelEU Maritime – in the EU.

Moreover, collaborative ventures between the public and private sectors are fostering synergies to address emissions reduction challenges holistically across sectors. These ventures include: IRENA's Alliance for Industry Decarbonisation (AFID); the Industrial Deep Decarbonisation Initiative, led by the United Nations Industrial Development Organisation and the Clean Energy Ministerial; and the Decarbonising Transport Initiative of the International Transport Forum. There are also several private sector-led initiatives, such as the Mission Possible Partnership, which addresses several hard-to-abate sectors, and the Getting to Zero Coalition, which has a focus on shipping.

Yet, despite promising progress and increased attention from policy makers, **none of the hard-to-abate sectors is on a trajectory compatible with reaching net-zero emissions by mid-century.** The production volumes of green industrial commodities – such as primary steel and key chemicals like ammonia, methanol, and olefins – are still negligible. Similarly, sustainable fuels for aviation and shipping represent a negligible fraction of these sector's total fuel consumption. The adoption of battery electric heavy trucks, while growing fast, also represents a small fraction – between 1% and 2% – of global vehicles' sales ((BNEF, 2023b; IEA, 2023c). They also represent a negligible fraction in terms of global road freight services.

3.2 Recommendations for the G7

Several enabling conditions need to be put in place to accelerate the decarbonisation of hard-to-abate sectors. These will require decisive action by governments, as well as by the private sector. They also have fundamental implications in terms of national and international policy and regulatory environments, technology and infrastructure planning, global commodity markets, international supply chains and business models.

Creating an enabling policy environment

Hard-to-abate sectors need a supporting policy environment to accelerate the massive investments in energy technology and infrastructure that are required over the next two-to-three decades. Project developers and investors need to have sufficiently clear, stable, and credible signals of decarbonisation objectives and sufficient economic incentives to make final investment decisions. A suite of policies – adapted to the needs of specific sectors – will be needed. This suite should include both environmental regulations and economic support measures, among other policies.

RECOMMENDATION 1

Establish sector-specific decarbonisation targets. G7 countries can support the transition by establishing long-term, sector-specific, national objectives with clear intermediate milestones. Beyond national policies, G7 members can work with other countries, within and beyond the G7, towards further international convergence in the decarbonisation objectives for key traded commodities such as steel, ammonia, and methanol, as well as aviation and shipping fuels.

RECOMMENDATION 2

Take further steps towards creating a level playing field for green technologies. G7 countries can accelerate the adoption of green technologies in hard-to-abate sectors by implementing national carbon pricing policies that internalise the full value of the negative environmental externalities of fossil energy. Aligning energy taxes with decarbonisation objectives – for example, by reducing relative taxation of electricity *vis a vis* that of fossil fuels – can also play an important role by driving the electrification of heat and transport applications. Furthermore, G7 countries can work with other countries, within and beyond the G7, towards further convergence in international carbon pricing – for example, through sector-specific international agreements.

Fast-tracking infrastructure deployment and technology adoption

A key condition for progress in the decarbonisation of hard-to-abate sectors is the development of the required clean energy supply and value chains, at the required pace. Hard-to-abate sectors will need a massive scale up in power generation capacity, either for direct electrification solutions, or to produce hydrogen and synthetic fuels from clean power.

Over the last decade, renewable capacity additions have grown consistently, reaching a record 473 GW installed in 2023. However, IRENA's 1.5°C scenario indicates that the rate of deployment needs to roughly double, to 1 043 GW of new renewable generation capacity installed per year. At COP28, in line with IRENA's recommendation, more than 130 countries committed to triple installed renewable power capacity collectively to at least 11 000 GW by 2030.

RECOMMENDATION 3

Accelerate the deployment of renewable power supply in alignment with COP 28's pledge. G7 countries can support the transition in hard-to-abate sectors by scaling up deployment of renewable power supply in line with the COP28 pledge of tripling renewable capacity by 2030. This will require additional efforts, including a substantial scaling up of investments and updating of policies and regulations. The latter include, for example, streamlining permitting procedures and adaptations in power market design.

Scaling up bioenergy supply will also be critical. Sectors like aviation and shipping, as well as chemical production, will rely to a significant extent on sustainable bioenergy and bio feedstocks. The deployment of biomass with carbon capture and utilisation (BECCU) will be increasingly important, too, as the production of synthetic commodities – such as methanol or kerosene – will require a renewable source of carbon.

RECOMMENDATION 4

Scale up sustainable bioenergy production and sustainable carbon sourcing. G7 countries can support the transition in hard-to-abate sectors by working within and beyond the G7 to scale up global sustainable biomass supply chains. This can be achieved with policies that provide incentives for the production and/or use of bioenergy, coupled with strict sustainability governance procedures and regulations.

Green hydrogen supply will be key for the decarbonisation of some hard-to-abate sectors like steel and chemicals, as well as to produce synthetic fuels. IRENA estimates that the supply of hydrogen would need to expand about five-fold by 2050, to more than 500 Mt per year. This implies that electrolyser capacity would need to grow by three orders of magnitude (from about 3 GW installed today to about 5 700 GW in 2050). While hydrogen can be used directly in some energy applications, in practice most hydrogen will likely be converted into derivative commodities – such as ammonia, methanol and synthetic fuels – or be used to process other products (for example, in producing low carbon iron from iron ore).

RECOMMENDATION 5

Kick-start deployment of production capacity for green hydrogen derivatives. G7 countries can accelerate the transition in hard-to-abate sectors by supporting the first wave of commercial-scale plants to produce low carbon commodities using green hydrogen – such as ammonia, methanol and iron.

Timely infrastructure planning and deployment will be key. Investment in power grids at all levels – *i.e.* transmission and distribution, including the EV charging infrastructure – is needed to unlock investments in power generation capacity. Conversely, if not deployed on time, a lack of grids can be a critical bottleneck in the transformation of power supply and end-use sectors. Smart electrification strategies[34] applied to transport and industry can add flexibility to the power system. These make it more efficient, reducing the need for additional capacity in generation, transmission or distribution grids, while also making it possible to integrate more renewable sources and reduce peak loads and grid congestion.

[34] *See: www.irena.org/Innovation-landscape-for-smart-electrification*

Beyond power systems, timely planning and deployment of other infrastructure, such as hydrogen supply networks or sustainable fuel terminals in ports and airports, will be critical for those sectors relying on fuels. Cross-sectorial, integrative planning – involving authorities from multiple ministries and/or administration levels – will be required to accelerate planning, permitting and deployment of such critical infrastructure.

RECOMMENDATION 6

Enhanced planning to accelerate the deployment of critical infrastructure. G7 countries can support the transition in hard-to-abate sectors by strengthening cross-sectoral planning and international co-ordination in energy, industry, trade, transport and the environment. They can also support the transition by accelerating permitting and deployment of critical energy infrastructure. Among others, this includes power grids – paired with smart electrification strategies – bioenergy conversion plants, hydrogen networks, and fuel terminals in ports and airports.

The transition in hard-to-abate sectors requires fundamental shifts, rather than gradual steps. The window of opportunity for action to counter the global climate threat and realise the 1.5°C target of the Paris Agreement is closing fast. Meeting the climate agenda requires solutions beyond partial emission reductions. Decision makers should prioritise solutions that are consistent with net-zero emissions, avoid delaying their decarbonisation objectives and the risk of future stranded assets. Most of these solutions rely on renewable energy.

RECOMMENDATION 7

Drive the adoption of innovative technologies to avoid lock-in. G7 countries can accelerate the global transition in hard-to-abate sectors by prioritising and promoting the deployment of technologies that are consistent with net-zero emissions. These include battery electric trucks, hydrogen-based steel, SAF, and others. G7 members can also work with non-G7 countries towards the widespread adoption of such new solutions, particularly in developing nations. This can be done through *inter alia* technology co-operation programmes, the exchange of best practices, and many other methods to avoid lock-in.

Driving markets and financial flows

The international markets for industrial commodities like steel, chemicals and transport fuels are characterised by strong international competition and low margins. As the production of low carbon commodities comes at a cost premium, industry players facing international competition are disincentivised to invest in assets for their production, as this would put them at a commercial disadvantage.

In the absence of a sufficiently high and widespread carbon price, there is a need to kickstart markets for low carbon commodities. The private sector can contribute to such market creation through voluntary schemes that leverage the willingness of some end-consumers to pay a premium. However, these voluntary markets have limited scalability. Public sector support will be needed to create demand at scale and establish the necessary regulatory framework for those markets to operate.

RECOMMENDATION 8

Create initial markets for low carbon commodities. G7 countries can support the transition in hard-to-abate sectors by establishing green public procurement programmes or mandates for low carbon commodities. G7 members can also work within and outside the G7 to accelerate international convergence in definitions, standards, thresholds, and certification procedures to enable the international trade of such low carbon commodities.[35]

Today, hard-to-abate sectors receive a disproportionately low share of global climate finance. While overall, climate finance flows have nearly doubled since 2020 – reaching USD 1.4 trillion in 2022 – they are significantly below the levels needed to avoid the worst impacts of climate change. This situation is starker when looking at the hard-to-abate sectors in isolation. The industrial sector only received USD 14 billion of climate finance in 2022 (roughly 1% of total climate finance), despite being responsible for almost a third of all CO_2 emissions. In that same year, shipping and aviation received just over USD 6 billion, or 0.4% of all climate finance, despite being responsible for roughly 5% of global CO_2 emissions (Buchner *et al.,* 2023).

RECOMMENDATION 9

Bridge the finance gap. G7 countries can drive an increase in global investment flows towards hard-to-abate sectors by working together with the private sector and financial institutions in de-risking projects within and outside the G7. Government support for project bankability can be implemented through several mechanisms, such as via the provision of guarantees, concessional loans, and blended finance, among other instruments.

Developing a skilled workforce

The deployment of new technologies in hard-to-abate sectors will require a workforce with a new set of skills compared to those needed for legacy, fossil-based technologies. Supporting the current workforce through the transition, and building a new workforce with the right skills, will be essential. This will require the implementation of new educational programmes for the next generation of workers, as well as reskilling or upskilling programmes for today's workforce.

[35] *An upcoming report from IRENA delves deeper into the status of the regulation, standards and certification for the development of international markets in green hydrogen and low emission derivative commodities (IRENA, Forthcoming).*

RECOMMENDATION 10

Support the development of a skilled workforce. G7 countries can play a significant role in developing the skills needed for the transition in hard-to-abate sectors. Potential measures include exchanging information on innovative technologies and best practices and providing financial support to specialised educational programs and trainings. G7 countries can also work closely with non-G7 countries to foster multilateral collaboration among national governments, international organisations, industry stakeholders, and educational institutions. This collaboration can also help developing and emerging economies to build the right set of skills and capacity for the transition in hard-to-abate sectors.

Leveraging international co-operation

To a great extent, the decarbonisation of hard-to-abate sectors is a multi-lateral challenge. Industrial commodities like steel, chemicals or fuels for shipping and aviation are internationally traded. Similarly, the supply chains for the technologies that hold the key to reduce emissions in those sectors are also international. **Multi-lateral co-operation will be critical if the world is to accelerate the adoption of those technologies and bring sectors that are hard to abate closer to net zero by 2050.**

A large fraction of the projected growth in activity from hard-to-abate sectors is expected to come from non-G7 countries, particularly developing economies. While action within the G7 is critical, it will not be sufficient to steer the world on track to net zero by mid-century.

The increasing cost-competitiveness of renewable power technologies may reshuffle the geographical footprint of some hard-to-abate industries. Regions with inexpensive, abundant, and high-quality renewable energy resources may be in the best position to produce the lowest cost, low carbon commodities. This creates an opportunity for international co-operation to reduce the costs of the transition in hard -to-abate sectors globally. Commodity exporters with abundant and low-cost renewables could capture more value in the supply chain by exporting processed products rather than raw materials. They could, for example, export iron processed with renewable hydrogen, rather than export iron ore. Importing countries, on the other hand, could reduce the overall costs of decarbonising their national industries while retaining some downstream, high added-value processes within their borders.

RECOMMENDATION 11

Foster international co-operation. G7 countries can work together with developing countries towards mutually beneficial partnerships to decarbonise supply chains for industrial commodities. This can be done through co-operative long-term investment planning that results in a lower cost of decarbonisation for all.

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