In collaboration
with Accenture

Net-Zero Industry Tracker
2024 Edition

INSIGHT REPORT

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Contents

Foreword

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The energy transition is rapidly progressing in areas where technologies, supportive policies and the business case for investments align. However, to achieve a net-zero future, faster advancements across all sectors and countries are required, particularly in hard-to-abate industries such as **steel, aluminium, cement, primary chemicals, oil and gas, aviation, shipping** and **trucking**. These sectors play an important role in our economies, with heavy industry alone contributing to around 30% of global gross domestic product (GDP)[1]. Significantly reducing emissions in these sectors present unique physical, macroeconomic, and business challenges.

The World Economic Forum's *Net Zero Industry Tracker 2024* offers a data-driven assessment of energy transition progress in these eight challenging sectors, which collectively account for around 40% of global GHG emissions. These sectors are vital to the global economy as demand for heavy industry and heavy transport sectors is projected to rise by more than 60% on average by 2050.

This publication marks the third edition of the report, and we are encouraged to see some progress. We have observed a reduction in average emissions intensity of 4.1% in the last five years (2019-2023), with an accelerated reduction in the last year (2022-2023) of 1.2%. Nevertheless, the current pace of progress is insufficient to meet net-zero emissions scenarios. As the recent report by the United Nations Environment Programme highlights, current promises and commitments place us "on track for best-case global warming of 2.6°C this century".[2] This underscores the urgent need to accelerate energy transition efforts.

The physical challenges of emissions reduction have been further compounded by macroeconomic and geopolitical conditions. Higher interest rates strain investments in energy transition technologies, especially given most of these sectors operate in highly competitive profit margin environments. Geopolitical tensions and conflicts have led to an increase in energy prices, leading to some nations prioritizing energy security and national industrial protectionism over sustainability. Additionally, trade restrictions and tariffs increase the cost of products with already-high green premiums, such as green steel and aluminium. However, technology, particularly artificial intelligence (AI), shows significant potential to drive progress. Over the past year, AI has enhanced the speed and economics of capital projects, improved asset management, optimized energy efficiency and enabled more accurate emissions tracking.

The World Economic Forum, with support from Accenture, seeks to identify key barriers in these sectors, align stakeholders on essential actions, and promote collaboration to accelerate progress. These sectors cannot achieve their targets in isolation and require support from the broader ecosystem, particularly for capital deployment, as our report highlights that around 57% of the necessary investments must come from sources outside of these sectors. The majority of these investments will be needed to build infrastructure for clean power, clean fuels, and carbon capture, utilization and storage (CCUS).

The most challenging aspects of the transition necessitate close public-private collaboration. The Forum embraces this multistakeholder approach and is working to drive action with leading governmental bodies such as Clean Energy Ministerial and G20, as well as multilateral initiatives like the First Movers Coalition (FMC), Transforming Industrial Clusters, Mission Possible Partnership (MPP) and the Industrial Transition Accelerator (ITA). Only by advancing this collaborative spirit can we enable a more effective approach to the energy transition, ensuring that all sectors contribute to a sustainable future.

Executive summary

A system-wide approach versus point solutions is needed in hard-to-abate sectors to effectively transition to net-zero emissions by 2050.

This is the first time since the launch of the *Net Zero Industry Tracker* report that there has been a reduction in absolute emissions of hard-to-abate sectors in scope. Sectors have reduced absolute emissions by 0.9% between 2022 and 2023, compared to total global energy-related emissions increasing by 1.3%.[3] Emissions intensity decreased by 4.1% between 2019 and 2023, with an accelerated 1.2% drop in the last year. Five out of eight sectors in scope reduced emissions intensity in the last year, i.e. aluminium, cement, chemicals, aviation and trucking. Additionally, energy intensity decreased by 3.2% in 2022 in these sectors, 1.6 times more than the global level.[4]

To gain the required trajectory for net zero, an estimated $30 trillion in additional capital is required by 2050 for the sectors in scope. This figure represents around 45%[5] of the total incremental net-zero investment required by 2050. This need for investment is particularly challenging given the competitive profit margins of most of these sectors, which limits companies' capacity to absorb the substantial costs while maintaining adequate profitability.

Data and artificial intelligence (AI) have emerged as powerful tools to support the transition to net zero. **Accenture estimates that use of generative AI could improve capital efficiency by 5-7%, reducing capital requirements of hard-to-abate sectors by $1.5-2 trillion for the net-zero transition**. Additional value levers include asset management and energy efficiency, research and development (R&D) acceleration, and enhanced transparency through product-level reporting. However, the increased use of AI is expected to raise electricity demand, potentially competing with hard-to-abate sectors for access to low-carbon power.

The *Net Zero Industry Tracker* highlights the key steps that the industries must take to further progress towards their respective emission reduction goals across five key dimensions of the readiness framework – technology, infrastructure, demand, capital and policy. Each dimension has a readiness score based on a set of metrics.

Technology readiness scores have improved this year due to improved economics and adoption; however, nearly half of the required emissions reductions need to be achieved through technologies that are not commercially viable. The adoption of methane abatement, electric transport and industrial processes, and energy efficiency technologies has increased. However, deep emission reduction in hard-to-abate sectors relies heavily on disruptive technologies that are not economically viable today. **Investments in R&D need to be ramped up in carbon capture, utilization and storage (CCUS), new production pathways for materials, and hydrogen and its derivatives.**

Infrastructure development has been slow; the sectors covered in this report are forecast to represent nearly 70% and 55% of the total hydrogen and CCUS capacity required by 2050, respectively. While infrastructure development for low-carbon power has been encouraging, hydrogen and CCUS infrastructure currently address less than 1% of sector requirements. **Clean power, hydrogen and CCUS infrastructure need to be developed faster in countries with large heavy industry and heavy transport sectors.**

Demand readiness scores have shown limited progress due to the conditions not being met for scaling demand for low-emission products. Major barriers for scaling clean demand include high green premiums, lack of clarity on customer willingness to pay the premium, and limited industry-wide adoption of carbon threshold standards for green products. Current estimates suggest a 40-70% increase in the price of net-zero base material products. **Standardized carbon thresholds need industry-wide adoption, and businesses need to enhance product-level reporting.**

Capital readiness scores have remained stagnant due to lack of material flow of capital to decarbonize the sectors in scope, driven by the challenge of generating returns on clean investments. This report estimates that the $30 trillion additional capital required by 2030 across the sectors in scope is split 43% ($13 trillion) directly by these sectors and 57% ($17 trillion) for clean energy infrastructure. The sectors must generate returns to raise investments on energy transition initiatives, which represent an 80% increase in investment relative to today's levels. **Sectors should increase investments in retrofitting existing assets and building new climate-compatible assets, while energy suppliers need to build the enabling infrastructure.**

Policy support has been fragmented and lacking cross-regional collaboration. As of 2024, there are 75 carbon-pricing instruments in operation worldwide, covering 24% of global emissions.[6] However, increased protectionism through tariffs on green products add an incremental cost on green premiums. Moreover, there are insufficient incentive-based policies to drive focus on low-emission production. **Policy-makers should create stronger incentives that align with the goals of hard-to-abate sectors, energy suppliers and consumers.**

The sectors in this report face a gridlock as businesses, policy-makers, consumers, energy suppliers and financiers hesitate, each waiting for others to commit to investments and measures that can significantly reduce emissions. Hence, there is a need to shift from a point-solutions approach to a system-wide, partnership-based approach, to simultaneously solve several problems, align supply and demand, and overcome cost and risk hurdles.

1

Context

The physical challenges of reducing emissions in hard-to-abate sectors are compounded by technological, economic and political challenges.

> **While inflation is seeing a decline, interest rates have remained elevated despite recent cuts. This negatively impacts the ability of hard-to-abate sectors to invest towards reducing emissions.**

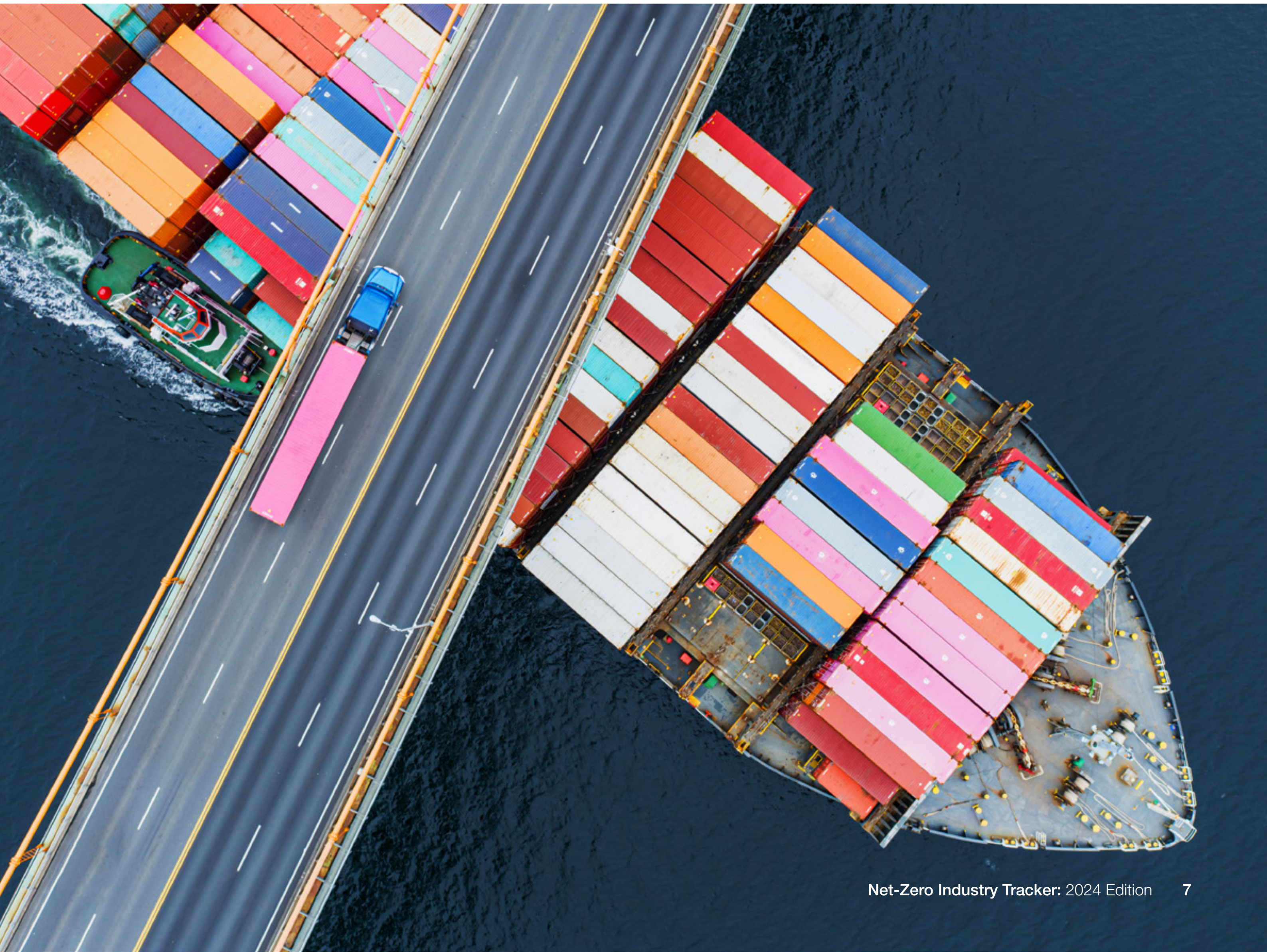
The 2030 milestone of the Paris Agreement is fast approaching, and while substantial progress has been made, hard-to-abate sectors remain among the most difficult sectors to reduce emissions. This is owed to the difficulty of reducing emissions in processes that rely on high-temperature heat or specialized or energy dense fuel.

There have been encouraging developments in renewable energy, electric vehicles (EVs) and battery technology. Global renewable energy capacity is projected to expand by 2.7 times by 2030,[7] exceeding current national targets by 25% and nearing the COP28 goal to triple capacity, mainly driven by improving economics, climate and energy security policies. Battery technology has also experienced significant advancement. The deployment of battery storage systems within the power sector more than doubled in 2023, making clean power supply less intermittent. This progress across various technologies has primarily been driven by substantial investments, supportive policy frameworks and a continued decline in costs.

Other technologies that are essential for industry emission reduction, such as certain types of clean fuels and carbon capture, utilization and storage (CCUS), have not reached the scale-up phase. Their widespread deployment will require further maturation, scalability and cost reduction before they can be used in industrial applications. For instance, global hydrogen growth projections have seen a downward revision by 10-25% compared to earlier estimates, due to a 20-40% increase in green hydrogen costs and continued uncertainty around regulations.[8] The global CCUS capacity grew by only 4% in the last two years,[9] and future growth is uncertain.

Rising geopolitical tensions are also impacting the global path towards net-zero emissions. Energy security was already tested by the Ukraine-Russia conflict, and ongoing conflict in the Middle East risks further strain on global supply chains. Energy prices saw an uptick due to supply constraints driven by these events, caused some major companies, to scale back their net zero targets.

While inflation is seeing a decline, interest rates have remained elevated despite recent cuts. This negatively impacts the ability of hard-to-abate sectors to invest towards reducing emissions, especially in emerging and developing countries where the weighted average cost of capital (WACC) is higher than in advanced economies. Recent fluctuations in commodity prices, such as the drop in steel prices, have also placed strain on these industries and directed their focus towards maintaining profitability at the expense of investing in the energy transition.

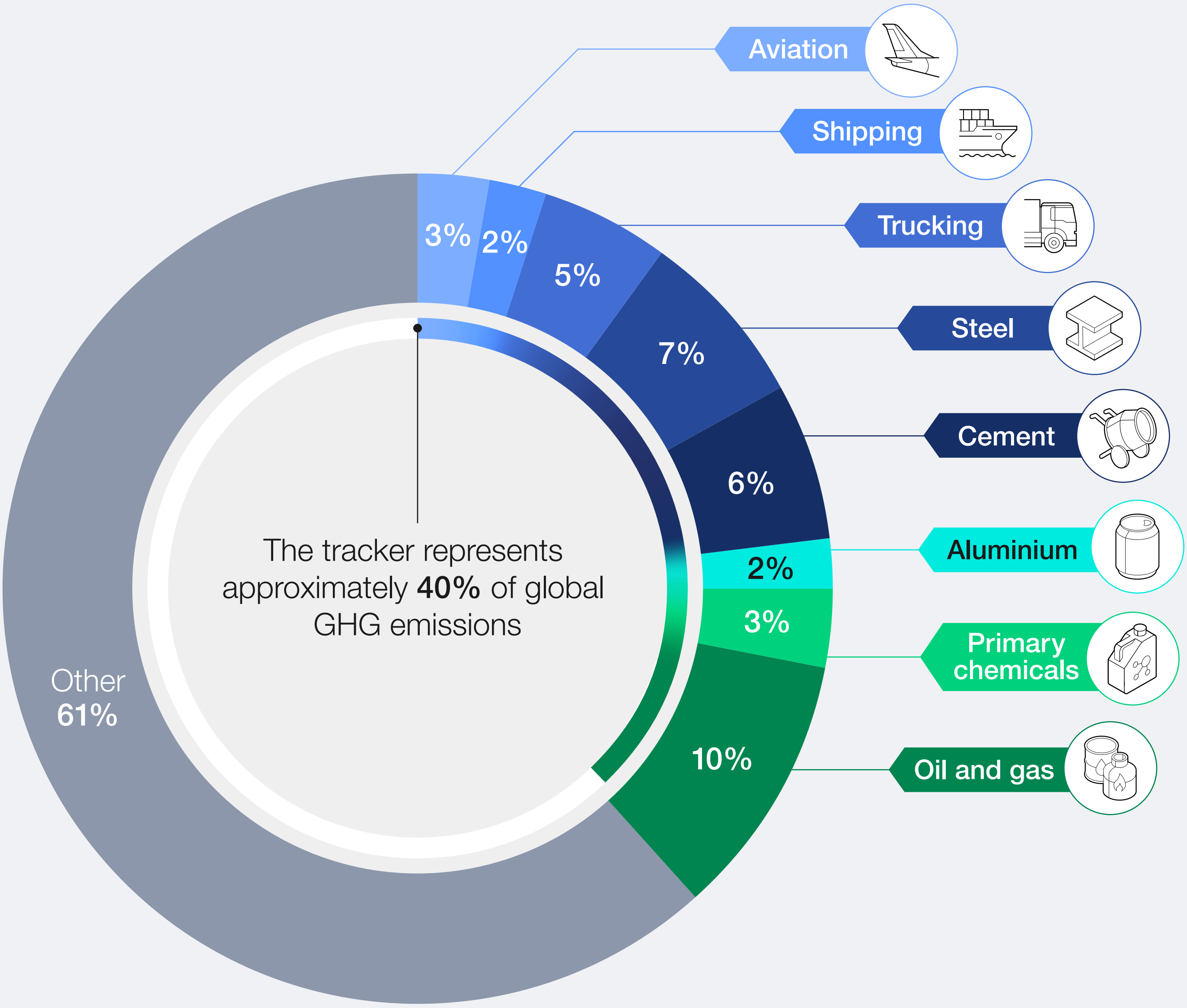


Due to years of shock, including the COVID-19 pandemic and changing geopolitical dynamics, some countries are re-evaluating their trade partnerships and becoming more self-reliant to promote domestic production, through protectionist policies including trade tariffs. For instance, a rise in US tariffs on imports from China, such as a 100% duty on the import of Chinese EVs, and the EU's carbon border tax are expected to reduce the volume of imports. As per the International Monetary Fund (IMF), new trade restrictions have more than tripled since 2019. Thus, global trade is becoming increasingly fragmented, and this is leading to higher costs due to the erosion of economies of scale.

Advancements in generative artificial intelligence (AI) are driving transformative changes in businesses globally by enhancing productivity, streamlining operations and reducing costs. Despite progress, many companies face challenges in the effective and transparent collection and reporting of data across their operations – an essential element in their efforts to reduce emissions. A comprehensive data strategy, supported by digital reporting platforms' power, can streamline carbon accounting and enable detailed product-level emissions reporting. In addition to the enhancement of companies' emissions reporting, these innovations have the potential to free up capital, which can be used to invest in clean energy projects and advanced technologies. Accenture estimates $10 trillion in economic value can be unlocked by 2038 by companies adopting gen AI at scale.[10]

Due to a combination of these technological, economic and political challenges, the eight hard-to abate sectors in scope – which contribute to around 40% of the global Scope 1 and 2 greenhouse gas (GHG) emissions – have seen limited progress towards their net zero goals. These sectors span across production (i.e. steel, cement, aluminium and primary chemicals), energy (i.e. oil and gas) and transport (i.e. aviation, shipping and trucking).

FIGURE 1 **Global GHG emissions (Scope 1 and 2) by sector**



Sources: IEA and IAI.

2

Framework

The *Net Zero Industry Tracker* analyses the progress of eight sectors across production, energy and transport, in achieving net-zero emissions by 2050.

The *Net-Zero Industry Tracker* offers stakeholders a framework and methodology to understand the key drivers of industrial emissions, and the key enablers of the transition to net-zero for eight emission-intensive sectors. The tracker provides both quantitative and qualitative scorecards for the sectors in scope to continuously track their progress towards the net-zero goal. Furthermore, the tracker identifies priority areas for the industries to encourage targeted actions to facilitate progress.

Of the eight sectors in scope in the 2024 iteration of the tracker, ammonia has been expanded to primary chemicals (which also includes ethylene, propylene, benzene, toluene, mixed xylenes and methanol), which contribute to 2.5% of global GHG emissions, increasing the overall volume of emissions being tracked. For the production and energy sectors, the field of analyses covers Scope 1 and 2 emissions, while for transport sectors, the GHG emissions in the fuel supply and operational value chains (well-to-wake emissions) have been covered. While the overarching framework of the tracker remains the same as last year, the quantitative methodology has been updated this year. In addition, numerous cross-cutting themes have been outlined into the five readiness dimensions, distilling some of the key technologies and efforts needed across sectors that deserve elevated attention.

FIGURE 2 **Performance framework – the four drivers of industry net GHG emissions**

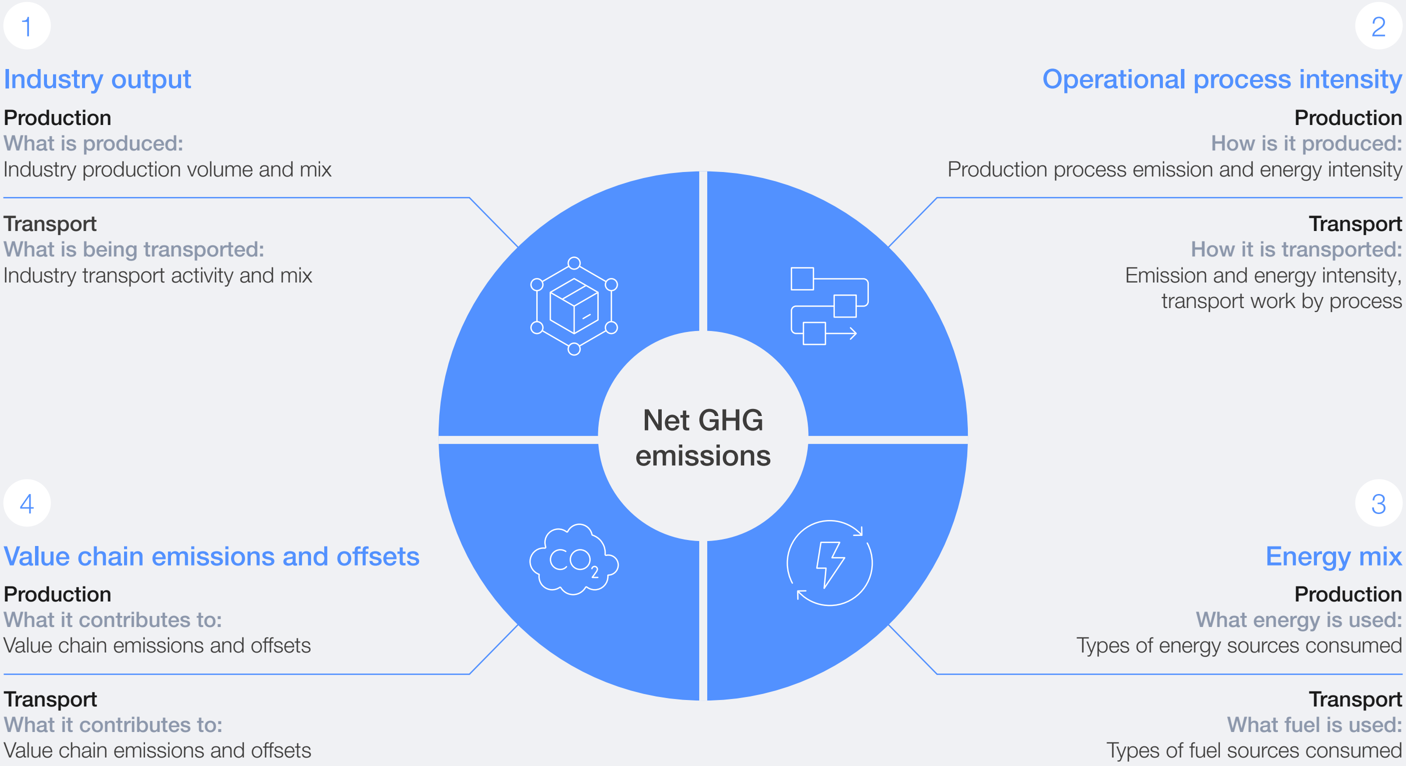
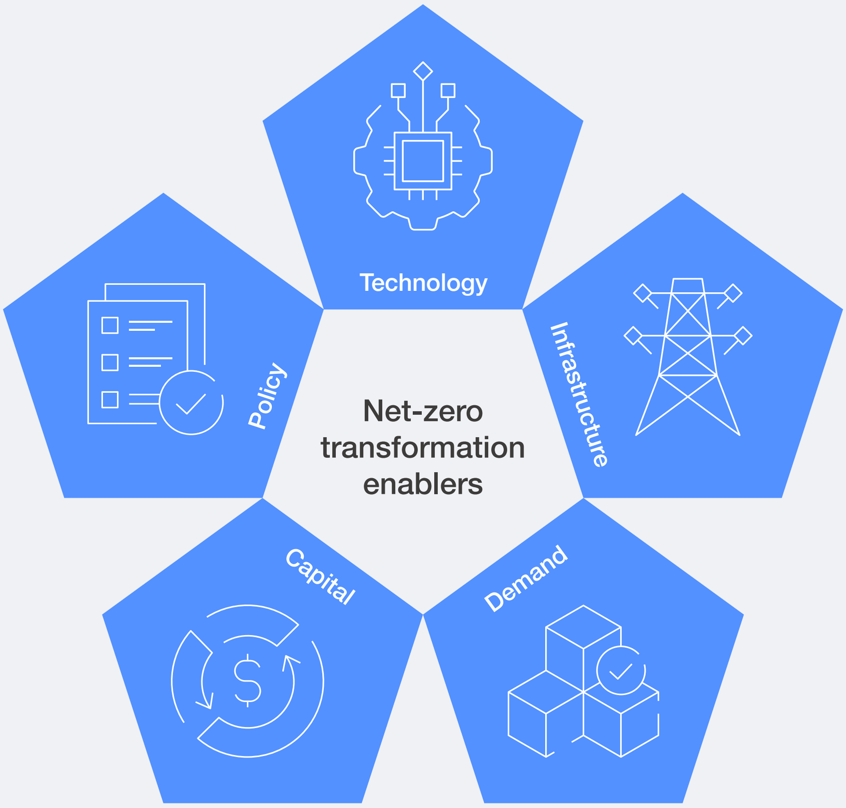


FIGURE 3 **Readiness framework – the five readiness dimensions of industry net-zero transformation**



The underlying framework of the tracker combines two complementary lenses to track industries' progress on the ground – performance and readiness. Performance refers to the drivers of industry net GHG emissions, including industry output, emission and energy intensity, value chain emissions and energy mix. To measure industry readiness for net-zero transformation, a scoring system has been developed across five readiness dimensions:

– **Technology**: Are the technologies needed for net-zero emissions commercially available?

– **Infrastructure**: Is the infrastructure to enable use of low-emission technologies available?

– **Demand**: Can the market support low-emission products, given the green premiums and 2030 project progress?

– **Capital**: Are returns sufficient to drive investments towards low-emission assets?

– **Policy**: Are the supporting policies to enable the growth of low-emission industry in place?

Each of the five dimensions is scored by averaging the values of its sub-dimensions, which are scored on a scale of 1 to 5. A detailed methodology can be found in the appendices. Each sub-dimension has specific thresholds. Dimensions rated at stage 5 demonstrate significant advancements towards net-zero goals, while stage 1 indicates that substantial progress is still required. For instance, in technology readiness levels (TRL), a score of 1-3 indicates that the technology is in the concept stage, 4-6 signifies prototype testing, 7-8 indicates the demonstration phase, 9 represents early adoption and 10-11 indicates a fully developed, mature technology. A detailed methodology can be found in the appendices.

The targets in the tracker refer to the 2030 and 2050 emission intensity thresholds based on sector-specific net-zero trajectories used for the analysis. These trajectories are scenarios based on the analysis of data from the International Energy Agency (IEA) Net Zero by 2050,[11] the International Air Transport Association's (IATA) net-zero roadmaps,[12] the International Civil Aviation Organization's (ICAO) long-term aspirational goal (LTAG),[13] the International Maritime Organization's (IMO) GHG strategy,[14] the International Aluminium Institute's (IAI) GHG pathways,[15] and the IEA's net-zero report on oil and gas.[16] Business-as-usual (BAU) trajectories have also been considered based on the International Council on Clean Transportation (ICCT), the IEA's Stated Policies Scenario[17] and Mission Possible Partnership's (MPP) sector-specific trajectories.[18] These trajectories have been used for this analysis only and are not a final recommendation for the sectors.

FIGURE 4 **Scoring matrix for transformation dimensions**

Dimension	Technology	Infrastructure	Demand	Capital	Policy
Sub-dimensions	– Technology readiness level (TRL)	– Infrastructure capacity required	– Price elasticity of demand – B2B green premium (cost) – B2C green premium – Progress towards 2030 projects goal (announced projects)	– Required increase in capital – Capital efficiency – Ease of increasing capital current return margins – Progress towards 2030 projects goal (investment stage)	– Availability and maturity of policy
Stages	Stage 5	Stage 4	Stage 3	Stage 2	Stage 1

Note: Individual key performance indicators scoring is in the appendices.

Definitions

Clean power: A combination of renewable energy, including solar, offshore wind, on-shore wind, hydropower, biomass, nuclear and geothermal energy, used to electrify thermal processes in production and as an alternative propulsion source in transport sectors

Clean hydrogen: Considers both blue hydrogen (produced with natural gas abated by CCUS) and green hydrogen (produced through electrolysis), though the preference in most cases is green hydrogen

Green premium: Additional products/fuel costs passed to businesses and end consumers, associated with adoption of low-emission technologies

“Low-emission” production: Defined quantitatively for each industry in terms of product emission intensity (Scope 1 and 2)

Carbon capture, utilization and storage (CCUS): A technology that captures carbon dioxide (CO_2) emissions from large point sources, such as power generation and industrial facilities, and then utilizes or transports the captured CO_2 for storage in deep geological formations

3

Cross-sector findings

The sectors in scope last year have made progress in emissions reduction, but improvement in sector readiness scores has been limited.

3.1 Performance

Current emissions

The eight hard-to-abate sectors in scope collectively contribute to around 40% of direct CO_2 equivalent (CO_2e) emissions. This includes five heavy industry sectors (steel, cement, aluminium, primary chemicals, and oil and gas) and three heavy transport sectors (aviation, shipping and trucking).

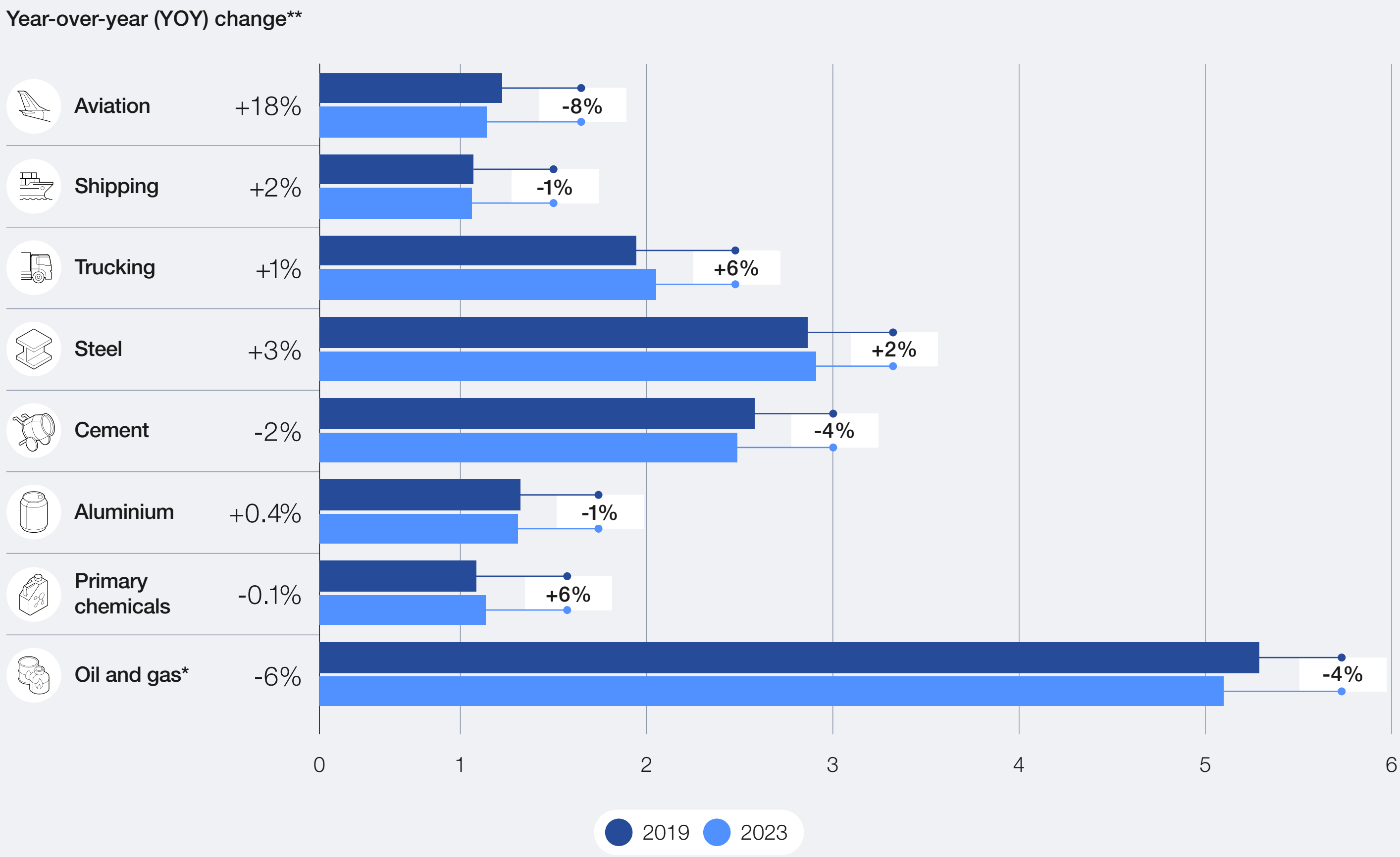
Emissions historical trend

From 2019 to 2023, the total direct CO_2e emissions for the sectors in scope decreased by 1.2%. The decline in emissions was mainly driven by aviation, cement, and oil and gas, and was partially offset by an increase in emissions in trucking and chemicals. Trucking saw the highest increase of 6.2%,[19] while aviation emissions declined the most, with a reduction of 8.4%.[20]

More recently, from 2022 to 2023, the total absolute direct CO_2e emissions for the sectors in scope decreased by 0.9%. This decline in emissions was mainly driven by oil and gas and cement, and was partially offset by the increase in emissions in aviation, steel and shipping. Aviation saw the highest increase of 17.6%,[21] while oil and gas emissions declined the most, with a reduction of 6.4%.[22]

FIGURE 5

2019 vs. 2023 absolute direct CO_2e emissions by sector in gigatonnes (Gt) CO_2e



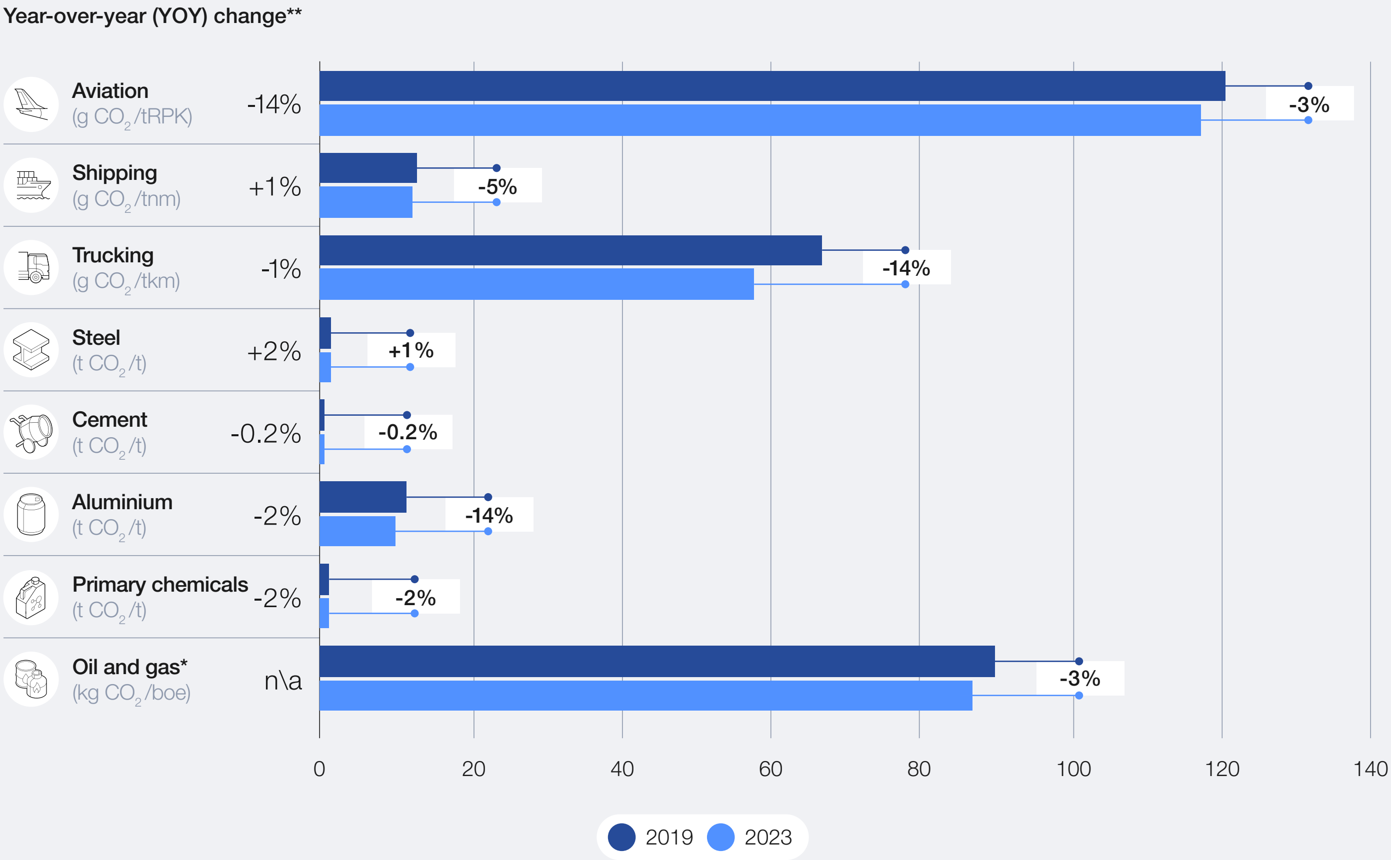
Notes: *Oil and gas data for 2018-2022 since 2023 data is not available; **YOY change represents 2023 vs. 2022 (except for oil and gas, which is 2022 vs. 2021).

Sources: IEA and IAI.

From 2019 to 2023, the sectors in scope saw a 4.1% decline in emissions intensity on average. All sectors (except steel) saw a decrease in emissions intensity in this period, with the highest drop of 13.7%[23] seen in trucking, closely followed by a 13.6%[24] drop in aluminium.

More recently, from 2022 to 2023, the sectors in scope saw a 1.2% decline in emissions intensity on average. All sectors except steel and shipping saw a decrease in emissions intensity in this period, with the highest drop of 14.1%[25] seen in aviation.

FIGURE 6 | 2019 vs. 2023 emissions intensity by sector



Notes: *Oil and gas data for 2018-2022 since 2023 data is not available; **YOY change represents 2023 vs. 2022.

Sources: Accenture analysis based on IEA and IAI.

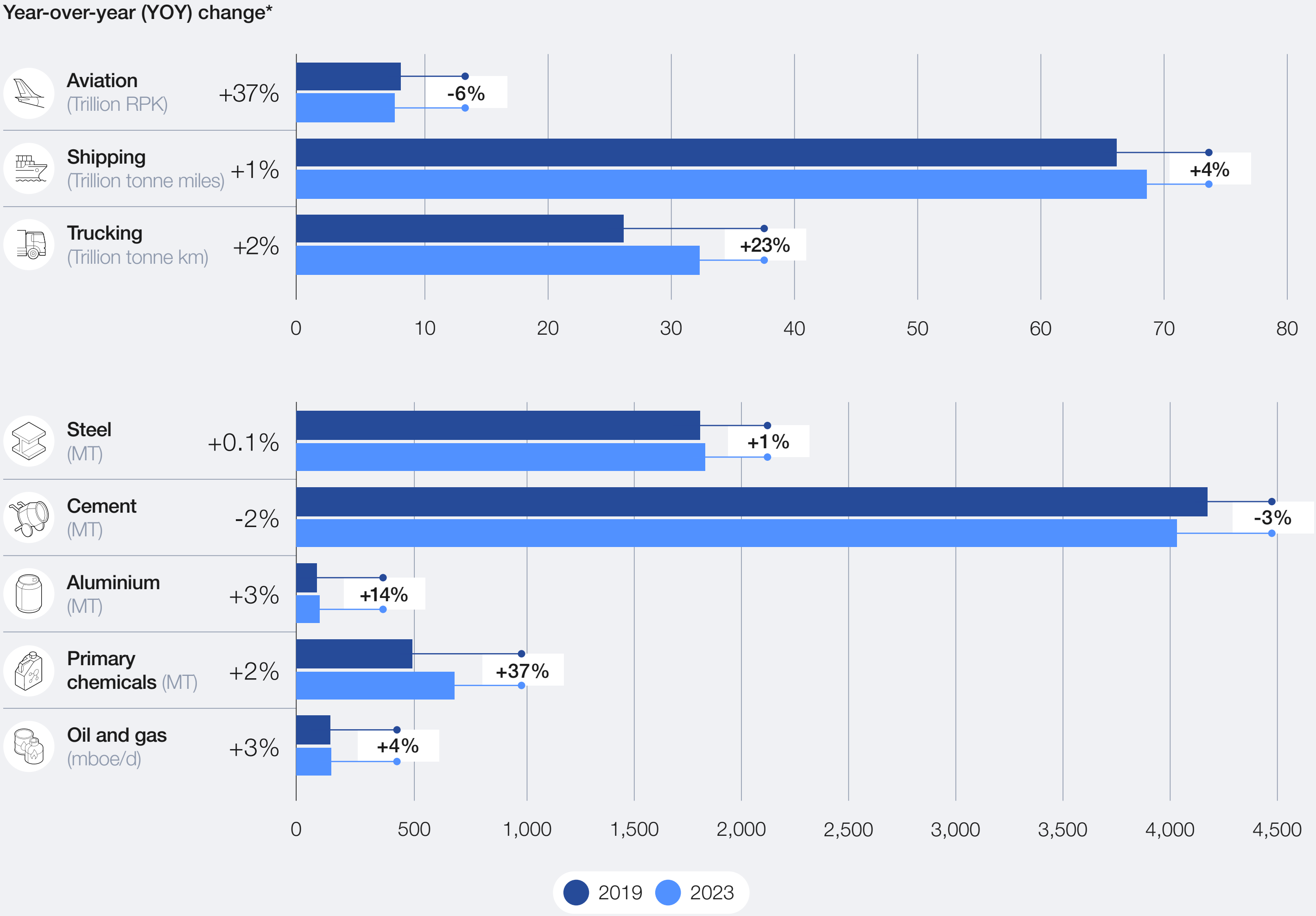
Industry output

The overall demand across the eight sectors in scope saw an average 9.2% increase in the 2019-2023 period. The rise in demand has been driven by the heavy industry sectors, which saw an average 10.6% increase, where all sectors except cement saw an increase. Primary chemicals and aluminium saw the highest growth across the heavy industry sectors. Cement saw a decline, mainly due to decreased production in China, which accounts for around half of global production, due to its real-estate crisis and COVID-19 pandemic-related policies. The heavy transport sectors saw an average 6.9% increase, mainly driven by the sharp rise in trucking demand, followed by shipping, while aviation demand saw a decline.

More recently, from 2022 to 2023, the sectors in scope saw an average 5.8% increase. All sectors except cement saw an increase during this period. The rise in demand was mainly due to aviation, which saw a 36.9%[26] increase recovering from the exceptional COVID-19 pandemic period drop, followed by oil and gas with a 2.9% increase.[27]

FIGURE 7

2019 vs. 2023 demand by sector



Notes: *YOY Change represents 2023 vs. 2022.

Sources: IEA and IAI.

Operational process and energy intensity

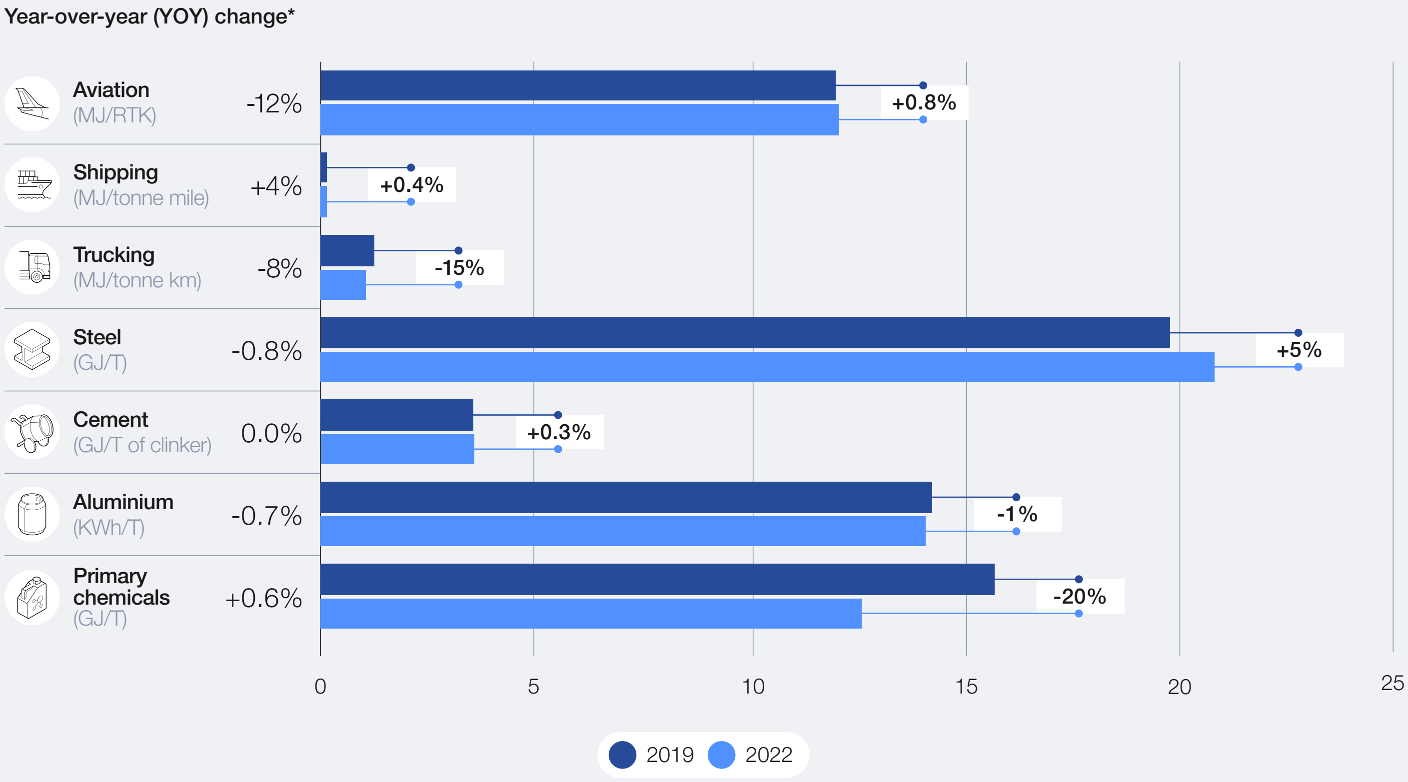
Production processes in heavy industry and operations in heavy transport sectors consume large amounts of energy, which contributes to a significant share of their GHG emissions. Efforts are being made across sectors to reduce the energy intensity and bring down energy-related emissions.

From 2019 to 2022, the sectors in scope saw a 3.9% decline in energy intensity on average. This decline was mainly driven by primary chemicals, trucking and aluminium, and was partially offset by an increase in energy intensity in steel. For primary chemicals, energy intensity has reduced due to a shift towards more efficient production processes. For trucking, increasing electrification and fuel efficiency improvements have contributed to this decline. Recycling and reuse of materials have played a major role in reducing energy intensity for aluminium. For steel, the increase in energy intensity is mainly due to increase in production in China, which predominantly uses primary processes, which are more energy intensive than secondary production processes.

More recently, from 2021 to 2022, the sectors in scope saw a 3.2% decline in energy intensity on average. This decline was mainly driven by aviation and trucking and was partially offset by an increase in energy intensity in shipping. By comparison, the global energy intensity – global energy consumed per unit of gross domestic product (GDP) – improved by 2% in the same period,[28] which shows that the sectors in scope are moving faster than the global economy in terms of improving their energy efficiency.

FIGURE 8

2019 vs. 2022 energy intensity by sector



Notes: *YOY change represents 2022 vs. 2021.

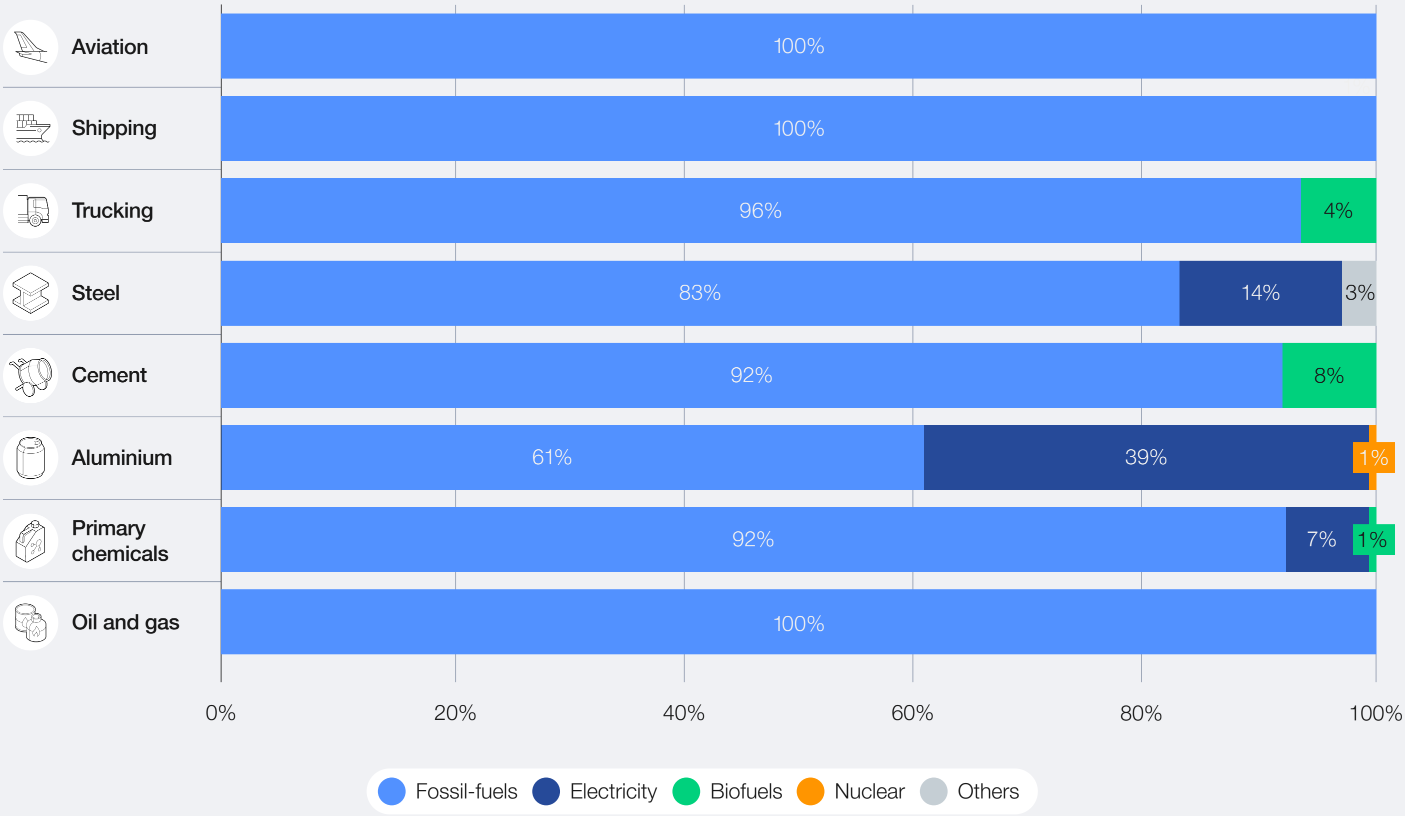
Sources: Accenture analysis based on IEA, IAI and World Steel.

Energy mix

Progress in evolving the energy mix has been relatively slow, as fossil fuels continue to be the primary source of energy, forming a 90% share of the energy mix on average across the sectors in scope. In comparison, fossil fuels form 81% of the total global energy supply,[29] which shows that the sectors in scope are lagging behind in their energy transition journey. Heavy industry sectors like aluminium, steel and primary chemicals have increased the use of electricity in place of coal for generating heat for their production processes. Additionally, the aluminium sector is using nuclear energy for its production. Heavy transport sectors are yet to significantly replace fuel oil with alternative fuels, though slight progress has been made in the trucking sector, where the use of biofuels has increased.

FIGURE 9

2022 energy mix by sector (fossil fuels include coal, oil and gas)



Sources: Accenture analysis based on IEA, IMO and IAI.

Value chain emissions and offsets

Value chain emissions (or Scope 3 emissions) remain high in the heavy industry sectors, largely because their upstream supply chains (e.g. raw materials) are highly carbon intensive or the products they produce rely on petrochemical feedstocks (such as plastics). Carbon offsets that result in additionality continue to be a valuable short-term solution towards emissions reduction, until the technologies and alternative fuels required for industry deep-emission reduction are commercially available. Heavy transport sectors like aviation and shipping have seen growth in the use of offsets, supported by industry-wide carbon offset policies such as voluntary carbon offsetting in aviation, and book and claim in shipping. The oil and gas sector is also one of the largest users of offsets to compensate for emissions that cannot be easily reduced through operational changes.

3.2 Readiness

Readiness assesses the impact of energy transition strategies within the industrial and transport sectors and discusses key cross-sector themes across the five readiness dimensions: technology, infrastructure, demand, capital and policy.

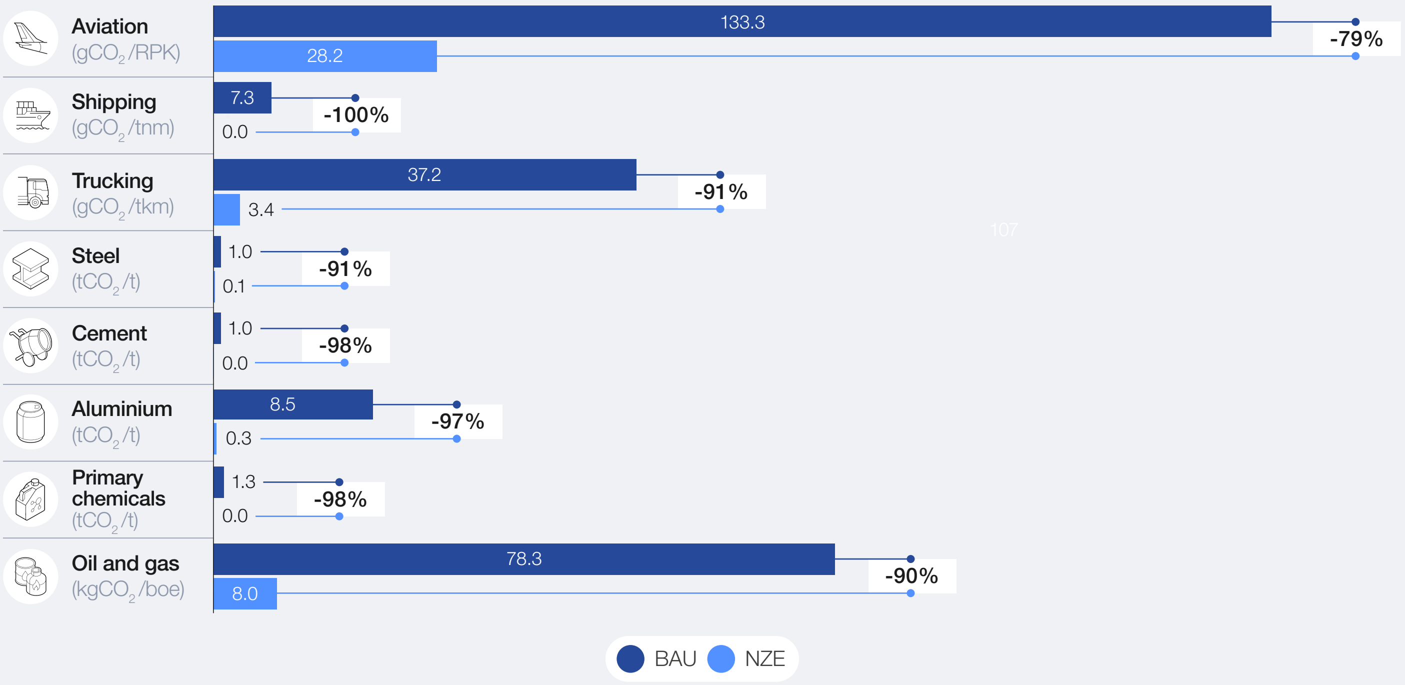
- According to several scenarios cited in this report, the eight sectors are projected to reduce emission intensity by 93% by 2050. Key pathways for industrial sectors are process shifts, electrification and CCUS, while transport sectors focus on energy efficiency, hydrogen-based fuels and biofuels.
- Notable progress has been made in technologies, including battery electric planes, hydrogen and hybrid electric planes, hydrogen bunkering, ammonia-powered engines in shipping, combining blast furnace-basic oxygen furnaces (BF-BOF) with bioenergy with carbon capture and storage (BECCS) in steel, hydrogen and CCUS in cement, and downstream electrification in oil and gas.
- Infrastructure for clean power, clean fuels and CCUS requires significant expansion to meet the 2050 net-zero goal. Fossil fuels still account for about 90% of the energy used across these sectors, and less than 1% of the necessary infrastructure for the target energy mix has been established.
- Demand for low-carbon products is increasing, but the gap between demand commitments and willingness to pay green premiums limits scaling.
- To reach net zero by 2050, $30 trillion in investment is needed, with most sectors operating on limited margins, making it challenging for companies to absorb the additional costs needed to develop clean technologies while maintaining sufficient profits.
- Policies can create an enabling environment for decarbonization and adoption of clean energy across industries to support the global 2050 net zero target.

Target emissions

To achieve net-zero emissions by 2050 and evaluate progress across the eight sectors, this section analyses target emissions for both BAU and net-zero emissions (NZE) scenarios.

By 2050, according to several scenarios cited in this report, industries like shipping, cement and chemicals will need to nearly eliminate their direct emissions, while sectors such as aviation, trucking, and oil and gas will need to reduce direct emissions by 79%, 91% and 91%, respectively. These reductions highlight the significant efforts required across all sectors to achieve net zero, especially in those that face more challenges in reducing emissions.

FIGURE 10 **BAU 2050 and NZE 2050 emission intensity by sector**



Note: Emission intensity figures are not comparable between sectors due to different units for production volumes.

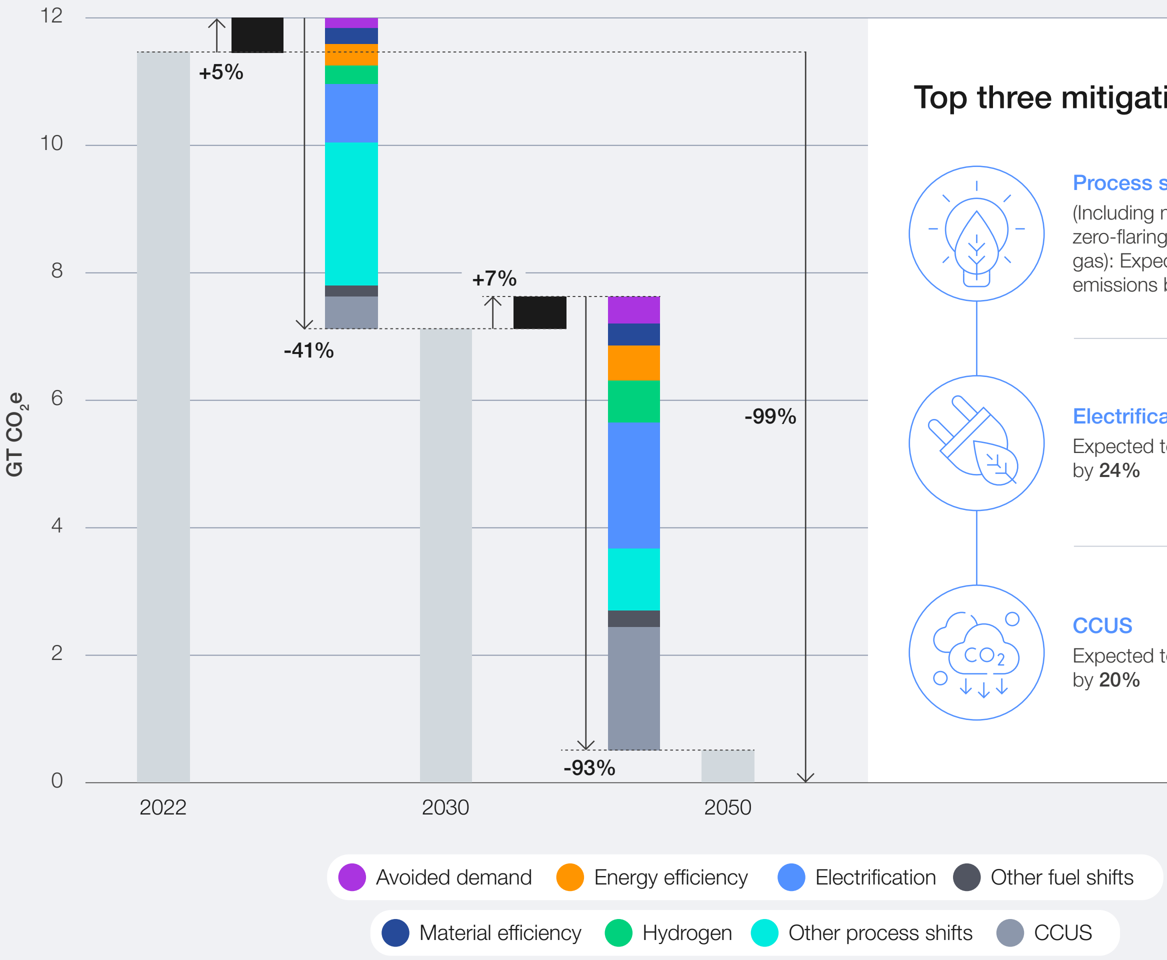
Sources: IATA,[30] IMO,[31] IAI[32] and IEA.[33,34,35]

Decarbonization levers

Absolute direct emissions from industrial sectors (steel, cement, aluminium, primary chemicals, and oil and gas) are projected to decrease by 41% by 2030 and 93% by 2050, largely due to the adoption of various technologies.

FIGURE 11

Contribution to emission reduction by decarbonization lever for industrial sectors and top mitigation methods



Top three mitigation methods

Process shift
(Including methane reduction and zero-flaring technologies in oil and gas): Expected to reduce emissions by **27%**

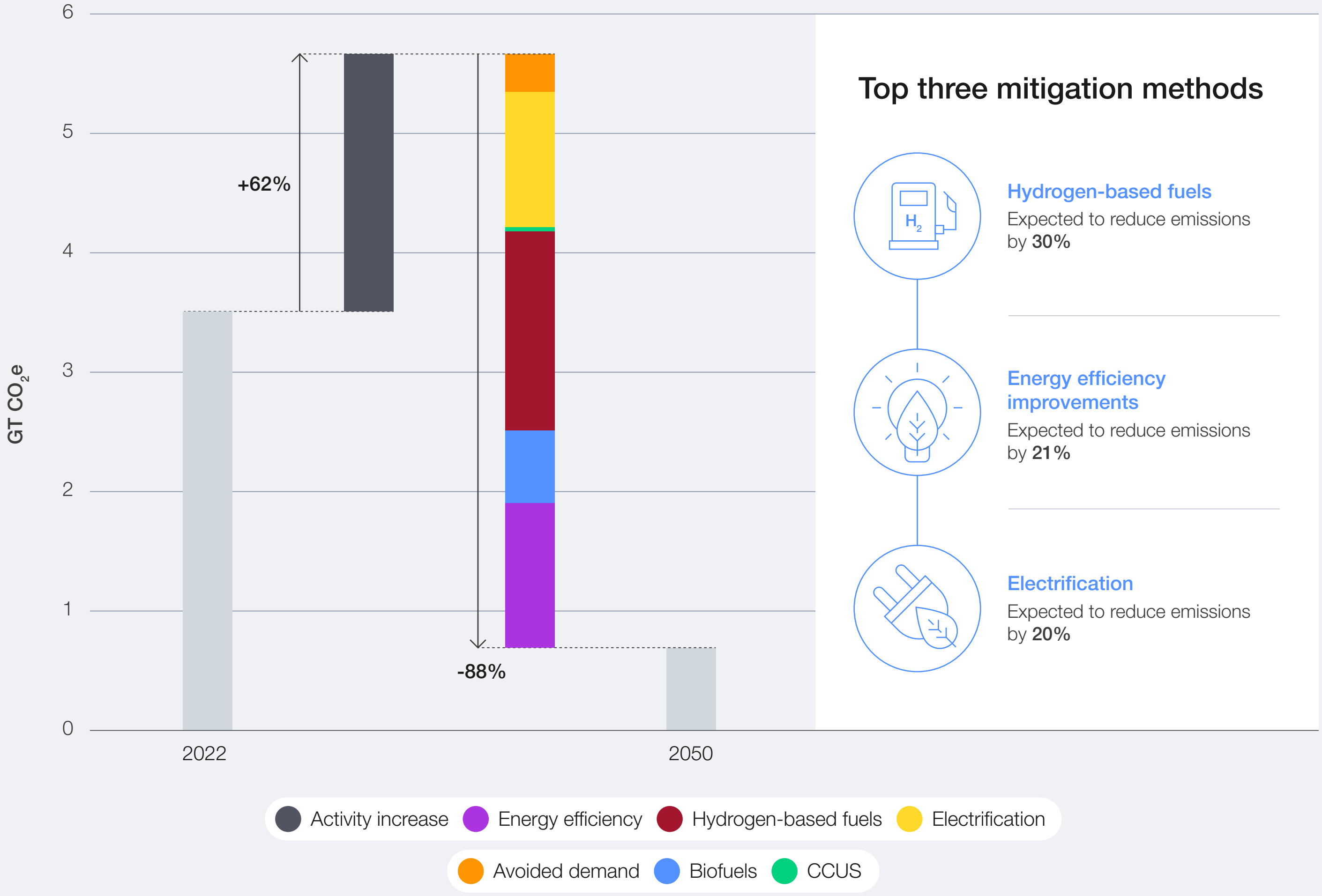
Electrification
Expected to reduce emissions by **24%**

CCUS
Expected to reduce emissions by **20%**

Source: Accenture analysis based on IEA.

For the transport sectors (aviation and shipping), direct emissions will need to decrease by around 84% by 2050. Achieving these reductions across all sectors will require coordinated efforts and significant investment in the necessary technologies and infrastructure.

FIGURE 12 | **Contribution to emission reduction by decarbonization lever for transport sectors and top mitigation methods**



Top three mitigation methods

Hydrogen-based fuels
Expected to reduce emissions by **30%**

Energy efficiency improvements
Expected to reduce emissions by **21%**

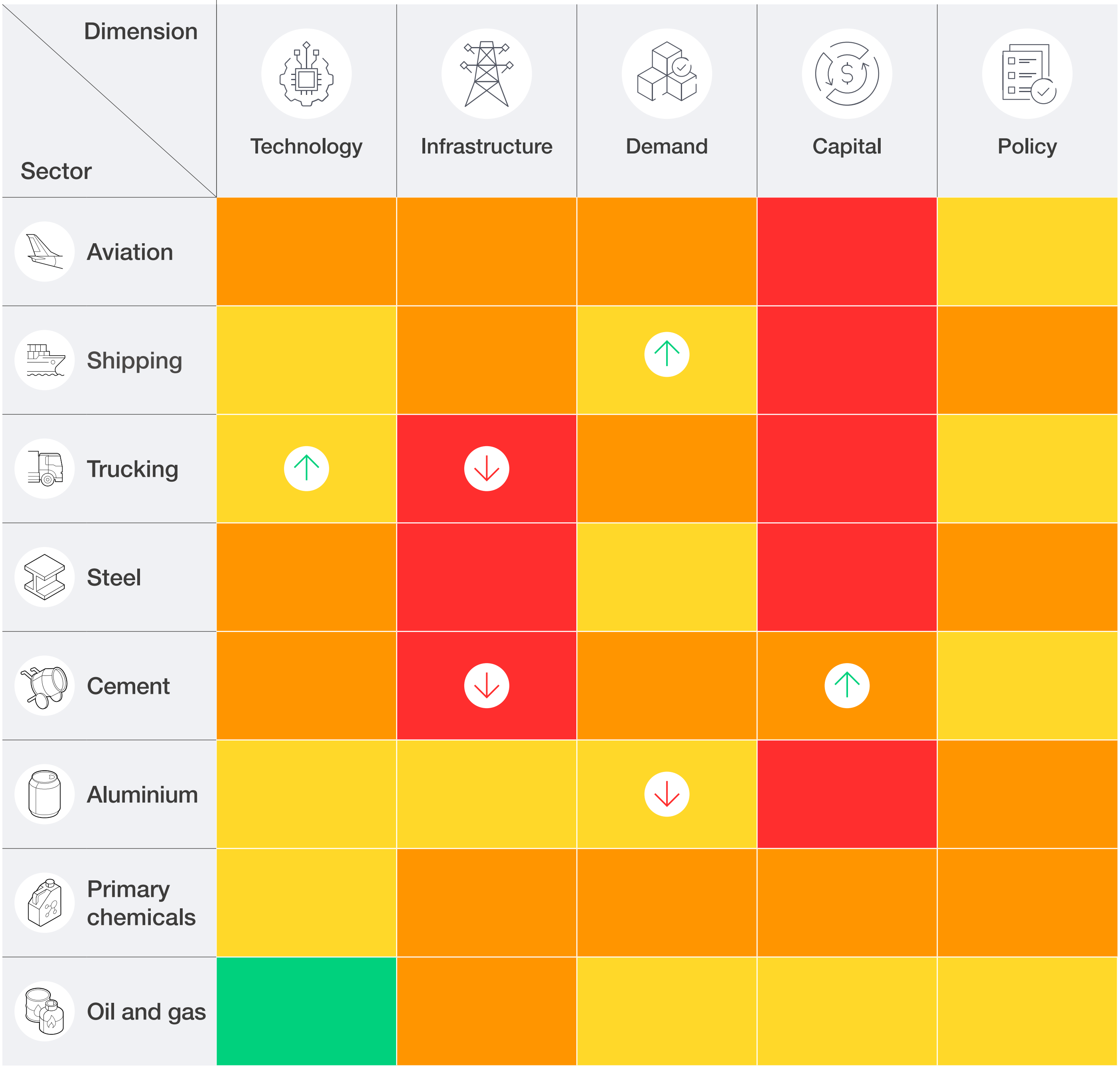
Electrification
Expected to reduce emissions by **20%**

Source: Accenture analysis based on IEA.

Readiness scores

According to the readiness framework, each of the eight sectors in scope has been evaluated and assigned a score across five readiness dimensions: technology, infrastructure, demand, capital and policy. Each dimension was analysed for all sectors and scored based on the relevant sub-dimensions detailed in Section 2. The arrows indicate which dimensions and sectors have undergone changes in scores compared to 2023.

TABLE 1 **2024 readiness scores by sector and dimension**



Dimension / Sector	Technology	Infrastructure	Demand	Capital	Policy
Aviation	🟧	🟧	🟧	🟥	🟨
Shipping	🟨	🟧	🟨 ↑	🟥	🟧
Trucking	🟨 ↑	🟥 ↓	🟧	🟥	🟨
Steel	🟧	🟥	🟨	🟥	🟧
Cement	🟧	🟥 ↓	🟧	🟧 ↑	🟨
Aluminium	🟨	🟨	🟨 ↓	🟥	🟧
Primary chemicals	🟨	🟧	🟧	🟧	🟧
Oil and gas	🟩	🟧	🟨	🟨	🟨

Readiness stages: 🟥 Stage 1 🟧 Stage 2 🟨 Stage 3 🟩 Stage 4 ⬟ Stage 5

↓ Decrease vs. 2023 ↑ Increase vs. 2023

Technology

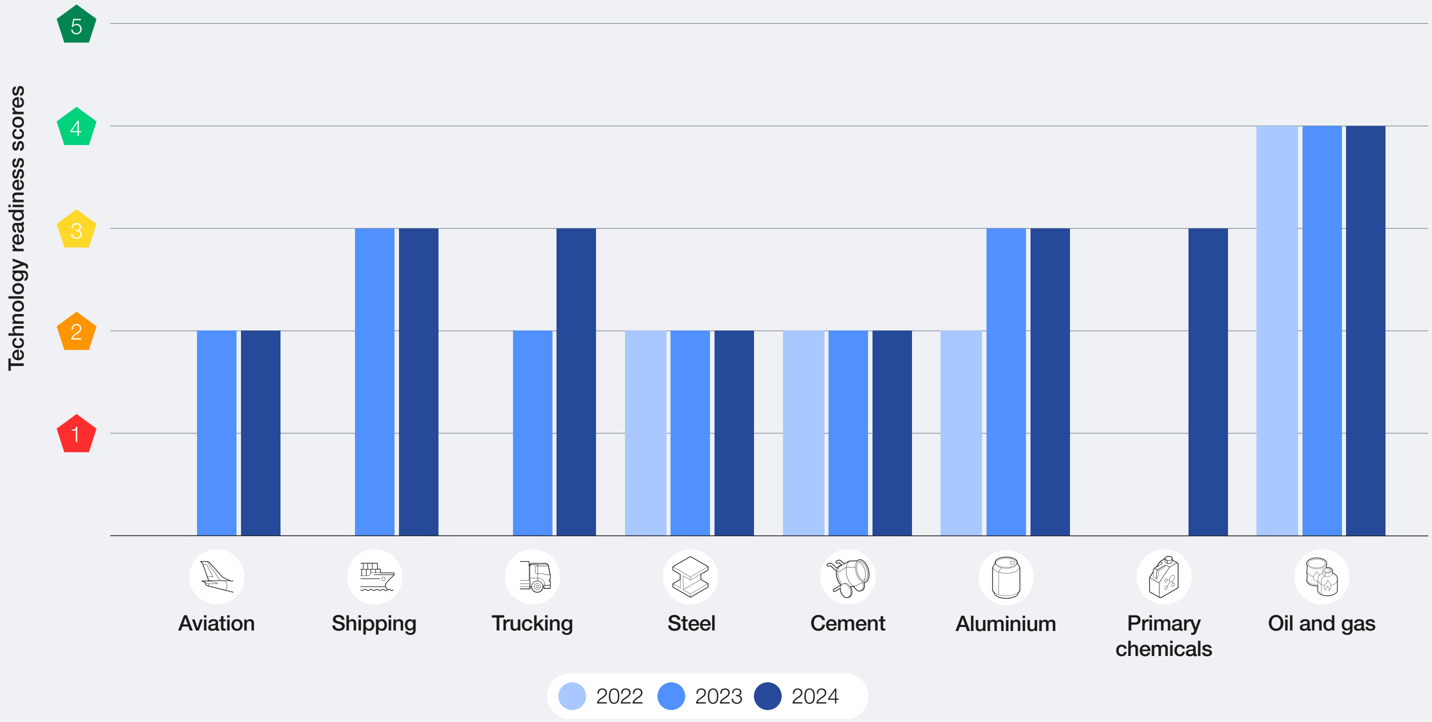
Key readiness question

Are the technologies needed for net-zero emissions commercially available?

Key messages

- Several technologies have seen an increase in their TRL scores compared to last year, including battery electric planes, hydrogen and hybrid electric planes, hydrogen bunkering and ammonia-powered engines in shipping, BF-BOF with BECCS in steel, hydrogen and CCUS in cement, and downstream electrification in oil and gas.
- Generative AI significantly enhances decarbonization efforts by improving asset management and operational processes, optimizing capital allocation, and automating carbon management, thereby helping companies reduce emissions and costs.
- Despite its advantages, the growing energy demands of AI systems may contribute to increased electricity consumption and modest inflation, as investments in AI could outweigh efficiency gains.

FIGURE 13 **Scores for net-zero emissions technologies across sectors (2022-2024)**



Note: Aviation, shipping and trucking sectors were not included in the 2022 report, and the primary chemicals sector has been added this year.

Readiness score movements in the past year:

- **Trucking**: The score increased from 2 to 3 during the past year, mainly driven by the advancement in hydrogen-electric trucks to early adoption phase.

Decarbonizing hard-to-abate sectors requires the development of innovative technologies, many of which are expected to become available between 2025 and 2030. However, several technologies, such as methane and flaring reduction in the oil and gas sector, as well as the decarbonization of electricity for secondary aluminium smelting, are already mature technologies, having a TRL of 10. Meanwhile, methanol-powered engines and ammonia bunkering are nearing widespread implementation with a TRL of 9.

Challenges:

- The development and deployment of new decarbonization technologies often face prolonged timelines

> It is essential to focus on reducing energy consumption by improving the energy efficiency of processes, adopting clean fuels across sectors, switching to low-carbon power sources and scaling CCUS technologies.

- Many industrial sectors in scope require temperatures exceeding 500°C, making electrification challenging. For instance, the steel industry relies on high-temperature heat for 83% of its operations, while cement production requires it for 45%.[36]

- Many companies in these sectors operate with limited research and development (R&D) budgets due to relatively low profitability, limiting their ability to invest in innovative technologies for decarbonization.

- The increasing doubts about the feasibility of green hydrogen and CCUS are causing targets and projects to be cancelled.

Way forward:

Several sectors are expected to rely heavily on technologies that are not currently commercially available, such as CCUS and clean hydrogen. For example, it is estimated that CCUS could reduce emissions in the cement sector by 60% by 2050.[37] As a result, it is essential to focus on reducing energy consumption by improving the energy efficiency of processes, adopting clean fuels across sectors, switching to low-carbon power sources and scaling CCUS technologies.

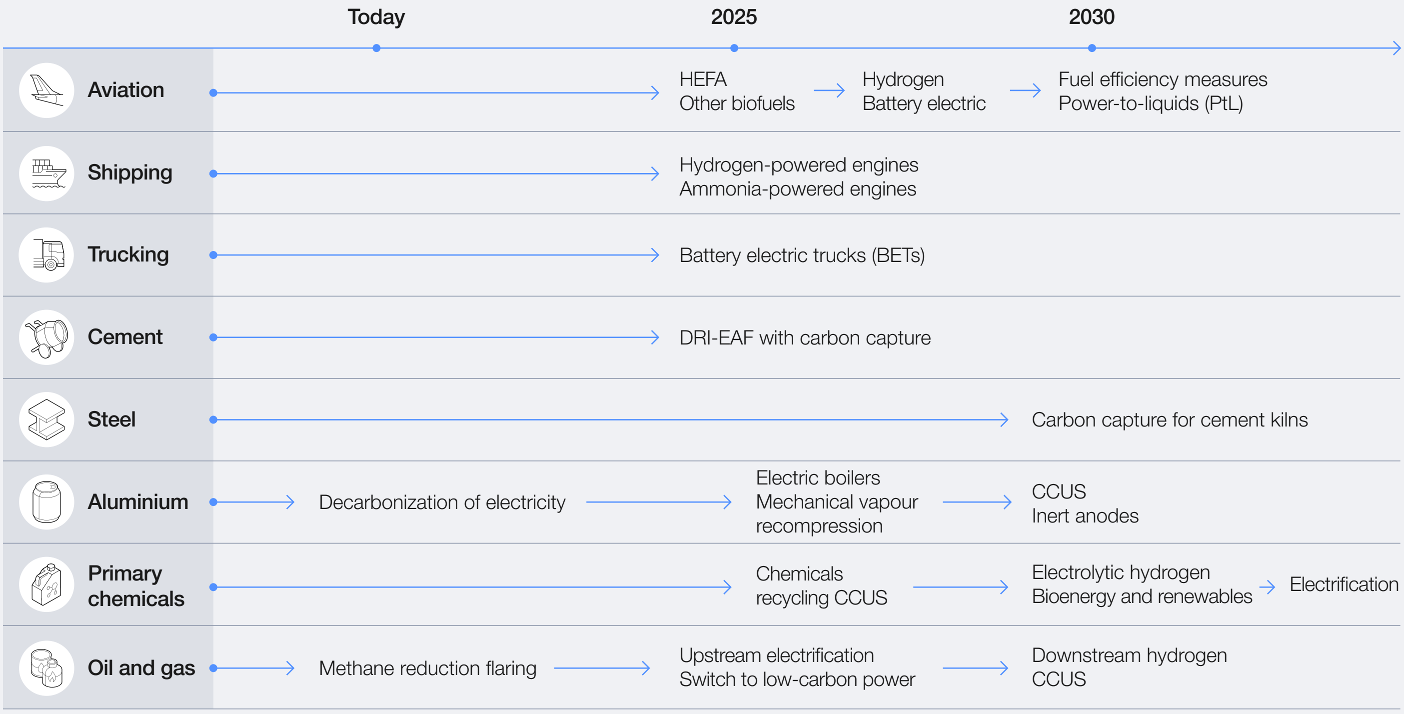
- **Improving energy efficiency of processes**: Enhancing energy efficiency is a cost-effective strategy to lower energy demand and CO_2e emissions from fossil fuels. IRENA's 1.5°C scenario suggests that improving efficiency could provide about 20% of the necessary CO_2e reductions in shipping by 2050. Measures like high-efficiency propellers and waste heat recovery can significantly cut fuel consumption and emissions.[38]

- **Adopting clean fuels across sectors**: Transitioning to clean fuels, such as hydrogen and biofuels, is crucial for decarbonizing industries and transport. Clean hydrogen supply is expected to increase thirtyfold to 16.4 million tonnes (MT) by 2030 due to supportive policies. Regions with abundant renewable resources can produce green hydrogen for €3 to €5 per kilogram (kg).[39] In the IEA's 2°C Scenario, biofuels are projected to rise tenfold in the transport sector by 2060, reaching 30% of transport energy.[40]

- **Switching to low-carbon power sources**: Renewable energy sources will provide 85% of global electricity production in 2050, led by solar photovoltaic (PV) and onshore wind.[41] Various sectors will need to electrify operations, although applications like electric arc furnaces (EAFs) in steelmaking may face challenges.[42] In 2023, battery storage emerged as the fastest-growing energy technology, increasing over twofold year-on-year to add 42 gigawatts (GW) globally. Lithium-ion batteries experienced a remarkable price drop of 14% from 2022 to 2023,[43] driven by advancements in manufacturing and economies of scale.

- **Scaling of CCUS technology**: According to the IEA, CCUS could contribute over 25% of emissions reductions in iron and steel by 2050. CCUS is also emerging as a key solution for chemicals manufacturing.[44]

FIGURE 14 Expected commercialization date of major technologies by sector



Source: Accenture analysis based on IEA ETP Clean Energy Technology Guide and MPP

Digital technologies offer significant advantages to help companies in their decarbonization efforts, specifically in operational efficiency, capital and carbon management.

Digital technologies offer significant advantages to help companies in their decarbonization efforts, specifically in operational efficiency, capital and carbon management. Three major value levers have emerged for data and AI applications.

Operational efficiency: Generative AI enhances asset management and operational processes. By using predictive asset management, companies can:

- **Optimize production systems**: AI helps streamline the entire production process, balancing output, margins and emissions. This boosts efficiency while minimizing energy use and emissions, directly supporting decarbonization.
- **Improve asset energy efficiency**: AI enables better equipment monitoring, ensuring that assets run at peak energy efficiency, reducing both emissions and energy costs.

Capital projects: Generative AI optimizes capital allocation and project management by:

- **Modelling energy transition scenarios**: AI helps companies simulate various energy transition scenarios, enabling informed decisions on capital allocation for low-carbon and carbon-neutral projects.
- **Enhancing project design**: AI can generate and refine capital project designs, reducing time-to-market and minimizing capital expenditure (CapEx) overruns.
- **Improving CCS**: AI has the potential to lower CCS costs by up to 30%, according to the IEA.[45] It enhances site selection for carbon storage through geological data analysis and optimizes CCS efficiency by monitoring the capture process.

Carbon management: Generative AI supports carbon management and sustainability initiatives by:

- **Automating emissions management**: AI tracks real-time energy consumption and optimizes energy efficiency at the equipment and process levels, reducing GHG emissions and lowering carbon footprints.
- **Managing carbon credits**: AI automates the purchase and use of carbon credits, ensuring compliance with emissions regulations while maximizing green premium opportunities.
- **Decarbonizing the supply chain**: AI continuously assesses suppliers' carbon performance, helping companies choose low-carbon suppliers and reduce Scope 2 and 3 emissions across the supply chain.
- **Forecasting energy and emissions**: AI predicts energy demand and deviations, allowing companies to take preventive measures to avoid higher emissions and align operations with sustainability goals.

Despite its advantages, generative AI presents several challenges. The continuous operation of AI systems results in a constant peak demand for electricity from data centres, with projections indicating that their energy consumption could surpass 9% of total US electricity usage by 2030.[46]

Infrastructure

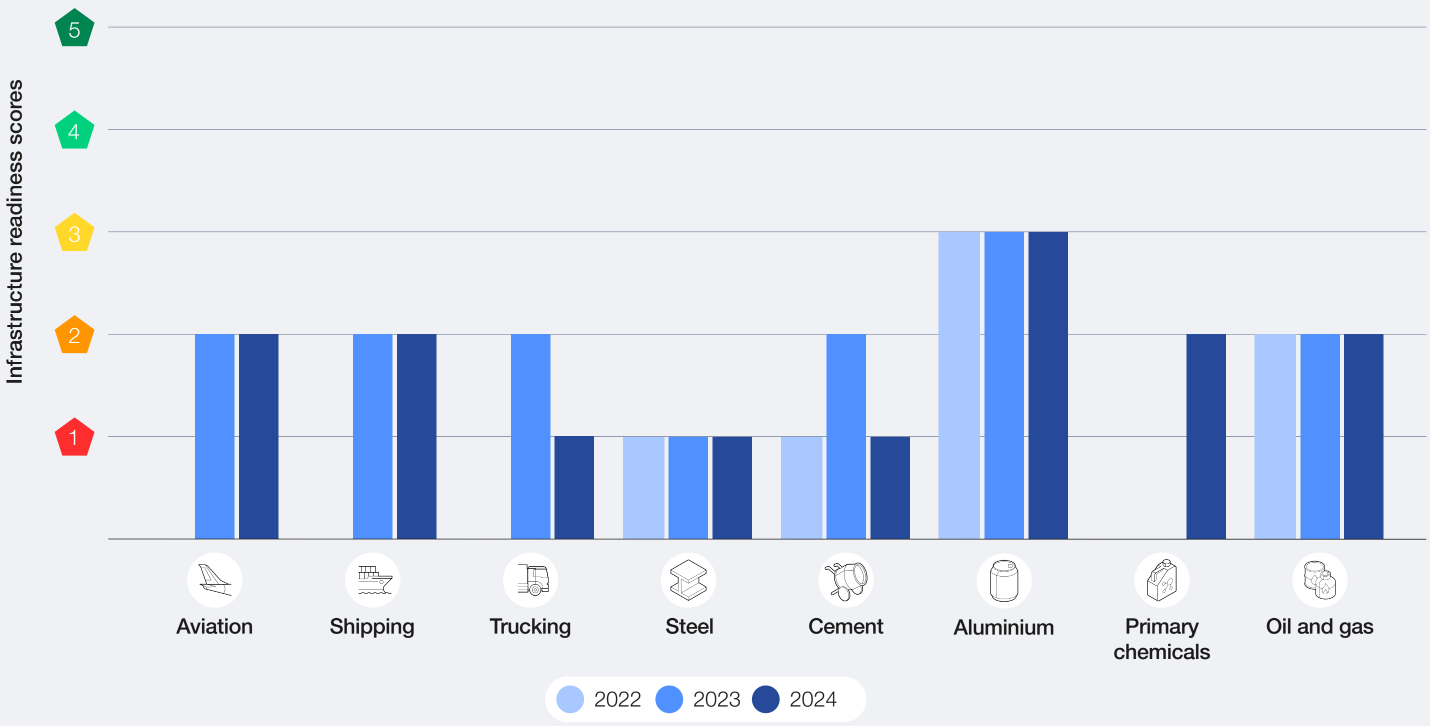
Key readiness question

Is the infrastructure to enable the use of low-emission technologies available?

Key messages

- The cumulative infrastructure capacity required by 2050 across the sectors in scope in their net-zero scenario is 4.8 terawatts (TW) of clean power, 297 million tonnes per annum (MTPA) of clean hydrogen and 4.2 gigatonnes per annum (GTPA) of CCUS.[47]
- Compared to IEA estimates for the global target capacity in 2050 in their Net Zero Emissions by 2050 Scenario, the requirement from these sectors contributes to 42% of the global target for clean power, 69% for clean hydrogen and 55% for CCUS.[48]

FIGURE 15 **Scores for low-emission technology infrastructure across sectors (2022-2024)**



Note: Aviation, shipping and trucking sectors were not included in the 2022 report, and the primary chemicals sector has been added this year.

Readiness score movements in the past year:

- **Cement**: The score decreased from 2 to 1 during the past year, mainly due to limited advancements in expanding clean power and CCUS capacity, and the significant capacity increase required to meet the 2050 infrastructure requirements as compared to the other sectors in scope.
- **Trucking**: The score decreased from 2 to 1 during the past year, mainly due to lack of substantial increase in the use of clean hydrogen and clean power to meet energy requirements, and the significant capacity increase required to meet the 2050 infrastructure requirements as compared to the other sectors in scope.

To achieve the 2050 net-zero target for the hard-to-abate sectors in scope, clean power, clean hydrogen and fossil fuels abated by CCUS will need to form over 90% of the final energy mix. Thus, it is important to look at the availability of infrastructure to support this energy requirement across each of the sectors in scope.

Currently, fossil fuels contribute to approximately 90% of the energy used across these sectors, and less than 1% of the required infrastructure to meet the final energy mix targets is in place. In comparison, fossil fuels form 81% of the total global energy supply,[49] which shows that the sectors in scope are lagging behind in their energy transition journey.

The cumulative infrastructure capacity required across the sectors in scope is 4.7 TW clean power, 297 MTPA clean hydrogen and 4.2 GTPA CO_2 utilization. Compared to IEA estimates for the global target capacity in 2050, the requirement from these sectors contributes to 42% of the global target for clean power, 69% for clean hydrogen and 55% for CCUS.[50]

FIGURE 16 **2050 NZE infrastructure capacity required by sector**

	Aviation	Shipping	Trucking	Steel	Cement	Aluminium	Primary chemicals	Oil and gas	Total	Global target*	%
Clean power generation (TW)	~0	~0	0.7	0.8	0.6	0.2	2.2	0.2	**4.7**	**11.2**	42%
Clean hydrogen production (MTPA)	44	72	50	48	6	10	60	8	**297**	**430**	69%
Carbon capture, utilization and storage (GTPA)	0.7	0.13	0	0.85	1.4	0.086	0.64	0.39	**4.2**	**7.6**	55%

Note: *Global targets as per IEA[51]

Source: Accenture analysis based on data from IATA, IMO, MPP, IEA and CGI.

> In aggregate, by 2050, clean power is expected to be an average 22% of the final energy mix for the heavy transport sectors and 33% for the heavy industry sectors including oil and gas.

Clean power:

Clean power derived from sources like solar, wind, hydropower and nuclear is expected to be the primary means for reaching global net-zero ambitions. Regarding decarbonizing hard-to-abate heavy industries and transport, clean power has direct and indirect applications, including the electrification of industrial processes and the production of clean fuels like green hydrogen. In aggregate, by 2050, clean power is expected to be an average 22% of the final energy mix across the sectors in scope. However, the application and impact of clean power on these sectors vary.

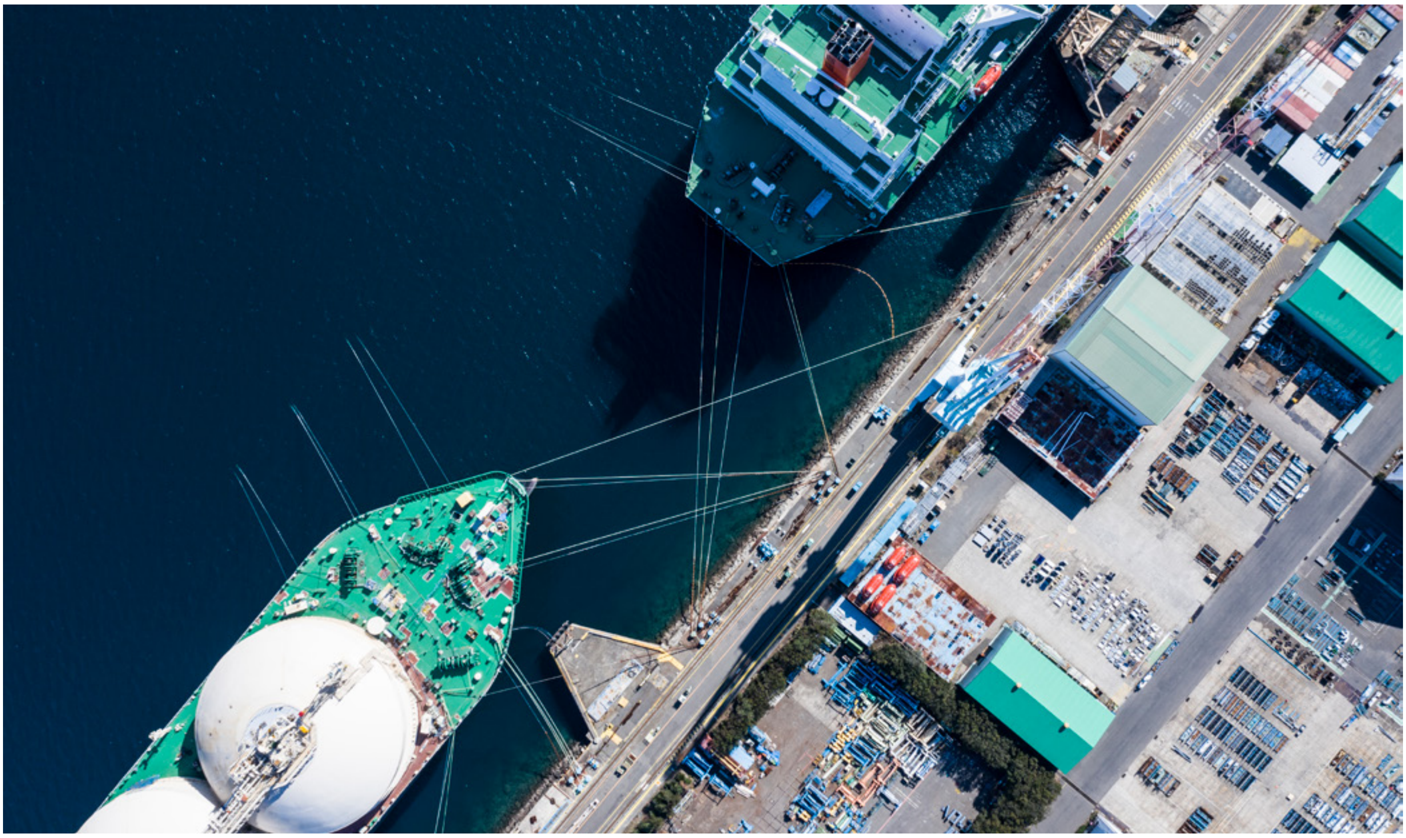
Clean power's direct application in decarbonizing is especially critical for sectors like steel, aluminium and trucking, where clean electricity is better positioned to replace fossil fuels in specific processes. For instance, aluminium production has already made strides by using renewable electricity, which currently accounts for 39%[52] of its smelting energy mix for primary aluminium. Steel production can benefit from electrifying operations like steel rolling, and the trucking industry can adopt battery-electric trucks (BETs), which run directly on clean electricity, reducing emissions in short- and medium-haul transport.

Indirectly, clean power is necessary for the production of green hydrogen and other clean fuels, which are expected to account for 40% of emissions reduction in heavy transport sectors, and 12% in heavy industry sectors (including oil and gas) by 2050. For industries like steel and chemicals, which require high temperatures and use fossil fuels as feedstock, green hydrogen offers a solution. Green hydrogen, produced via electrolysis powered by renewable energy, can help replace coal in steelmaking or serve as a clean feedstock in chemical production, such as for ammonia and methanol. In transport, green hydrogen and synthetic fuels produced from renewable electricity will be vital in decarbonizing long-haul trucking, aviation and shipping, where direct electrification is challenging due to limited availability of electrification technologies and nature of their energy needs.

Clean fuels:

The transition to clean fuels and feedstocks is essential for achieving emissions reductions in heavy industrial and transport sectors by 2050. The key types of clean fuels used in these sectors include:

- **Clean hydrogen**: Hydrogen (particularly green hydrogen) produced using renewable energy sources is essential for various industrial applications. Blue hydrogen is also expected to play a role.
- **Advanced biofuels**: Derived from feedstocks like agricultural residues and waste oils, and sustainable energy crops that do not compete with food need. Sustainable aviation fuel (SAF), in particular, is crucial for reducing aviation emissions.



❝ The analysis shows that an average 61% of energy needed in 2050 climate scenarios for heavy transport sectors (excluding trucking), and 21% for heavy industry will be sourced from clean fuels.

- **Ammonia**: Used as a zero-emission fuel (ZEF) in the shipping industry, ammonia can be produced from green hydrogen or from natural gas coupled with CCS.

- **Methanol**: Another clean fuel for shipping, methanol can be produced from renewable sources and offers a lower carbon footprint.

- **Waste**: Renewable municipal waste, sewage and landfill gas, and residue waste are important in some applications such as in kilns in the cement industry.

The analysis shows that an average 61% of energy needed in 2050 climate scenarios for heavy transport sectors, and 21% for heavy industry sectors will be sourced from clean fuels.

The sectors in scope often require high energy density fuels (such as in shipping and aviation), high temperature process heat (steel, cement) or feedstock to produce secondary products (chemicals). While some of these processes and fuels can be replaced by other energy carriers (such as electricity), many cannot, and there will be strong competition for those clean electrons for uses in other sectors. Thus, it is imperative that clean fuels develop alongside electrification.

In the shipping industry, clean fuels such as ammonia and methanol are essential to meet the International Maritime Organization's (IMO) targets for achieving net-zero emissions by or around 2050. Ammonia and methanol offer an alternative to traditional marine fuels, significantly lowering the carbon footprint of maritime transport when they are produced from low- to zero-carbon energy sources (such as biomass or clean electricity). In the aviation sector, SAF is expected to play a crucial role. SAF, derived from renewable feedstocks like agricultural residues and waste oils, can reduce lifecycle emissions by up to 80% compared to conventional jet fuel. The analysis shows that 400 MTPA of SAF alone is needed in the sector by 2050. Meanwhile, the trucking industry is exploring the use of hydrogen and biofuels to replace diesel, thereby reducing emissions and improving air quality; however, the sector can be more easily electrified for certain transport cases.

In the heavy industrial sectors such as steel, chemicals and cement, clean fuels are equally critical. The steel industry is transitioning to green hydrogen to replace coal in the production process, and green hydrogen is expected to contribute to 21% of steel emissions reduction by 2050.[53] The chemicals industry receives 93% of its energy from fuels but will also need to shift towards green hydrogen, ammonia and methanol to reduce emissions. In the cement industry, the use of alternative fuels like biomass and waste-derived fuels is being explored to lower the carbon footprint. These transitions are not only essential for meeting environmental targets but also for ensuring the long-term viability and competitiveness of these industries in a low-carbon economy.

Carbon capture utilization and storage (CCUS):

Hard-to-abate sectors such as cement, steel, chemicals and aluminium are characterized by emission-intensive processes that are challenging to decarbonize using methods such as clean power and process changes. To address this, a multi-faceted approach involving CCUS and

❝ CCUS is expected to account for 18% of global emissions reduction in the heavy industry sectors, and 1% in the heavy transport sectors in scope by 2050.

carbon offsets is essential. CCUS, in particular, is expected to account for 18% of global emissions reduction in the heavy industry sectors, and 1% in the heavy transport sectors in scope by 2050. Moreover, CCUS facilitates the production of blue hydrogen, which can significantly reduce emissions by providing a low-carbon fuel alternative for heavy industry and transport.

In 2024, global operational CCUS capacity reached over 50 MT of CO_2 per year, with over 110 commercial-scale projects potentially reaching final investment decision (FID).[54] If these projects proceed as planned, CCUS investment could rise almost tenfold to $26 billion by 2025, boosting global CO_2 capture capacity to 430 MT per year and storage to 620 MT per year by 2030.[55] However, despite progress, current CCUS deployment lags behind net-zero needs, with only 20% of the announced capture capacity and 15% of the storage capacity for 2030 in place or reaching FID.[56] Industrial sectors are even further behind, representing less than 10% of the announced global capacity, far below the 25% of CO_2 they need to capture by 2030 under the IEA Net Zero Scenario.[57] High costs, technological challenges, insufficient CO_2 transport and storage infrastructure, and regulatory uncertainties remain major barriers to scaling CCUS in time to meet emission reduction targets.

Government investments, such as the $12 billion from the US Infrastructure Investment and Jobs Act and various European initiatives, have significantly supported the expansion of CO_2 pipelines and storage infrastructure, which must be available promptly to meet growing CCUS demand. ENI has successfully secured UK government funding to support its Hynet Project on creation of a CCUS infrastructure network by 2030.[58] Equinor, Shell and Total have invested in the Northern Lights project, the world's first cross-border CO_2 transport and storage facility, which is now ready for use.[59]

Challenges:

- **Clean power**: Policy uncertainties and delayed policy responses to the new macroeconomic environment, insufficient investment in grid infrastructure preventing faster expansion of renewables, cumbersome administrative barriers and permitting procedures and social acceptance issues, and insufficient financing in emerging and developing economies
- **Clean fuels**: Limited international collaboration in terms of supportive policies to increase production of hydrogen-based fuels and biofuels, and needed infrastructure, combined with a lack of clear demand signals in terms of demand projections across sectors and pricing that is competitive with fossil fuels. Carbon standards and accounting are also insufficient to accurately measure and assess fuel options, and enable comparability and cross-border trade.
- **CCUS**: High costs related to technology and infrastructure, insufficient regulatory frameworks and incentives to support large-scale adoption, and the need for enhanced public and industry trust in its effectiveness and safety

Way forward:

While clean power is increasingly available and crucial for decarbonizing hard-to-abate sectors, much greater investment is needed to achieve net-zero targets. Approximately 50% of the total investment will come from the broader ecosystem, with a notable portion allocated to energy infrastructure. By 2050, clean power is projected to account for 26%,[60] 100%[61] and 60%[62] of the steel, aluminium and trucking energy mix by 2050, respectively. On the other hand, the relative role of renewables and electrification in the cement and chemicals sectors is more limited, with clean power expected to be only 8%[63] of the 2050 power mix for cement, and approximately 0% for chemicals.[64]

To reach net-zero targets, a wider array of solutions, including clean fuels, will be essential. The IEA and IRENA indicate that about half of final energy demand in net-zero scenarios will come from non-electron sources. These include renewable molecules such as liquid, gaseous and solid clean fuels, which are especially important for sectors with non-energy uses, such as feedstocks.

CCUS will also be a key component, with new players like gas infrastructure developers, chemical companies and capture-as-a-service providers entering the market. This increased competition helps reduce costs, particularly through the creation of CCUS hubs, where infrastructure is shared by multiple emitters. Despite the growth in CCUS, sectors like aviation will still require carbon offsets for remaining emissions, necessitating collaboration among governments, businesses and stakeholders to address challenges like verification and transparency.

Industries and co-located companies from different industries can benefit from collaborating with each other through shared infrastructure models (such as infrastructure hubs and industrial clusters) to improve access to the required clean energy, by capitalizing on economies of scale.

Demand

Key readiness question

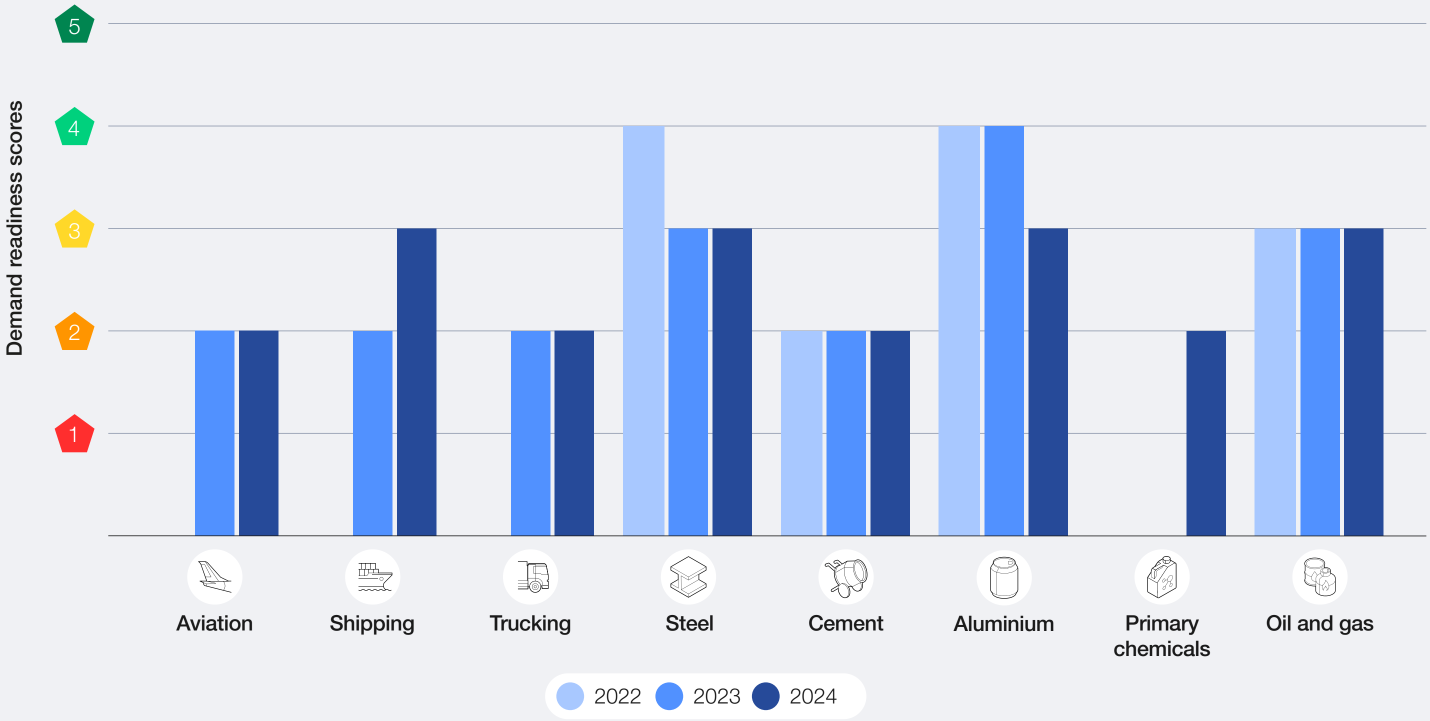
Can the market support low-emission products given the green premiums and 2030 project progress?

Key messages

- Demand signals for low-carbon products are increasing, but the gap between demand commitments and willingness to pay green premiums puts clean technology investments at risk.
- Key barriers for scaling demand include unclear standards for carbon thresholds, uncertainty in measurements, low willingness to pay and limited previous experiences and typically unbinding offtake agreements at scale for low-carbon products.
- Collaboration between sectors and policy-makers is needed to establish clear standards, improve reliability of carbon measurements and address high costs to encourage the adoption of low-carbon products.

FIGURE 17

Demand scores for low-emission products across sectors (2022-2024)



Note: Aviation, shipping and trucking sectors were not included in the 2022 report, and the primary chemicals sector has been added this year.

Sectors with readiness score movements in the past year:

- **Shipping**: The score increased from 2 to 3 compared to last year as MPP's announced projects exceeded the 2030 target.
- **Aluminium**: The score decreased from 4 to 3 compared to last year due to limited progress towards the MPP's announced projects of 70 low-carbon refineries and smelters by 2030.

Demand signals for low-carbon products are gradually growing and are starting to be tested for scale and associated green premium potential. The apparent disconnect between demand commitments and readiness to pay a green premium is weakening the business case for low-carbon producers being willing to invest in clean technologies.

Challenges

Currently the main barriers for scaling demand include:

- **Standards and definitions**: Lack of clear and unified industry-wide standardized thresholds for low-carbon and near-zero emission products impedes product comparison. Carbon footprint methodologies and emissions tracking standards have been developed in most sectors but are not being implemented consistently to reach widespread adoption.

> Hard-to-abate sectors face a gridlock in decarbonization due to systemic inability to effectively distribute the costs along the value chain.

- **Auditability**: There is a lack of clear verification for carbon footprint calculations, which affects trust in these methods and slows down demand for low-carbon products.
- **Willingness to pay premium**: The layered costs of using multiple low-carbon materials in products can add up significantly, especially in business-to-business (B2B) markets, making adoption costly and limiting demand.
- **Offtake agreements**: The critical mass needed for offtake agreements in most sectors has not been established yet. Additionally, the non-binding nature of most offtake agreements limits pace.

Way forward:

Hard-to-abate sectors face a gridlock in decarbonization due to systemic inability to effectively distribute the costs along the value chain. Breaking through would require unparalleled collaboration and realization that the costs of decarbonization need to be shared among the industry players and society.

Sectors have started addressing barriers to standardizing carbon content measurement through various initiatives. For example, IATA's TrackZero provides a comprehensive methodology for aviation. The Industrial Transition Accelerator (ITA) is collaborating with standard-setters to promote standards in key sectors like aviation fuel, ammonia, aluminium, cement and steel.[65] Companies must enhance transparency in carbon accounting and collaborate across value chains with policy-makers and industry bodies to align sector-wide standards, methodologies and definitions, ensuring consistent implementation for decarbonization progress.

The First Movers Coalition (FMC), accounting for over 100 corporate members, has established ambitious purchasing commitments for low-carbon and near-zero industrial products across several sectors. For example, regarding steel, FMC members have set a target for at least 10% of their steel purchases to be on near-zero emissions steel by 2030. The coalition helps in resolving the "first mover disadvantage" challenge by establishing a strong demand signal to encourage suppliers and investors to break the gridlock.

The sectors must reduce the currently high B2B green premiums to align consumer expectations with willingness to pay. For example, for the shipping sector, biofuels and hydrogen-based synthetic fuels are 1.5 to 4 times and 2 to 6 times the cost of conventional bunkering fuel, respectively. Having clear price points on consumer willingness to pay for different products would incentivize suppliers to target cost reduction innovation and build economies of scale.

TABLE 2 **Key industry standards, green premium and the percentage of low-emission products**

Sector	Examples of notable industry standards	Percentage of low-emission products	B2B green premium*	B2C green premium*
Aviation	– **IATA TrackZero (2021)**: Framework for companies to report on their individual progress on performance metrics such as fuel efficiency, carbon intensity and SAF share – **Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (2019)**: Framework for airlines to report their emissions annually	**Less than 1%** of current aviation energy consumption comes from low-emissions sources.	300-400% per litre of fuel	3-12% per ticket
Shipping	– **IMO Data Collection System (2019)**: Framework for ships to report fuel oil consumption to guide future IMO measures for reducing GHG emissions – **Sea Cargo Charter (2019)**: A framework for assessing and disclosing the climate alignment of ship chartering activities worldwide	– **5%** current LNG usage in total fuel consumption – **Less than 1%** of low-emission fuels, such as methanol, in total fuel usage	30-80% per shipment	1-2% per product unit
Trucking	**Global Logistics Emissions Council Framework (2016)**: Establishes comprehensive global standardized frameworks to measure GHG emissions from private and public sector operations, including the trucking sector	**Less than 1%** of the battery and fuel cell electric trucks needed by 2050 are available.	33-133% per vehicle	1-3% per item

TABLE 2 **Key industry standards, green premium and the percentage of low-emission products (continued)**

Sector	Examples of notable industry standards	Percentage of low-emission products	B2B green premium*	B2C green premium*
Steel	– **The worldsteel Climate Action Data Collection (2008)**: Framework for companies to report CO_2 emissions, enabling steel plants to benchmark against average and best performances to identify improvement areas – **Climate Group Steelzero Reporting Framework (2020)**: Organizations are required to report to the Climate Group annually on their progress towards their SteelZero commitment	**Less than 10%** of steel was produced using low-emission processes, with nearly all progress occurring in low-emission secondary production like recycling	40-70% per ton of steel	0.5% per car
Cement	**Global Cement and Concrete Association (GCCA) sustainability guidelines (2018)**: Framework for companies to report on specific KPIs such as CO_2 emissions, fuels and raw materials used in manufacturing	**Less than 1%** near-zero-emissions clinker production for cement	60-70% per ton of cement	1-3% per built house
Aluminium	**Aluminium Carbon Footprint Methodology (2018)**: Specifies the principles and requirements for quantifying GHG emissions from primary aluminium production processes	**Approximately 30%** of primary production emits less than 5t CO_2e/t	40% per ton of aluminium	1% per car
Primary chemicals	**GRI Sector Program (2019)**: Framework designed for companies to report on sector-specific standards in the manufacturing of chemical products, including plastics and fertilizers	**Less than 2%** of low-emission primary chemicals are currently being produced	55%	1-3%
Oil and gas	**Oil and Gas Climate Initiative (OGCI) Reporting Framework (2016)**: Framework for companies to report on specific metrics including GHG figures and low-carbon investment	**1%** contribution of the oil and gas sector to the total clean energy investments globally	10% per barrel of oil 7% per metric million British thermal unit (MMBtu) of gas	6% per litre of gasoline 1% per MWh of electricity

Note: *Accenture analysis.

Sources: Smart Freight Centre. (n.d.). *The GLEC Framework*; International Civil Aviation Organization (ICAO). (n.d.). *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*; International Maritime Organization (IMO). (n.d.). *IMO Data Collection System (DCS)*; Sea Cargo Charter. (2024). *Sea Cargo Charter: Aligning global shipping with society's goals*; Worldsteel Association. (n.d.). *Climate Action Data Collection*; Climate Group. (n.d.). *SteelZero*; Global Cement and Concrete Association (GCCA). (2019). *Sustainability Charter and Guidelines*; World Aluminium. (2018). *Aluminium Carbon Footprint Technical Support Document*; GRI. (n.d.). *Sector Program*; Oil and Gas Climate Initiative (OGCI). (2023). *Oil & Gas Climate Initiative Reporting Framework*.

> **By promoting energy efficiency and demand-side management, we can reduce overall consumption, helping to alleviate the pressure on prices.**

By promoting energy efficiency and demand-side management, we can reduce overall consumption, helping to alleviate the pressure on prices. Programmes that encourage energy-saving behaviours can help consumers save money while contributing to carbon reduction goals.

The transition to a low-carbon economy presents an opportunity to enhance daily life, encouraging beneficial behavioural changes and innovation. While some price adjustments for essential products may occur, proactive planning and supportive policies can help balance these effects, paving the way for a more sustainable and equitable future for all. The share of societal costs of industry decarbonization and broad energy transition underscores the need for equitable transitioning. Policy-makers must prioritize support for vulnerable populations most affected by price increases and potential job losses. Measures such as subsidies for low-income households, investment in public transport and incentives for energy efficiency can encourage positive behavioural changes, easing the financial burden and protecting those least able to afford the transition. For instance, the Just Transition Fund not only provides grants and technical assistance but also promotes policy development and peer learning to support communities facing job displacement, such as those impacted by the decline of coal-based industries.[66]

Capital

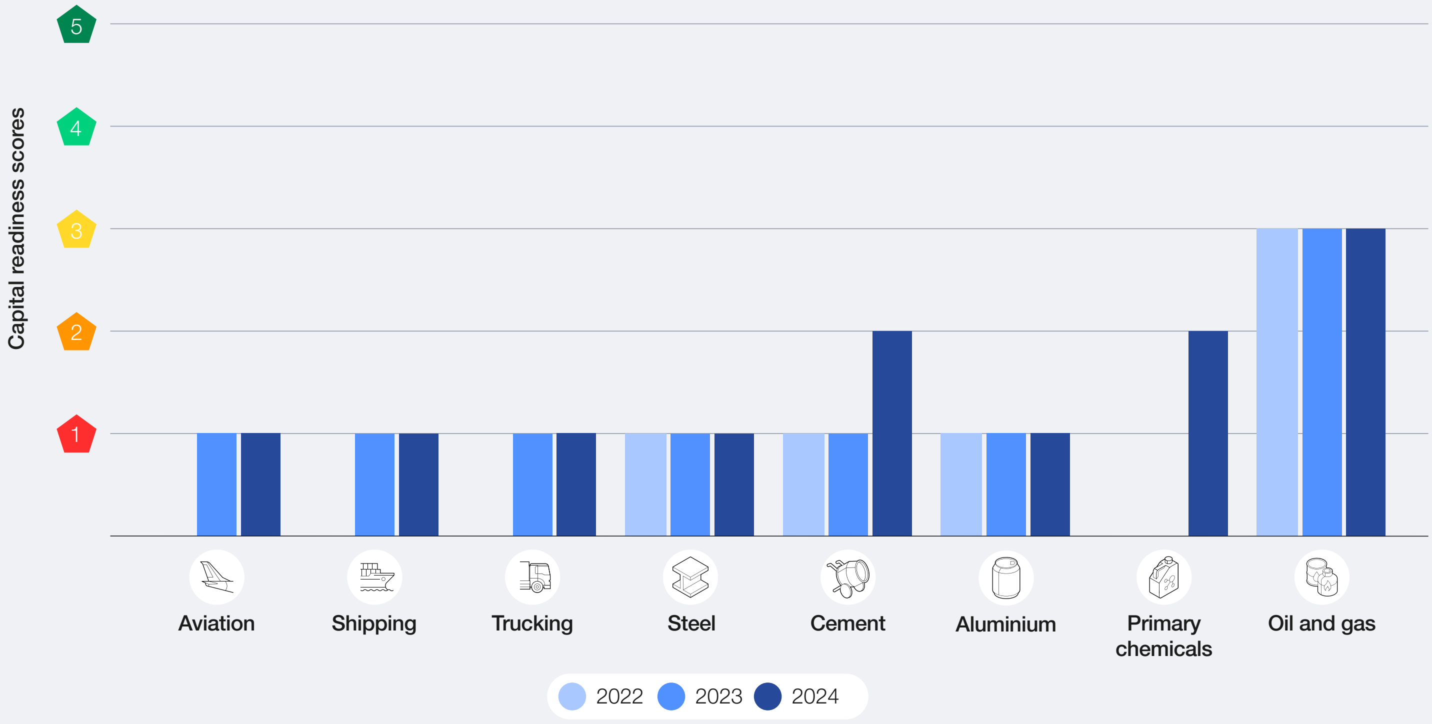
Key readiness question

Are returns sufficient to drive investments towards low-emission assets?

Key messages

- To meet net zero scenarios across the eight sectors by 2050, $30 trillion is needed as cumulative additional investment, with 57% required by the ecosystem and 43% by sectors.[67]
- Increased capital spending and funding strategies are essential for advancing clean technology development.
- Companies can offset decarbonization costs by tapping into new markets, setting premium prices, and lowering energy and material expenses.

FIGURE 18 **Capital scores for low-emission assets across sectors (2022-2024)**



Sectors with readiness score movements in the past year:

- **Cement**: The score increased from 1 to 2 during the last year, as current capital levels increased, leading to an additional 35% of annual CapEx needed, compared to 71% previously.

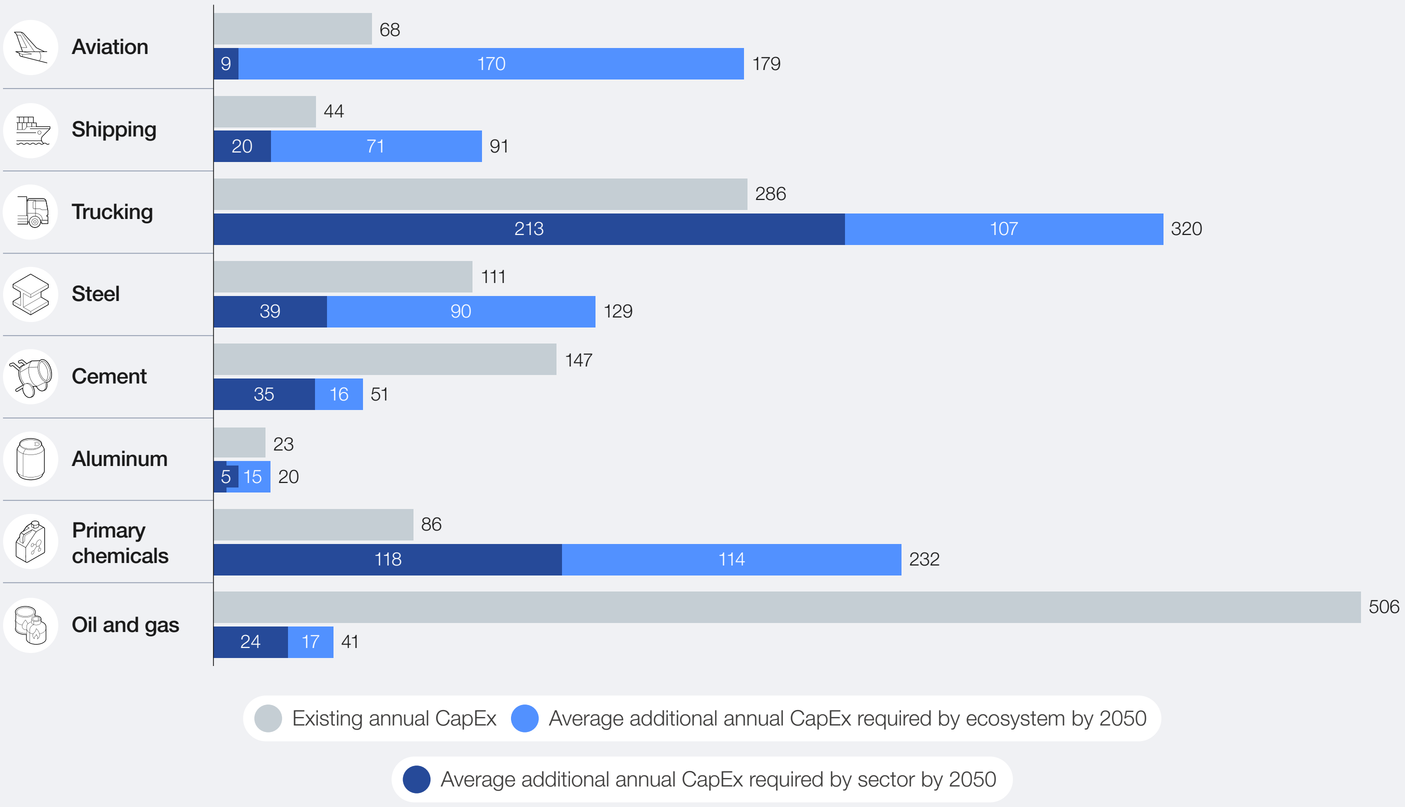
To meet net-zero scenarios, the eight sectors in scope need an estimated additional $30 trillion in investments with more than 68% of this needed for trucking, aviation and primary chemicals. Of the total investments, 57% will be required from the ecosystem for enabling infrastructure, while 43% will be needed within the sectors to retrofit existing assets and develop new technologies.[68]

In last year's report, the investment was divided across infrastructure and capital sections, with $13.5 trillion for infrastructure and $11 trillion for industries to retrofit assets. This year, those figures have been combined into the capital section.

Challenges

- Investments in low-carbon technologies, such as clean hydrogen and CCUS, require significant capital that often exceeds current spending levels.
- Most sectors in scope operate with low profit margins (typically between 3% and 10%), except for the oil and gas sector, which has a higher margin of about 15%.[69] This makes it hard to cover the additional costs of decarbonization while maintaining profitability.
- Increased demand for capital from multiple companies increases competition, making it harder for smaller firms to secure necessary funding.

FIGURE 19 **Existing annual CapEx vs. additional annual required by 2050 by sector and ecosystem ($ billions)**



Source: Accenture analysis based on MPP, S&P, DNV, Center for Global Commons and IEA data

Way forward

To decarbonize high-emission sectors, companies can use several capital-raising strategies.

Green debt issuance, such as green bonds or sustainability-linked loans (SLLs) can provide the required funding by linking loan terms (e.g. interest rate) to sustainability metrics. This incentivizes companies by linking financial impact directly with sustainability performance. For example, voestalpine, an Austria-based steelmaker, has successfully issued the first green corporate bond for around $550 million to finance sustainable projects. Among these is voestalpine's greentec steel, which refers to the production of high-quality steel with a reduced carbon footprint.[70] Green securitization can unlock financing in debt capital markets for smaller-scale, low-carbon and climate-resilient assets, improving access to capital and reducing costs.[71]

Moreover, special funds are helping to decarbonize high-emission sectors, such as the Climate Investment Funds (CIF), which recently announced the launch of its Industry Decarbonization Program. This programme offers up to $1 billion to support the transition of heavy-emitting sectors in developing countries. The programme will spur innovation, provide proof of concepts for new technologies and advance a just transition.[72]

In addition, public-private partnerships (PPPs) can help in raising capital for decarbonization efforts. For instance, the US Department of Energy has allocated $2.2 billion in funding for the Appalachian Hydrogen Hub and the Gulf Coast Hydrogen Hub.[73] National and regional development banks can enhance private sector investment by mitigating risks and facilitating access to capital, while development finance institutions (DFIs) improve the bankability of green projects through de-risking instruments and technical assistance.

Private equity firms are also increasingly investing in long-term decarbonization opportunities for high-emitting sectors. For example, Ara Partners focuses on investing in technologies that replace polluting industrial processes, as well as in businesses that support decarbonization platforms through their products and services.[74] Capital recycling also serves as an effective financing strategy for long-term decarbonization projects. By selling or leasing assets that have transitioned to a lower-risk phase, firms can repurpose the capital to invest in new green initiatives. This approach enhances asset efficiency while providing ongoing funding for decarbonization efforts.[75]

> **While the costs of these initiatives may be significant, companies can offset some of these expenses by generating returns from decarbonization initiatives across multiple value levers.**

Most of the investments needed will come from the private sector. Companies will invest only if the business case is robust enough and risk-adjusted returns can be earned over time. Governments and other relevant actors can play an important role in de-risking investments through targeted policies and blended financing, especially for "first-of-its-kind" applications of key technologies in hard-to-abate sectors.

Additionally, to further help developing countries raise capital, strategies such as increasing concessional capital from institutions, expanding private investment through tools like blended finance and risk mitigation, and enhancing domestic financial markets and tax systems have emerged. Additional approaches include sovereign debt restructuring, carbon market development and improved risk frameworks.[76] Developed countries also have a role to play, by providing concessional finance, supporting risk-reducing instruments and promoting global climate finance initiatives. An example of such collaboration is Pentagreen Capital, launched by HSBC and Temasek, aimed at mobilizing over $1 billion for sustainable infrastructure in South-East Asia. Their financing of solar and bioenergy projects exemplifies how developed countries can provide essential capital and expertise to stimulate private sector investment in developing nations.[77]

While the costs of these initiatives may be significant, companies can offset some of these expenses by generating returns from decarbonization initiatives across multiple value levers.

- **New markets**: To increase profits, companies can use their core businesses to tap into new markets. For example, Maersk is actively developing both the supply and demand for green shipping fuels. By investing in a green ammonia facility with Danish logistics group DFDS and establishing a green methanol company, Maersk aligns its operations with carbon reduction goals while positioning itself to capture market share in a growing sector.[78]

- **Premium pricing**: Companies that identify opportunities for greener products can command premium prices, as green premiums are becoming more prevalent across various commodities. These premiums can offer added value to consumers by supporting sustainable choices, allowing companies to maintain industry margins with moderate adjustments in consumer prices. Economic factors, including inflation and rising living costs, are influencing the supply-demand balance in these markets. For instance, high-quality recycled plastics have achieved an average premium of up to 60% over virgin plastics in recent years. Similarly, low-CO_2 steel is expected to command significant premiums by 2030.[79]

- **Energy and material expense reduction**: Companies that manage to reduce both their costs and carbon emissions can gain a bigger share of the market and save money for future projects aimed at reducing their environmental impact. Many industry leaders focus on cutting down their emissions by 20-40%. At the same time, they work on lowering their costs, which leads to higher profits.[80]

- **Enhanced branding**: Decarbonization enhances a company's brand reputation, cultivating trust and loyalty among environmentally conscious consumers while differentiating it in the marketplace. By adopting transparent and genuine green practices, companies improve brand perception and customer loyalty, which can lead to increased sales and profitability.

Policy

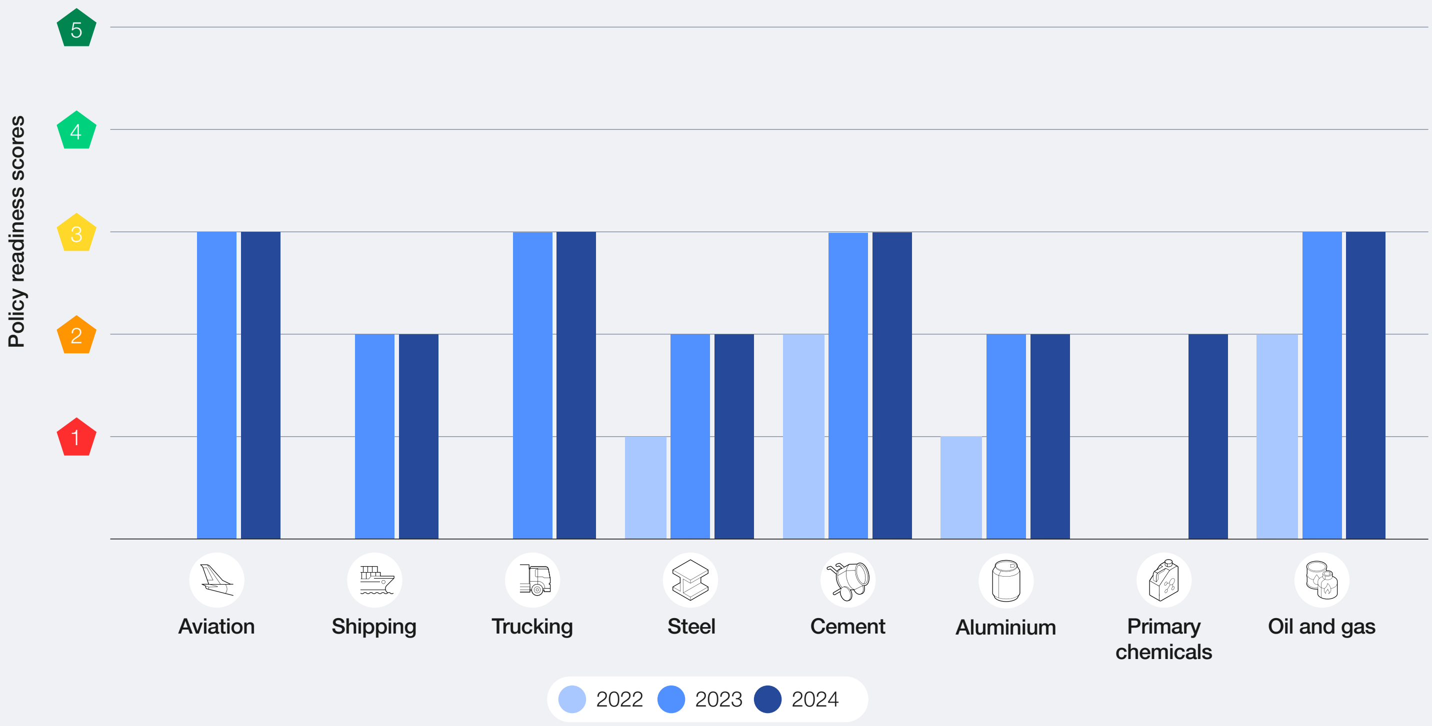
Key readiness question

Are the supporting policies to enable the growth of low-emission industry in place?

Key messages

- Effective policies are essential for creating an enabling environment to achieve the 2050 net-zero target.
- Decarbonization policies face challenges including increased costs, uneven global commitment, opposition from fossil fuel sectors and risks of carbon leakage.
- GHG emissions reduction policies can be classified into three main types: market-based, mandate-based and incentive-based.

FIGURE 20 **Policies scores supporting the growth of low-emission industry across sectors (2022-2024)**



Note: Aviation, shipping and trucking sectors were not included in the 2022 report, and the primary chemicals sector has been added this year.

Sectors with readiness score movements in the past year:

The policy scores for all the sectors have remained stagnant since last year, due to no major developments in terms of sector-specific policies and regulations.

To achieve the global 2050 net-zero target, policies can help create an enabling environment for decarbonization and adoption of clean energy across industries.

Challenges

Decarbonization policies face several significant challenges, which vary depending on the region, industry and the specifics of the policy:

- Clean energy policies can, in some instances, raise costs for businesses and consumers, leading to social resistance and implementation difficulties.
- Uneven commitment to decarbonization across countries complicates coordinated efforts across global product value chains and can undermine national progress.
- Distributional effects on suppliers and workers in emissions-intensive industries can weaken policies aimed at reducing emissions.
- Regulatory arbitrage may drive businesses to relocate to less regulated regions, diminishing overall emission reduction efforts.

Way forward

Currently, the different policies on GHG emissions reduction are of three key types:

- **Market-based**: This type of policy involves the construction of systems that make the polluting entity incur a cost for their emissions. These systems can be carbon taxes, emissions limits or cap-and-trade programmes. The European Union's (EU) Emission Trading Scheme (ETS)[81] is an example of a market-based GHG emission reduction policy. This type of policy can be classified as a "push" policy because it pushes the industry to move away from emission-intensive practices. The EU ETS policy covers the steel, cement, chemicals, aviation and shipping sectors.
- **Mandate-based**: This type of policy involves the introduction of direct regulations or setting up of government targets for decarbonization initiatives such as installed capacity of specific types of clean energy. The EU's Net Zero Industry Act (NZIA),[82] China's 14th Five Year Plan[83] and India's National Action Plan on Climate Change[84] are examples of a mandate-based GHG emission reduction policy. This type of policy can also be classified as a "push" policy, since it pushes the industry to move away from emission-intensive practices.
- **Incentive-based**: This type of policy involves direct funding, tax credits or subsidies from the government to support decarbonization initiatives like increasing the production of clean energy or the development of low-emission technologies. The US Inflation Reduction Act (US IRA)[85] and Japan's Green Transformation (GX) Policy[86] are examples of an incentive-based GHG emission reduction policy. This type of policy can be classified as a "pull" policy, as it pulls the industry towards low-emission practices.

Each policy type has specific objectives and covers key sectors and technologies. A balanced approach, combining push and pull strategies, can encourage long-term industry participation, providing pathways for sectors like transport and industrial sectors to decarbonize effectively.

TABLE 3 **Policy summary**

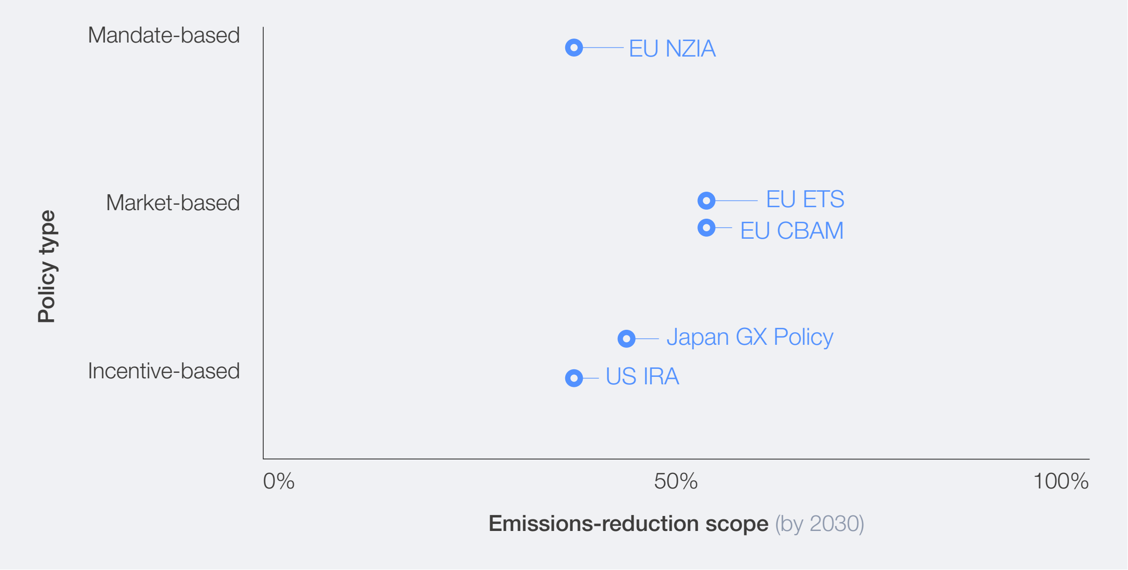
Policy name	Policy type	Policy objectives	Key points	Sector/technology coverage
US IRA (2022)	**Incentive-based (pull)**	– A 40% reduction in US GHG emissions by 2030, relative to 2005 levels	– Uses tax incentives to encourage private sector investment in clean energy projects – $369 billion in federal funding towards clean energy – This funding includes $100 billion to solar energy, $53 billion to enhance energy storage solutions, $78 billion for advancing battery manufacturing, $23 billion for developing hydrogen technologies, $27 billion to support wind energy, and $20 billion allocated to carbon capture and other emerging technologies.	– Energy (low-carbon power) – Transport (low-carbon fuels e.g. hydrogen and EV adoption) – CCUS technology for manufacturing (steel, cement, chemicals)
EU NZIA (2024)	**Mandate-based (pull)**	– At least 40% of the annual deployment needs for strategic net-zero technologies to be met through EU-based manufacturing by 2030 – Target to achieve an annual CO_2 storage capacity of at least 50 million tonnes by 2030	– Focused on dismantling legislative gridlocks – Emphasizes reducing dependency on non-EU countries for critical technologies and resources – Net-Zero Technologies Manufacturing Projects ("NZT Manufacturing Projects") will benefit from streamlined permitting procedures. – NZT Manufacturing Projects that are deemed "strategic" will benefit from expedited permitting timelines.	– Energy (low-carbon power, energy storage, nuclear power) – Transport (low-carbon fuels e.g. hydrogen, biofuels, sustainable fuels) – CCUS technology – Heat technology

TABLE 3 | **Policy summary (continued)**

Policy name	Policy type	Policy objectives	Key points	Sector/technology coverage
EU Carbon Border Adjustment Mechanism (CBAM) (2023)	**Market-based (push)**	– Aligned to EU's Fit for 55 package target, i.e. reducing net GHG emissions by 55% by 2030 – Prevent carbon leakage – Encourage global decarbonization	– Focused on taxing carbon emissions – **Transitional phase (2023-2025)**: During the transitional phase, importers are required to report the emissions embedded in the covered goods without having to pay any financial adjustment. – **Full implementation (from 2026)**: From 2026 onwards, importers will need to purchase and surrender CBAM certificates to cover the emissions embedded in their imports, fully aligning with the EU ETS carbon price.	– Iron/steel – Cement – Fertilizers – Aluminium – Hydrogen – Electricity – (To be expanded further from 2026 onwards)
EU ETS (2005)	**Market-based (push)**	– At least a 55% reduction in EU's GHG emissions compared to 1990 by 2030, and net zero by 2050 – Cost-effective reduction of GHG emissions	– Focused on taxing carbon emissions – "Cap and trade" principle, where the cap refers to the limit set on the total amount of GHG that can be emitted, and this cap is reduced annually. This cap is expressed in emission allowances with one allowance giving right to emit one tonne of CO_2e.	– Power generation and heat production – Steel – Cement – Chemicals – Refineries – Glass – Aviation – Shipping
China's 14th Five Year Plan (2021) and Action Plan for Energy Saving and Carbon Reduction (2024)	**Mandate-based (pull)**	– Reduce energy intensity by 13.5% and emissions intensity by 18% by 2025 from 2020 levels	– Control of coal consumption, optimization of oil and gas use, increased non-fossil energy consumption, and energy savings and carbon emission reductions across industries – Reduce emissions from existing coal plants through biomass co-firing, green ammonia co-firing and CCUS technologies	– Steel – Petrochemicals – Metals – Buildings – Transport
India's National Action Plan on Climate Change (2008)	**Mandate-based (pull)**	– Reduce GHG emissions by enhancing renewable energy production and improving energy efficiency	– Focused on expansion of solar energy use and improvement of energy efficiency	– Renewable energy (especially solar) – Agriculture
Japan GX (Green Transformation) Policy (2023)	**Incentive-based (pull)**	– Achieve 46% of emissions reduction compared to 2013 levels by 2030 and net zero by 2050	– Includes a 10-year roadmap outlining the allocation of JPY 150 trillion (Japanese yen) of public-private investment for various sectors and technologies – A carbon levy starting from 2028 and the emissions trading system introduced in the future – Focused on fading out inefficient coal-fired thermal power generation, including promotion of hydrogen/ammonia co-firing and direct combustion, as well as investment in upstream liquified natural gas (LNG) development in cooperation with Asian countries – Promotes investment and development in electric furnaces and hydrogen reduction steelmaking – Goal of 100% EVs in new passenger car sales in 2035	– Renewable energy – Iron and steel – Automotive sector

Sources: U.S. Department of the Treasury. (n.d.). *Inflation Reduction Act*; European Commission. (n.d.). *Net-Zero Industry Act*; European Commission. (2024). *Carbon Border Adjustment Mechanism*; European Commission. (n.d.). *EU Emissions Trading System (EU ETS)*; Climate Cooperation China. (2024). *China Issues Action Plan for Energy Saving and Carbon Reduction (2024-2025)*; Climate Action Tracker. (n.d.). *India*; InfluenceMap. (n.d.). *GX (Green Transformation) Basic Policy and Roadmap.*

FIGURE 21 **Comparison of key cross-sector policies**



Note: This figure excludes China and India's policies, which focus on emissions intensity reduction.

Source: Accenture analysis based on data from European Commission, Climate Cooperation China, Climate Action Tracker, U.S. Department of Treasury and InfluenceMap (Japan).

3.3 Key priorities

In the last year, while the eight hard-to-abate sectors in scope have seen some progress in terms of emissions intensity reduction, their efforts have led to limited movement in their readiness scores across the five readiness dimensions. Going forward, these sectors must accelerate efforts to reduce emissions intensity to achieve their respective net-zero ambitions by 2050. In order to increase momentum, the key stakeholders across these sectors must consider the following priorities as the main impact drivers, and explore areas of collaboration:

FIGURE 22 **Key priorities for stakeholders impacting the transition for hard-to-abate sectors**

Collaboration areas

Industrial hubs/clusters
Leverage synergies and drive technological innovation

Data sharing and reporting
Promote transparency across stakeholders by data sharing and sustainability reporting

Financial instruments
Create financial models and environmental, social and governance (ESG) criteria together that support innovations in hard-to-abate sectors

Policy-makers

- **Targets:** Set short-term targets for emission reductions, maintaining long-term vision
- **Innovation:** Incentivize R&D and scaling for H2 and derivatives, CCUS
- **Tariffs:** Reduce/delay tariffs on sectors with high green premiums
- **Equity:** Address affordability, supply security and equity in policy-making

Industry bodies

- **Standards:** Set carbon standards with clear thresholds
- **Transparency:** Provide publicly available data, especially on green premium of offtake agreements
- **Collaboration:** Promote industrial hubs and collaboration
- **Demand:** Aggregate demand/offtake agreements

Companies

- **Electrification:** Electrify as much as possible, especially where low-carbon power is available
- **Commitment:** Commit to short-term emission reduction targets
- **Investment:** Invest in lower emission/transition fuels
- **Circularity:** Enhance circularity through supply chain traceability capabilities
- **Carbon reporting:** Build a strong digital core with accurate and auditable data on product-level carbon reporting

Customers/consumers

- **Circularity:** Embrace circular economy practices like recycling and reducing waste
- **Transparency:** Advocate for transparency in product emissions and carbon footprints
- **Green products:** Choose low-carbon, sustainable products to boost demand for green and energy-efficient products
- **Net-zero alignment:** Support companies aligned with net-zero goals through purchasing choices

Financiers

- **De-risk investments:** Provide equity for high-risk/high-return investments and debt for low-risk/low-return investments
- **Capital efficiency:** Channel funds to major production hubs where impact is biggest
- **ESG factors:** Consider special ESG factors for hard-to-abate sectors and prioritize financing
- **Novel instruments:** Develop innovative financial instruments that promote capital flow

While collective efforts on these key areas of collaboration can potentially enable a faster transition to net zero, the implementation of sector-specific strategies will be critical for each of the hard-to-abate sectors to successfully achieve their net-zero ambitions by 2050.

4

Aviation industry net-zero tracker

The industry must prioritize sustainable aviation fuel and aircraft design improvements while advancing novel propulsion technologies to reduce long-term emissions.

- With passenger numbers recovering to pre-COVID-19 pandemic levels, the aviation industry is encountering difficulties related to increasing emissions.
- Despite SAF production tripling in a year, it still accounts for a small portion of total jet fuel use, indicating the need for significant investment.

18%

Increase in absolute CO_2 emissions (2022-2023)

14%

Decrease in emission intensity (2022-2023)

37%

Increase in demand (2022-2023)

AVIATION

Key performance data 2023[87,88,89,90]

2.5%

Contribution to global CO_2e emissions

0.94 Gt CO_2e

Scope 1 and 2 emissions (2023)

8%

Emissions reduction (2019-2023)

118 gCO_2e/RPK

Emissions intensity (2023)

3%

Decrease in emission intensity (2019-2023)

2.1 times

Demand increase by 2050 in IEA's NZE scenario, compared to 2023

<1%

Low-emission aviation fuel consumption

$5 trillion

Additional investment required for net zero by 2050

Performance summary

- Global air passenger traffic surged by nearly 37% in 2023, with total revenue passenger kilometres (RPK) reaching 94% of pre-COVID-19 pandemic levels from 2019. This highlights a strong recovery in the industry.[91]
- The absolute direct emissions were 0.94 Gt CO_2e[92] in 2023 – an 8% reduction from 1.02 Gt CO_2e[93] in 2019.
- The industry has decreased emission intensity by 3%[94] in the last five years.
- In 2023, SAF volumes reached over 600 million litres (0.5 Mt), double the 300 million litres (0.25 Mt) produced in 2022, but still only amounting to 0.2% of all aviation fuel for the year.[95] SAF production volume is projected to triple to 0.53%[96] of aviation's fuel need in 2024.
- Energy intensity reduced by 19% from 14.9 megajoules of energy used per revenue tonne kilometre (MJ/RTK) in 2020 to 12.1 MJ/RTK in 2022.[97]

Future emissions trajectory

- The industry is forecasted to reduce emissions intensity by 13%[98] by 2030 and 76%[99] by 2050, compared to 2023 levels, according to IATA Net-Zero Roadmap S2 scenario. The absolute direct CO_2e emissions are expected to be 1.12 Gt[100] in 2030 and 0.47 Gt[101] in 2050.
- In the aviation industry, 75%[102] of publicly traded companies consider climate change in their operational decision-making processes.

Readiness key takeaways

Technology	2	⊖	– HEFA and other biofuels are the most advanced, with TRL of 8-10,[103] and are already commercially available. – Battery-electric and hydrogen fuel cell technologies are in the early prototype stage, with a TRL of 4-5, and are projected to become commercially viable by 2030.[104]
Infrastructure	2	⊖	– 100 MTPA of clean hydrogen, 700 MTPA of CCUS, and 400 MTPA of biofuel are required by 2050.[105] – Efforts are needed to build capacity for SAF, as less than 1%[106] of the 2050 SAF production capacity is currently available.
Demand	2	⊖	– Less than 1%[107] of current aviation energy consumption comes from low-emissions sources. – The green premium to produce SAF is estimated to be 2-5 times more expensive than conventional jet fuel.[108] – Identifying more potential feedstocks and diversifying SAF production could be a solution to meet the demand.
Capital	1	⊖	– Industry requires over $5 trillion[109] in cumulative investments to achieve net zero by 2050 (i.e. $179 billion[110] annual investment, compared to current CapEx of $68 billion[111] annually) – Of the investment required by 2050, 52% is for fuel production and 36% is for upstream renewable electricity generation by the ecosystem.[112]
Policy	3	⊖	– Establishing clear blending mandates, reducing cost differentials, de-risking projects and increasing SAF usage in public-sector travel are crucial initiatives. – In 2024, Japan, Brazil, Malaysia and the UK all introduced mandates for SAF entering into force in the coming years.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Reduce fuel consumption through air traffic management (ATM) improvement and operational efficiencies.
- Scale the use of SAF.

Long-term (by 2050)

- Invest in R&D for low-TRL technologies and efficiency measures to reduce energy demand.

Ecosystem-enabled solutions

Mid-term

- Reduce the cost differential between SAF and fossil jet fuel (e.g. by direct or indirect subsidies).

Long-term

- Develop refuelling/recharging infrastructure for zero-emission aircraft at key airports.
- Develop CCUS facilities to meet the 2050 demand.

Performance

The sector currently accounts for 2.5%[113] of global CO_2e emissions. Fossil fuels (mostly Jet-A and Jet A-1 kerosene) account for over 99%[114] of fuel consumption in the industry, making them a critical driver for emission intensity.

TABLE 4

Aviation industry performance

Performance metric	Change (2019-2023)
Industry activity (RPK)	-5.9%[115]
Emission intensity (gCO_2/RPK)	-3%[116]
Total CO_2e emissions	-8%[117]

In 2023, industry traffic (RPKs) reached 94%[118] of 2019 levels and rose 37% compared to 2022. The aviation industry has seen a significant rebound post-pandemic, with global revenues projected to surpass pre-2019 levels.

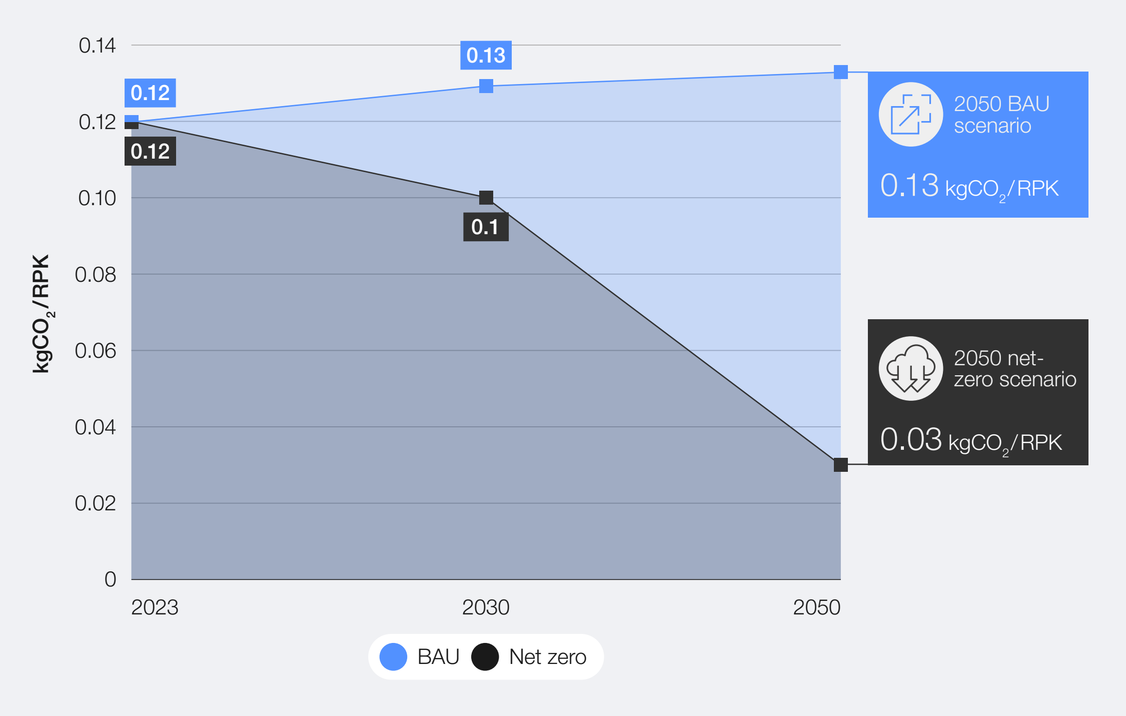
Airlines have started using SAF in limited quantities, aiming to reduce their dependence on traditional fossil fuels. However, the high cost and limited availability of SAF present significant challenges for scaling its use. Among the largest SAF users in 2023, DHL[119] partnered with IAG Cargo and Air France-KLM[120] to sign a major 10-year agreement for the supply with TotalEnergies, marking more milestones on the journey towards sustainable air freight.

Airbus[121] is making progress towards zero-emission propulsion, announcing a number of collaboration agreements with global airports in 2024. New market entrants such as ZeroAvia[122] are developing hydrogen-electric powertrain plans to bring a retrofitted hydrogen-powered aircraft with this ramped up capability to market by 2027.

Readiness

FIGURE 23

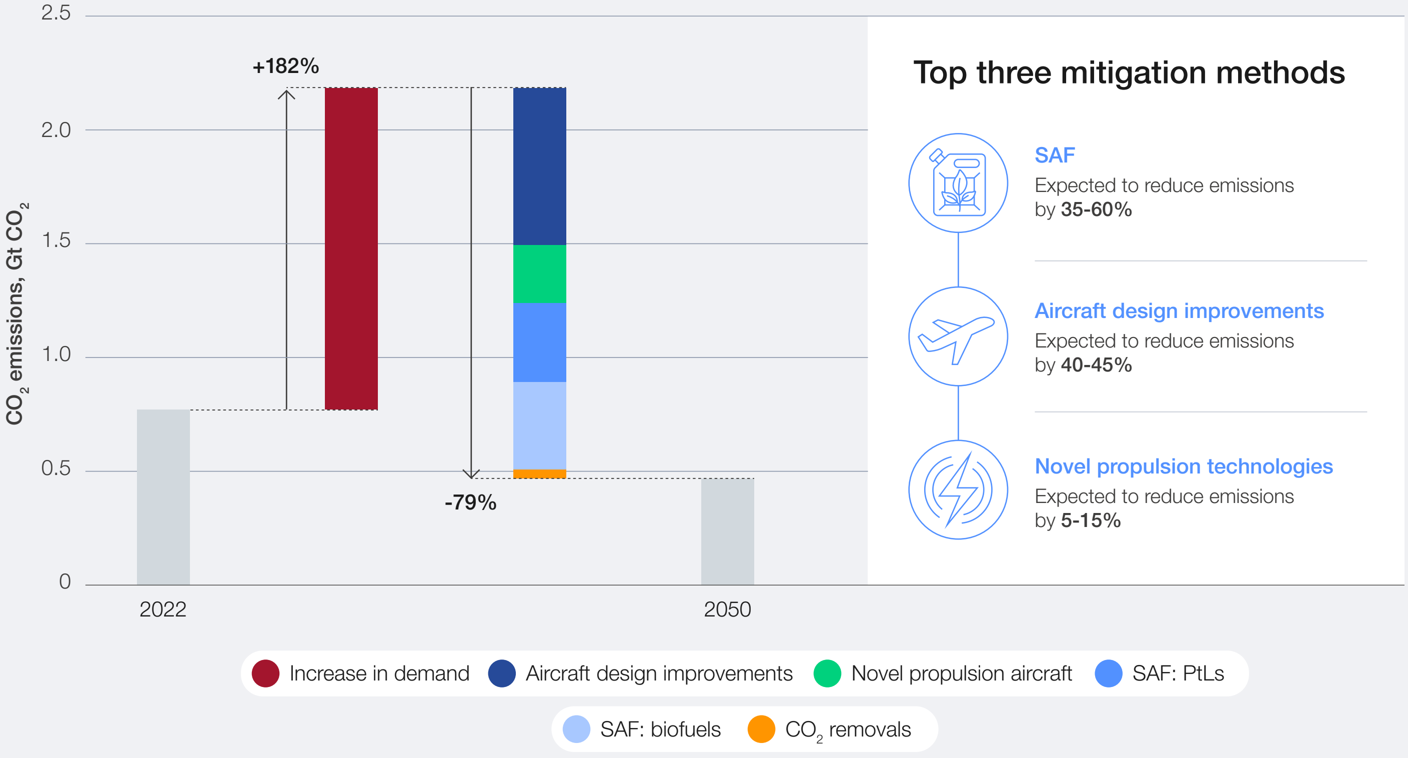
Emissions intensity trajectory for aviation sector



Source: IATA and ICCT.

Overall aviation activity demand is expected to more than double by 2050, increasing by a factor of 2.1 compared to 2023.[123] The Asia-Pacific[124] region is expected to account for about half of new passengers by 2036, driven by rapid income growth. In order to align with the Net Zero Emissions by 2050 Scenario, scaling up longer-term solutions like SAF and electric or hydrogen-powered aircraft is essential. Key strategies include diversifying SAF feedstocks, establishing blending mandates, reducing cost differentials and de-risking projects.

FIGURE 24 **Decarbonization levers and top mitigation methods (MPP's NZE Scenario)**



Source: MPP.

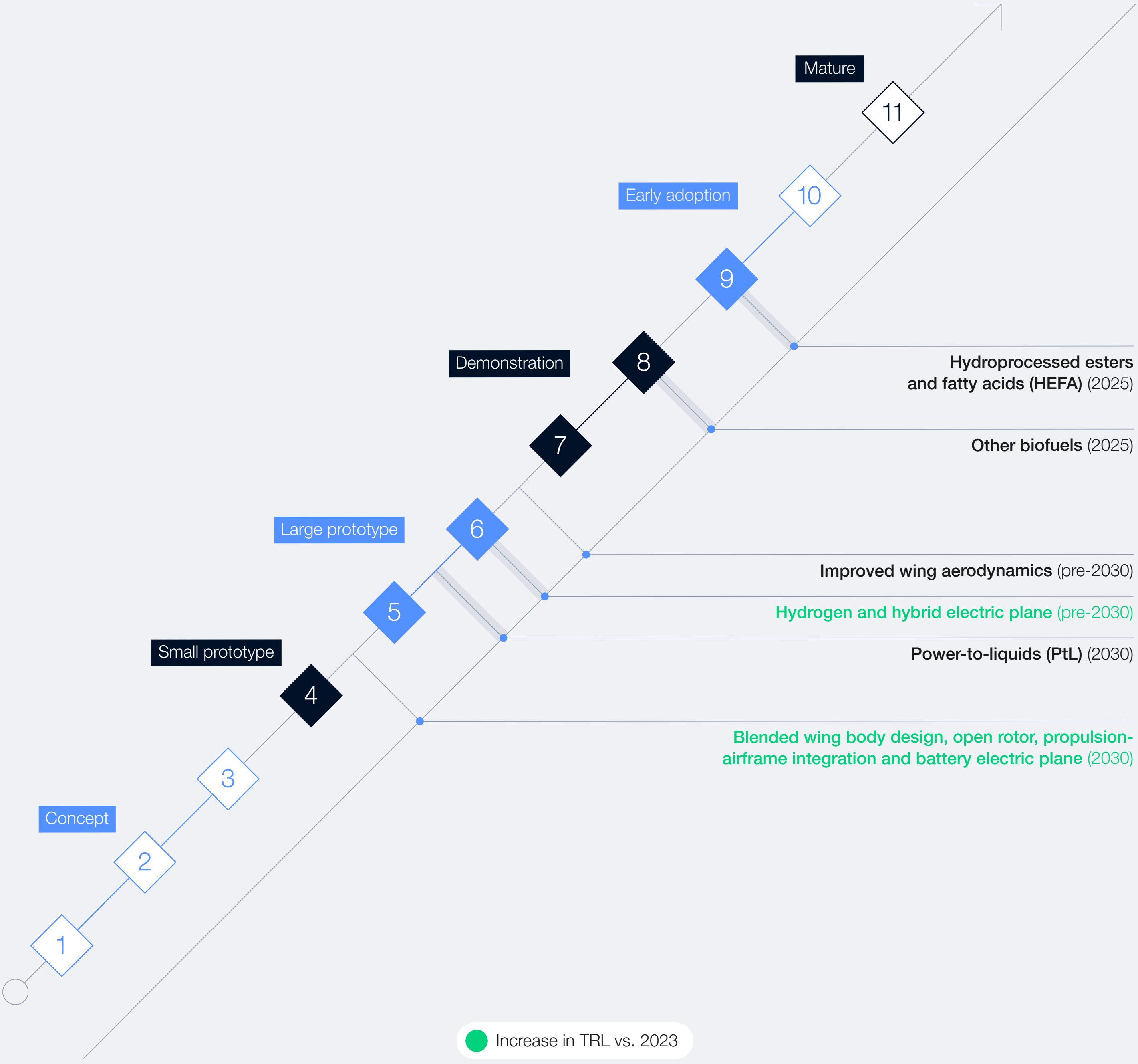
2

AVIATION

Technology

Technologies to implement aviation decarbonization levers are at different readiness levels. Three leading pathways have emerged: SAF, fuel efficiency and novel propulsion technologies.

FIGURE 25 **Decarbonization TRLs and year of commercial availability**



Source: Accenture analysis derived from data from IEA ETP Clean Energy Technology Guide and MPP.

Technology pathway 1: SAF

SAF includes biofuels made through various pathways such as hydroprocessed esters and fatty acids (HEFA), the Fischer-Tropsch process (FT) and alcohol-to-jet (AtJ), as well as synthetic aviation fuels made from captured carbon and low-emissions hydrogen electrolysis, known as power-to-liquids (PtL) or e-fuels. HEFA is currently the most mature, and likely to remain so until 2030, with 85%[125] of announced SAF production facilities using this pathway. PtL is advancing rapidly and offers long-term scalability due to its reliance on renewable resources, but costs remain high. Regulatory frameworks, like the EU's ReFuelEU initiative, are pushing for increased adoption, with targets of 70%[126] SAF blends of which half (35%[127]) must be PtL by 2050**.**

Technology pathway 2: Aircraft design and air traffic management improvements

Over the past decade, the aviation industry has made huge progress in making its aircraft and flight procedures more efficient. Within normal fleet turnover cycles, the replacement of retired aircraft with new, more efficient aircraft leads to regular efficiency improvements. Fuel efficiency measures in aviation, such as advanced engine designs and lightweight materials, are progressing rapidly but are still in early-stage development. Retrofitting winglets to aircraft wings could be a short-term solution to reducing emissions. Continued investment is essential in enhancing fuel efficiency for conventional engines, along with improved airframe design, ground operations, ATM and route planning. Other advancements such as reducing cabin weight or switching to electric taxiing, optimized approach/departure procedures, vertical speed inefficiency reductions during cruise from improved aerodynamics, improved congestion management, single-engine taxiing, and engine washes also offer potential for reducing emissions.

Technology pathway 3: Novel propulsion technologies

Novel propulsion technologies in aviation, such as hydrogen fuel cell/combustion, battery-electric and hybrid-electric aircraft are gaining momentum but at large prototype and demonstration stages of readiness and expected to be commercially available by 2030. Hydrogen-powered aircraft, like Airbus' ZEROe concept,[128] aim for commercial availability by 2035, with a TRL of 5-6, still in large prototype stages. For hydrogen, key challenges include its production, transportation and assessing its environmental impact (e.g. contrail formation when burned). Battery-electric aircraft, while promising for short-haul flights, currently suffer from low energy density, holding just one-fiftieth of the energy of jet fuel by weight. The main challenge with battery-electric aircraft is using batteries with high enough energy density, which do not exist for large passenger planes, limiting their potential application to small and short-range flights. Hybrid-electric aircraft, which combine traditional fuel with electric propulsion, are closer to commercialization and are expected to play a crucial role in the near term. Hybrid-electric aircraft, like the Ampaire Electric EEL,[129] are at demonstration phases (TRL 6-7), targeting broader use by 2030.

AVIATION

2

Infrastructure

The aviation industry needs SAF facilities to facilitate the conversion of feedstocks into fuel. Production is in early stages, with SAF accounting for less than 1%[130] of total fuel usage. The transition to alternative fuels beyond producing SAF will also require the adaptation and retrofitting of existing airport facilities. In the case of Chicago, Neste[131] needed to add new port terminals hundreds of miles away, while for other cases, new blending facilities or hydrant systems at airports may be required to supply SAF while keeping in mind the current blend limit of 50%. Some airports have begun implementing hydrogen-operated ground support equipment (GSE), and the UK has launched its first hydrogen landside-to-airside pipeline demonstrator.[132] However, there is currently no airport hydrogen infrastructure for aircraft propulsion anywhere in the world.

Substantial investments in renewable energy infrastructure are also required to meet future demand, alongside advancements in CCS technologies to mitigate emissions from conventional aviation operations during the transition phase. Selected airports are generating renewable energy on-site and are also deploying charging stations for both road vehicles and GSE.

FIGURE 26 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
SAF/biofuels	0.08 MTPA	400 MTPA
Clean hydrogen production	~0 MTPA	44 MTPA
CO_2 transport and storage	0.004 MTPA	700 MTPA

Source: Accenture analysis derived from data from IATA and IEA.

2

AVIATION

Demand

Less than 1%[133] of current aviation energy consumption comes from low-emissions sources, highlighting the nascent stage of SAF adoption. To meet the net-zero target by 2050, the IATA states that SAF must constitute at least 5.2% of the total jet fuel requirement by 2030.[134] The green premium to produce SAF is estimated to be 2-5 times more expensive than conventional jet fuel.[135] Despite the higher costs, SAF has lower density but higher energy content per kilogram of fuel compared to conventional kerosene. This gives some aircraft fuel-efficiency advantages, due to lower fuel burn and less fuel mass to achieve the same distance. Government incentives and policies are crucial to offset the high costs and encourage the adoption of SAF.

Increasing production through pathways that are already certified, fast-tracking of certification for new pathways and identifying more potential feedstocks are essential strategies to meet the growing demand for SAF. Identifying and prioritizing high-potential production projects for investment support and delivering a global SAF accounting framework are also key in supporting SAF production.

FIGURE 27

Air passenger market – world share, 2023[136] and top 5 busiest global airports by monthly seats – October 2024 (millions), 2024[137]

Air passenger market – 2023 world share % (industry RPKs)	
1 **Asia-Pacific**	31.7%
2 **Europe**	27.1%
3 **North America**	24.2%
4 **Middle East**	9.4%
5 **Latin America**	5.5%

Top five busiest global airports by seats (millions)	
1 **Atlanta Hartsfield-Jackson International Airport**	5.43
2 **Dubai International**	5.12
3 **Tokyo International** (Haneda)	4.77
4 **London Heathrow**	4.48
5 **Dallas Dallas/Fort Worth International Airport**	4.46

1

AVIATION

Capital

The aviation industry will require a capital investment of $5 trillion[138] to develop and implement low-emission technologies and infrastructure. This investment is required from the broader aviation ecosystem to build the necessary infrastructure, such as SAF production facilities and hydrogen refuelling stations at airports.

It is projected by MPP that out of the total additional investment required, about 52% ($2.6 trillion) is anticipated from fuel producers, 44% ($2.2 trillion) from energy providers (including CO_2 capture companies), less than 0.1% from airports, and 4% ($0.2 trillion) from airlines.[139] Thus, the vast majority of investment needs to be carried out to deliver low-carbon fuel, with significant pass-through of cost to airlines and eventually to passenger and cargo customers.

FIGURE 28 **Investments required by the sector and enabled by the ecosystem**

$5 trillion

required in investment by 2050

Investments by the sector
(around 5% of investments)

- 🟢 Retrofit airports with SAF infrastructure
- 🟢 Demand creation via offtake agreements
- 🟢 Invest in R&D for low-TRL technologies
- 🟠 Air traffic management improvement
- 🔵 CO_2 capture (from PSC and DAC)
- 🔵 Build refuelling/recharging infrastructure
- 🔵 Airport hydrogen storage infrastructure

Enabled by the ecosystem
(around 95% of total investments)

- 🟢 SAF production
- 🟢 Low-temperature electrolysers (for hydrogen production)
- 🟢 CO_2 capture plants for SAF
- 🟠 Manufacture more efficient turbines and aerodynamic airframes
- 🔵 Manufacture hydrogen and battery electric aircraft
- 🔵 Renewable electricity production

🟢 SAF 🟠 Fuel efficiency measures 🔵 Novel propulsion technologies

Note: Original equipment manufacturers (OEMs) and manufacturers are classified as the ecosystem in this figure.

Source: Accenture analysis based on data from MPP.

3

AVIATION

Policy

The EU, US and several other high-aviation countries have led the world in both mandate and incentive policies encouraging the adoption of low-carbon technologies, especially SAF. For example, the European aviation ecosystem has come together to develop an action plan to unlock final investment decisions (FIDs) for e-SAF projects in Europe.[140]

Nevertheless, aviation is inherently a cross-border activity and will require harmonization and mutual recognition of carbon accounting frameworks and sustainability standards to ensure transparency and accountability for low-carbon technology deployment. States will need to work with sustainability verification organizations to strengthen the accuracy of emissions reporting and ensure that ecosystem actors adhere to clear, consistent guidelines. The IATA's TrackZero[141] initiative underscores the industry's commitment to promoting standardization and transparency in emissions tracking, facilitating collaboration among airlines and stakeholders to share best practices, and supporting the development and adoption of SAF to reduce reliance on fossil fuels. Book and claim systems, which decouple physical SAF from its environmental attributes, allow buyers to pay for SAF while avoiding the extra cost and inefficiency of transporting SAF to areas that lack the infrastructure to receive it. The proper implementation of book and claim systems will require coherent and reliable policy frameworks across borders.

Improved carbon accounting will also ensure policy compliance and provide essential clarity to both consumers and industry stakeholders, promoting accountability across the sector.

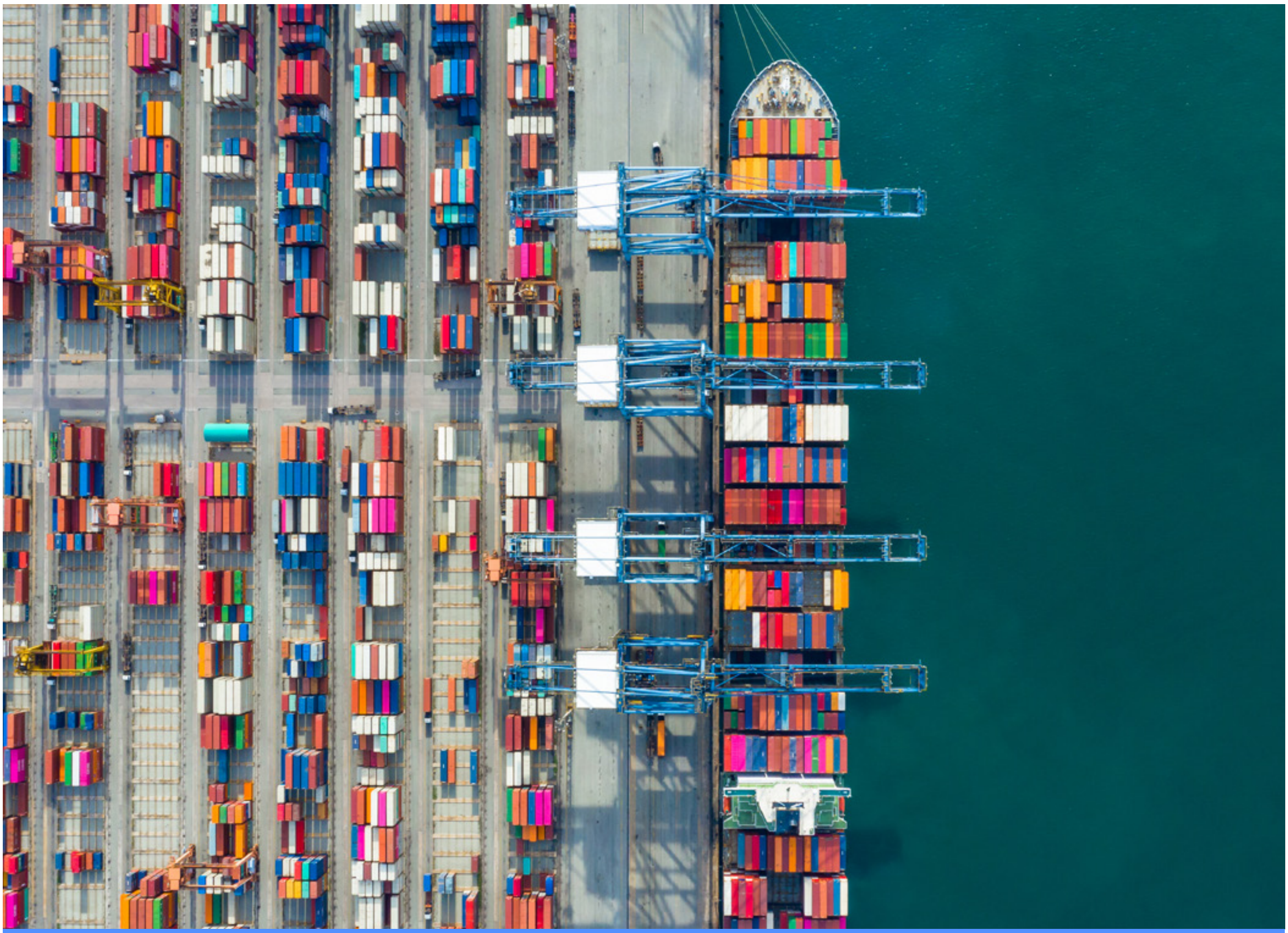
TABLE 5 **Aviation industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	EU Emissions Trading System (ETS)[142]	Sets a cap on carbon emissions that tightens over time. Obligated industries are required to buy allowances for each ton of carbon emitted above this cap and are thus incentivized to reduce emissions due to the cost of purchasing carbon credits or allowances. A total of 20 million "free" allowances are reserved for airlines that use SAF, serving as a quasi-incentive.
	Product standard	ASTM standards for SAF pathways[143]	ASTM is of crucial importance for the aviation fuel industry as it is the basis of the international standard for jet fuel quality, and SAF in particular. It defines which feedstocks must be used, the processes that act on those inputs and the properties of the outputs for each pathway.
Mandate-based	**Direct regulations**	ICAO CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation)[144]	CORSIA obligates certain airlines to offset all international aviation emissions above a baseline from 2019, and thus creates demand for certified carbon offset projects outside the aviation sector. Low-carbon technologies reduce emissions outright and thus lower the amount needed to be offset through CORSIA.
		FAA Aircraft CO_2 standards[145]	These standards mandate fuel efficiency improvements, which reduces emissions per flight, leading to cumulative reductions in CO_2 emissions over the life of an aircraft.
	Government targets	ReFuelEU Aviation mandate[146]	Mandates that from 2025 onwards, a proportion of the fuel supplied at EU airports must be SAF. Starting with a 2% share of SAF from 2025, this proportion is set to gradually increase to 70% from 2050.
Incentive-based	**Subsidies**	US Inflation Reduction Act 45Z tax credit[147]	Lowers the cost of SAF production, making it more competitive with conventional jet fuel, driving greater adoption by airlines.
	Incentives	UK revenue certainty mechanism for SAF[148]	As uncertainty over future revenues remains a barrier to investment, a revenue certainty mechanism will provide greater certainty to investors for a defined period of time, driving investment in SAF production in the UK.
	Direct R&D funds/grants	EU's Clean Sky Initiative[149]	This initiative funds projects on SAF, electric aircraft and advanced aerodynamics to cut carbon footprints.

5

Shipping industry net-zero tracker

Long-term emissions reduction relies on clean hydrogen fuels like ammonia and methanol, while short-term solutions include LNG and biofuels.



- Increased vessel size, improved design efficiency and operational changes like slow steaming have contributed to emission intensity reduction. Efficiency improvements in the short term are also enablers for the long-term transition.
- Continued reliance on fossil fuels remains a major barrier, as they make up nearly all the fuel mix in the sector.

2%	1%	1%
Increase in absolute CO_2 emissions (2022-2023)	Increase in emission intensity (2022-2023)	Increase in demand (2022-2023)

SHIPPING

Key performance data 2023[150,151,152,153]

2%
Contribution to global CO_2e emissions

0.86 Gt CO_2e
International shipping CO_2 emissions (2023)

1.2%
Emissions reduction (2019-2023)

12.4
Emissions intensity (grams per tonne miles, 2023)

99%
Fossil fuels in the fuel mix (2022)

~1.4 times
Demand increase in IRENA's NZE scenario by 2050, compared to 2023

$2.6 trillion
Investment required for 2050 net zero

Performance summary

- The absolute direct CO_2e emissions for shipping were 0.87 Gt in 2019, decreasing to 0.80 Gt in 2020, then increasing to 0.84 Gt in 2022 and 0.86 Gt in 2023.[154] Thus, there has been a 2% increase in absolute CO_2e emissions from 2022 to 2023.
- The industry has reduced emission intensity by 4.6% in the 2019-2023 period.[155] This is mainly driven by speed reduction (slow steaming) especially in bulk carriers, chemical tankers and oil tankers, increase in average ship size, and improvements in ship design efficiency. However, emission intensity increased by 1% from 2022 to 2023 due to the use of inefficient routes and port congestion.

Future emissions trajectory

- As per the IEA's Stated Policies Scenario, which is considered to be the business-as-usual scenario, the absolute CO_2e emissions are expected to be 0.90 Gt in 2030 (5% increase vs. 2023), 0.85 Gt in 2040 (0.2% decrease vs. 2023), and 0.80 Gt in 2050 (7% decrease vs. 2023).[156]
- The 2023 IMO GHG-reduction strategy, which is considered to be the net-zero emissions scenario, aims for at least 20%, striving for a 30% reduction in total annual GHG emissions by 2030 (vs. 2008) and net-zero emissions by or around 2050 for the shipping industry.[157] It also aims for at least 5%, striving for 10% of fuel used by the shipping industry to be zero or near-zero-emission fuels (ZEFs) by 2030.[158]

Readiness key takeaways

Technology	3	⊖	– Methanol engines are in early adoption stage (TRL 9).[159] – Hydrogen- and ammonia-powered engines are in large prototype stage (TRL 5 and 6).[160] – Battery electric (TRL 9)[161] and proton-exchange membrane (PEM) fuel cell technologies (TRL 8)[162] are also in progress.
Infrastructure	2	⊖	– To meet IMO targets, approximately 95% of energy from clean hydrogen-based fuels (like ammonia and methanol) is required by 2050, which will require 72 MTPA of clean hydrogen capacity. Currently, 99% of energy used comes from fossil fuels. – The current supply of low-emission fuels is limited. – The infrastructure readiness score remained the same as last year due to limited progress.
Demand	3	↑	– Only 4% of the 100 near-zero-emission shipping fuel plants needed by 2030 (as per MPP) are currently financed.[163] However, 132% of the plants needed were announced, which contributed to increase in the demand readiness score.[164] – The B2B green premium is high, at 30-80%, posing a challenge for ship owners to absorb the cost of a low-emission freight. While the business-to-consumer (B2C) premium is low, at 1-2%, it is a minor component of the final retail price of products.
Capital	1	⊖	– Achieving net zero by 2050 for shipping requires approximately $2.6 trillion,[165] out of which around $2 trillion is required for ZEFs production facilities and around $0.6 trillion to retrofit the existing fleet with ZEF-compatible engines. – Margins are low for the sector; it is difficult to raise investments in decarbonization due to low profitability. – The capital readiness score remained stagnant due to lack of substantial progress.
Policy	2	⊖	– To meet IMO targets, policies should set production goals for zero-carbon fuels, and establish operational, bunkering and safety standards. – Several proposals have been made to IMO to introduce economic measures and how they can be designed. For example, the World Shipping Council proposed a “green balance mechanism” in 2024 to help close the gap between low-carbon fuels any fossil fuels.[166]

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Adopt new fuels derived from clean hydrogen at scale and continue exploring biofuels for a transition period, since biofuels are expected to form approximately 8% of fuel mix by 2030 as per the IEA’s NZE scenario.[167]
- Improve efficiency measures reducing the emission intensity through engine improvements, operational behaviour and design and hull options. Energy efficiency is expected to reduce emissions by 20%.[168]

Long-term (by 2050)

- Develop and deploy next-generation ships that run on zero-carbon fuels, since hydrogen-based fuels are expected to form approximately 66% of fuel mix by 2050 as per the IEA’s NZE scenario.[169]
- Form partnerships with fuel providers to deliver alternative clean fuels.

Ecosystem-enabled solutions

Mid-term (by 2030)

- Expand the production and availability of low- and zero-carbon fuels like green ammonia, hydrogen and sustainable biofuels.
- Develop cold ironing infrastructure to provide shore power to ships while docked in port.
- Develop bunkering technologies and infrastructure to support next-generation ships that run on zero-carbon fuels.

Long-term (by 2050)

- Develop infrastructure to support ships using clean hydrogen-based ZEFs including ammonia and methanol. Ammonia is expected to form approximately 50% and methanol approximately 3% of fuel mix by 2050 as per the IEA’s NZE scenario.[170]

Performance

The sector currently accounts for 2% of global CO_2e emissions. Fuel combustion during maritime operations has a major contribution to emissions in the shipping sector. Thus, the fuel mix used is a critical driver for emission intensity.

TABLE 6 **Shipping industry performance**

Performance metric	Change (2019-2023)
Industry output	+3.6%[171]
CO_2e emission intensity	-4.6%[172]
Total CO_2e emissions	-1.2%[173]

In the last five years (2019-2023), shipping saw an increase in global demand, while the CO_2e emission intensity (CO_2e emissions per cargo ton mile) saw a reduction of 4.6%. This decrease can be attributed to several key factors:

1. **Increase in average ship size**: The increase in average ship size across various ship types played a crucial role in reducing emission intensity.

2. **Slow steaming**: The intentional reduction in vessel speeds, known as "slow steaming" for bulk carriers, chemical tankers, container ships and oil tankers significantly contributed to lowering emission intensity.

3. **Improvements in design efficiency**: Significant advancements in the overall design efficiency of oil tankers, bulk carriers and chemical tankers led to improvement in the energy efficiency of ships, and hence further contributed to the reduction in emission intensity.

However, these improvements in efficiency, speed and size optimization alone will not be sufficient to achieve net-zero targets. In addition, ship owners are confronted with the challenge of an ageing fleet, with the global fleet averaging 22.2 years of age in 2023.[174] This presents two key issues: firstly, there is a need to introduce new vessels that run on ZEFs to replace older ships, and secondly, the existing ships need to be retrofitted with dual-fuel engines to enable operation on ZEFs.

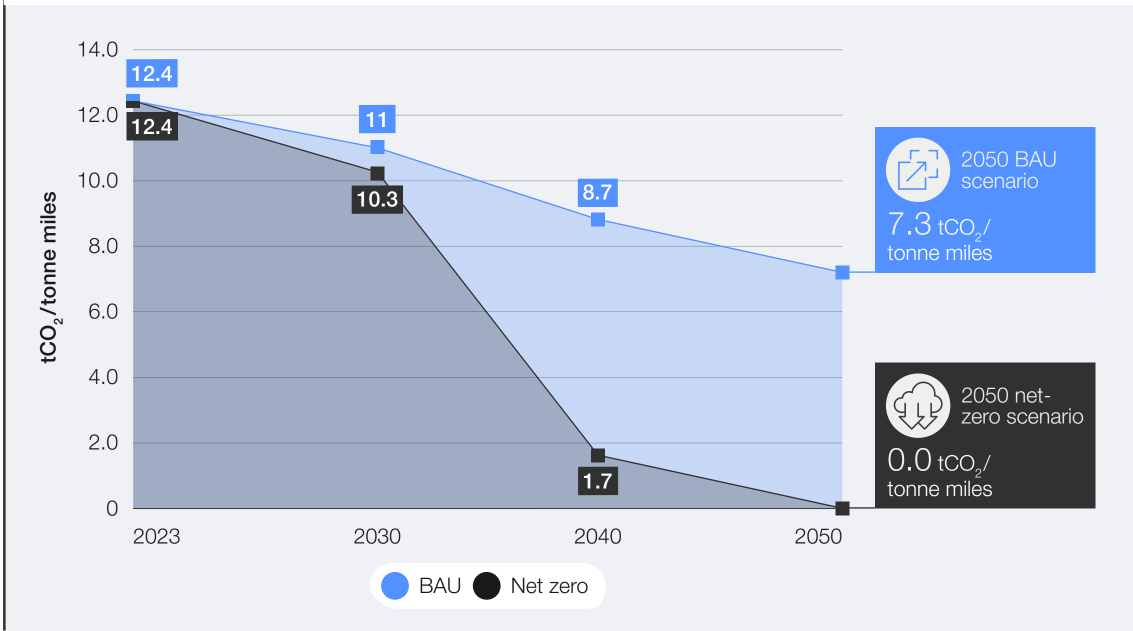
The fuel mix remains heavily dependent on fossil fuels, accounting for approximately 99% of total energy consumption. In 2022, heavy fuel oil (HFO) comprised 56% of the fuel mix, an increase from 49% in 2021, driven by a decline in the use of light fuel oil (LFO) and liquified natural gas (LNG). LNG represents approximately 6% of the fuel mix, while methanol usage remains minimal, representing less than 1% of the overall fuel mix. A substantial change in the fuel mix trajectory is required to effectively eliminate Scope 1 emissions.

Therefore, it is imperative to promote the production and use of clean hydrogen-based ZEFs. Yara Clean Ammonia, North Sea Container Line and Yara International formed a strategic partnership to develop the world's first container ship powered by clean ammonia as a fuel source in 2023.[175] Maersk launched its first methanol-powered container ship in 2024.[176] In collaboration with MAN Energy Solutions, MITSUI successfully tested the world's first hydrogen-powered marine engine in 2024.[177]

Readiness

FIGURE 29

Emission intensity trajectory for shipping sector



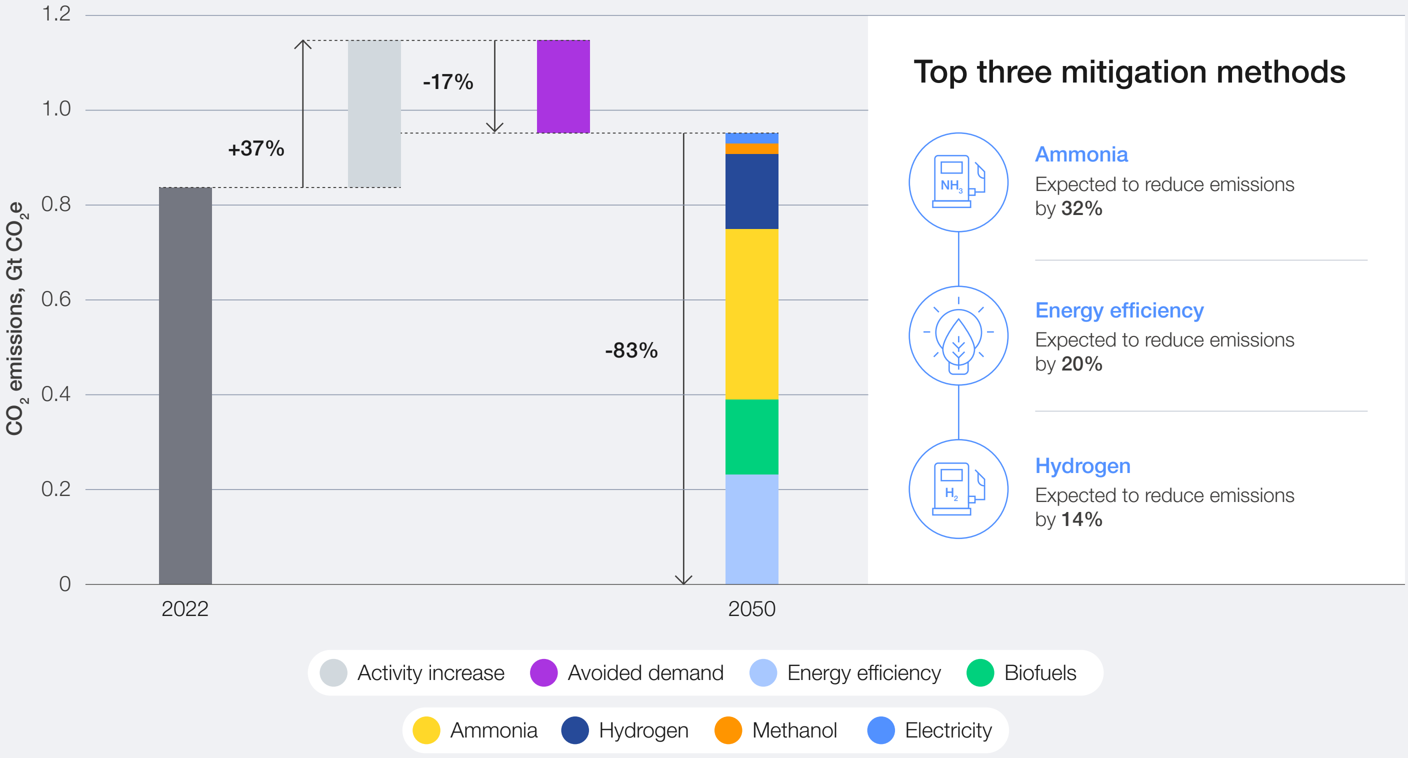
Source: Accenture analysis derived from IEA and IMO.

Overall shipping demand is expected to grow by 37% by 2050 as per the IRENA 1.5 degree scenario.[178] Dry bulk, containers, chemicals and gas tankers will account for most of the growth in shipping demand. Increasing international trade, industrialization and urbanization in emerging markets, and growth in global population (leading to rising consumption and infrastructure requirements) are expected to be the main drivers for demand growth.

Thus, the industry needs to act quickly on decarbonization to ensure reduction in emission intensity and to offset the increase in demand. The key mitigation pathways are expected to be use of hydrogen-derived alternative fuels in the fuel mix and increasing the energy efficiency.

FIGURE 30

Decarbonization levers and top mitigation methods (IRENA's NZE Scenario)



Top three mitigation methods

Ammonia
Expected to reduce emissions by **32%**

Energy efficiency
Expected to reduce emissions by **20%**

Hydrogen
Expected to reduce emissions by **14%**

Source: Accenture analysis derived from IRENA and IMO.

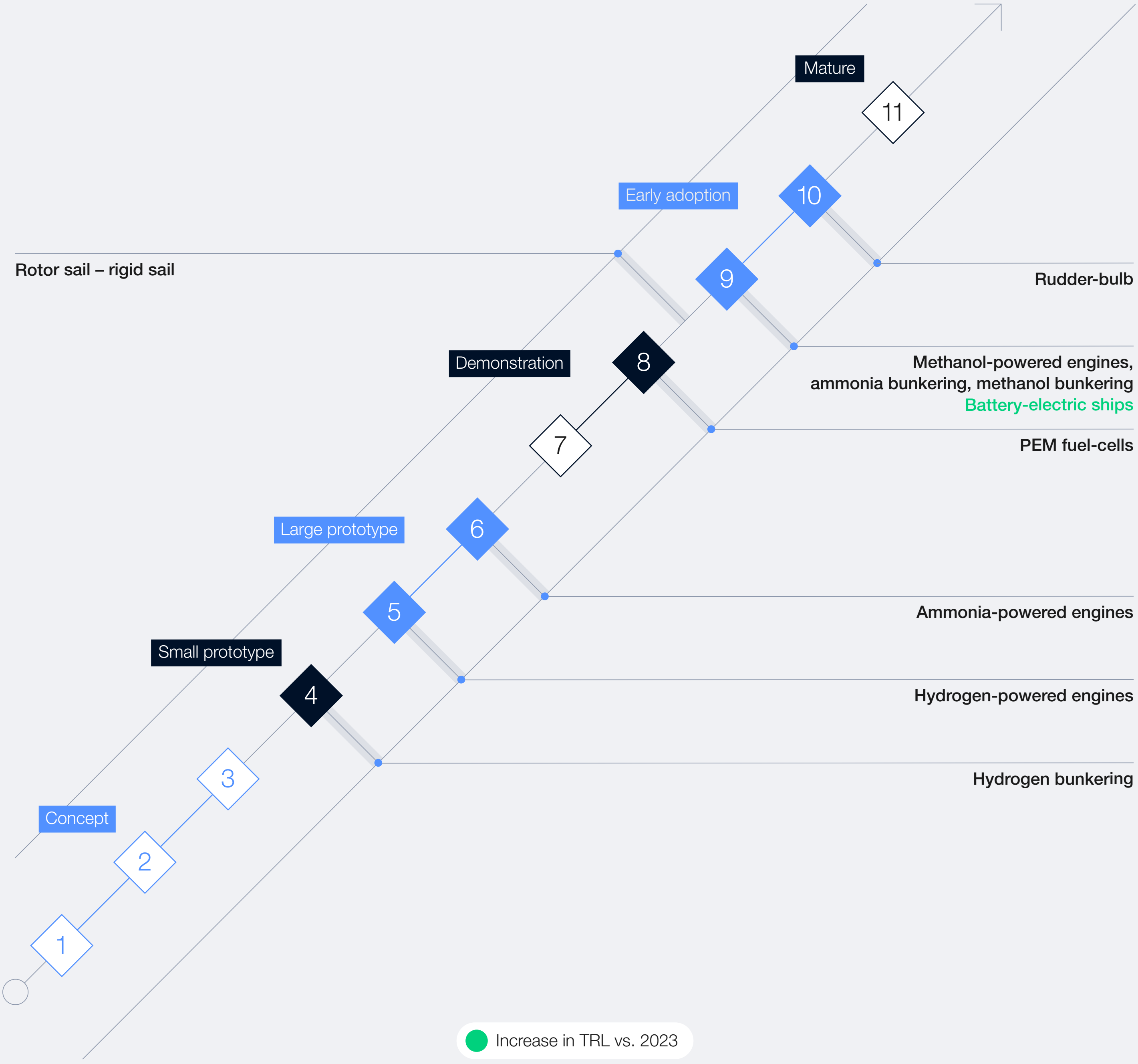
3

SHIPPING

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Three key pathways are currently available: zero emission fuels and propulsion technologies, low-emission transition fuels and energy efficiency.

FIGURE 31 **Decarbonization TRLs**



Source: Accenture analysis derived from data from IEA ETP Clean Energy Technology Guide.

Technology pathway 1:
ZEFs and propulsion technologies

Hydrogen, ammonia and methanol produced using low-carbon hydrogen have up to 99% GHG emission reduction benefits compared to low-sulphur fuel oil (LSFO).[179] The switch to alternative fuels will come at a cost. The ship owners' total cost of ownership (TCO) is expected to be 40-80% higher for methanol-powered ships and 30-70% higher for ammonia-powered ships, compared to ships running on LSFO, based on future cost projections.[180] Since methanol combustion generates CO_2, it is important to mitigate these emissions, which can be done by using CCS technology. This could lead to overall negative emissions if biogenic CO_2 is used for producing methanol, and the captured CO_2 is stored permanently afterwards. At present, the production of clean hydrogen-based fuels for the shipping sector remains primarily in the demonstration phase, with full-scale commercial deployment yet to be realized. Advancements have been made with the expansion of green hydrogen production facilities in China and the US, but production is stalling in Europe. H-TEC SYSTEMS, a subsidiary of MAN Energy Solutions has established a manufacturing facility in Germany for PEM electrolysis stacks to produce green hydrogen in 2023.[181]

The development of a ZEF-powered shipping fleet is essential for the industry to meet its net-zero emissions targets. Methanol-powered vessels are in early adoption stage (TRL 9),[182] and while they have already been commercialized, they have not been adopted at scale. Hydrogen- and ammonia-powered engines are in large prototype stage (TRL 5 and 6).[183] Battery-electric ships, in which the power of propulsion comes from batteries, are in early adoption stage (TRL 9),[184] and PEM fuel cells are in demonstration stage (TRL 8)[185] for small and medium vessels.

Technology pathway 2:
Low-emission transition fuels

While ZEFs are expected to lead the industry towards its net-zero targets, low-emission transition fuels like LNG and biofuels will be important to support emission reduction until the production and use of ZEFs reaches desired levels. LNG-fuelled ships have up to 21% GHG (well-to-wake) emission reduction benefits as compared to oil-based marine fuels.[186] The ship owners' TCO is expected to be only 0-8% higher for LNG-fuelled ships, and 10-30% higher for ships powered by biofuels, compared to ships running on LSFO, based on future cost projections.[187] Advancements have been seen in expansion of biofuel production. Finnish biofuel producer Neste started commercial production at its renewable fuels' expansion project in Singapore in 2023.[188]

Technology pathway 3:
Energy efficiency

Improving the energy efficiency of ships is a key lever for emissions reduction for the industry, and several technologies are being developed to optimize the energy consumption of ship engines. For example, the use of sails to harness wind power has demonstrated a 5-8% reduction in shipping power consumption, and this technology is currently in demonstration to early adoption stage (TRL 8-9).[189] Another example is the use of rudder bulbs and ship propellers, which can prevent loss of energy by reducing drag. These technologies are expected to reduce ships' fuel consumption by 10% and are in early adoption stage (TRL 10).[190] The use of different types of fuel cells – such as high temperature proton exchange membrane fuel cells (HT-PEMFC), molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) – is also being considered, since fuel cells are more energy efficient than internal combustion maritime engines and do not emit pollutants.

2

SHIPPING
Infrastructure

To meet the 2050 net-zero targets, a clean hydrogen capacity of 72 MTPA[191] will be required to produce ZEFs. This will have a 95% share of the total fuel mix in 2050 as per the Global Maritime Forum.[192] Shipyard capacities will also need to be expanded to accommodate the new dual-fuel and ZEF-compatible ships. The first ship-to-ship transfer of ammonia in an operational port environment was successfully completed in 2024, a result of the collaboration between Yara Clean Ammonia, Pilbara Ports Authority and the Global Centre for Maritime Decarbonisation (GCMD).[193]

With the addition of new ZEF-powered ships to meet the 2050 net-zero targets, it will be crucial to develop the supporting bunkering infrastructure for different ZEFs. In 2050, 95% of the fuel mix is expected to be ZEFs, which will require a bunkering capacity of approximately 913 MTPA.

FIGURE 32 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean hydrogen production	Less than 1 MTPA	72 MTPA
CO_2 transport and storage	Less than 1 MTPA	135 MTPA
Bunkering	Less than 1 MTPA	913 MTPA

Source: Accenture calculations based on GMF.

3

SHIPPING
Demand

There is a lack of clear demand signals from the market, particularly around customers' willingness to pay. For instance, the exact fuel requirements to achieve the net-zero targets are still unclear to fuel producers and ship developers. Due to this, companies are hesitant to develop new ZEF-powered engines and sign long-term fuel-offtake agreements. Moreover, carriers are currently used to buying fuel on the spot and expect the cost of ZEFs to decrease in the future, which reduces the attractiveness of long-term fuel-offtake agreements.

The estimated B2B green premium for the shipping industry is high, at 30-80%. The green premium projections for low-emission fuels and ZEFs also remain high. For example, biofuels are expected to cost 2-4 times the cost of heavy fuel oil, and hydrogen-based fuels are expected to cost 4-4.5 times the cost of heavy fuel oil.[194]

However, this green premium only translates to a 1-2% increase in the final retail price to customers (in case of high-value products such as IT equipment), since shipping costs form a small percentage of the price of products. While the percentage increase of end-customer price is low, in absolute terms this is a significant increase in price of essential commodities like oil, grains and metals, and has a significant impact on developing countries.

The FMC has set ambitious targets for the uptake of technologies by 2030 to enable longer-term decarbonization in 2050. Carriers have committed that at least 5% of their deep-sea shipping will be powered by ZEFs by 2030. Cargo owners have committed that at least 10% of their goods volume shipped via deep-sea shipping will be on ships powered by ZEFs by 2030, progressing towards 100% by 2040.[195]

Some players in the shipping industry are exploring the "book and claim" approach until the production and widespread availability of ZEFs improves globally. In this approach, shipping companies can purchase low-emission fuels or ZEFs (even if that fuel is not physically being used by their ships) in return for emission-reduction credits or certificates to offset their own emissions. This approach allows shipping companies to support the decarbonization of the industry (by contributing to the green premiums) and help sustain the demand for low-emission fuels and ZEFs. It also facilitates a faster, less challenging and more cost-efficient transition, as it allows a few assets to decarbonize fully, rather than asking all assets to marginally decarbonize year-on-year. Rock Mountain Institute (RMI) and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) are collaborating with the Zero Emission Maritime Buyers Alliance (ZEMBA) and Hapag-Lloyd to pilot a Maritime Book and Claim System.[196] Mitsui has become the first Japanese company to join the Book and Claim Community (BCC) board.[197]

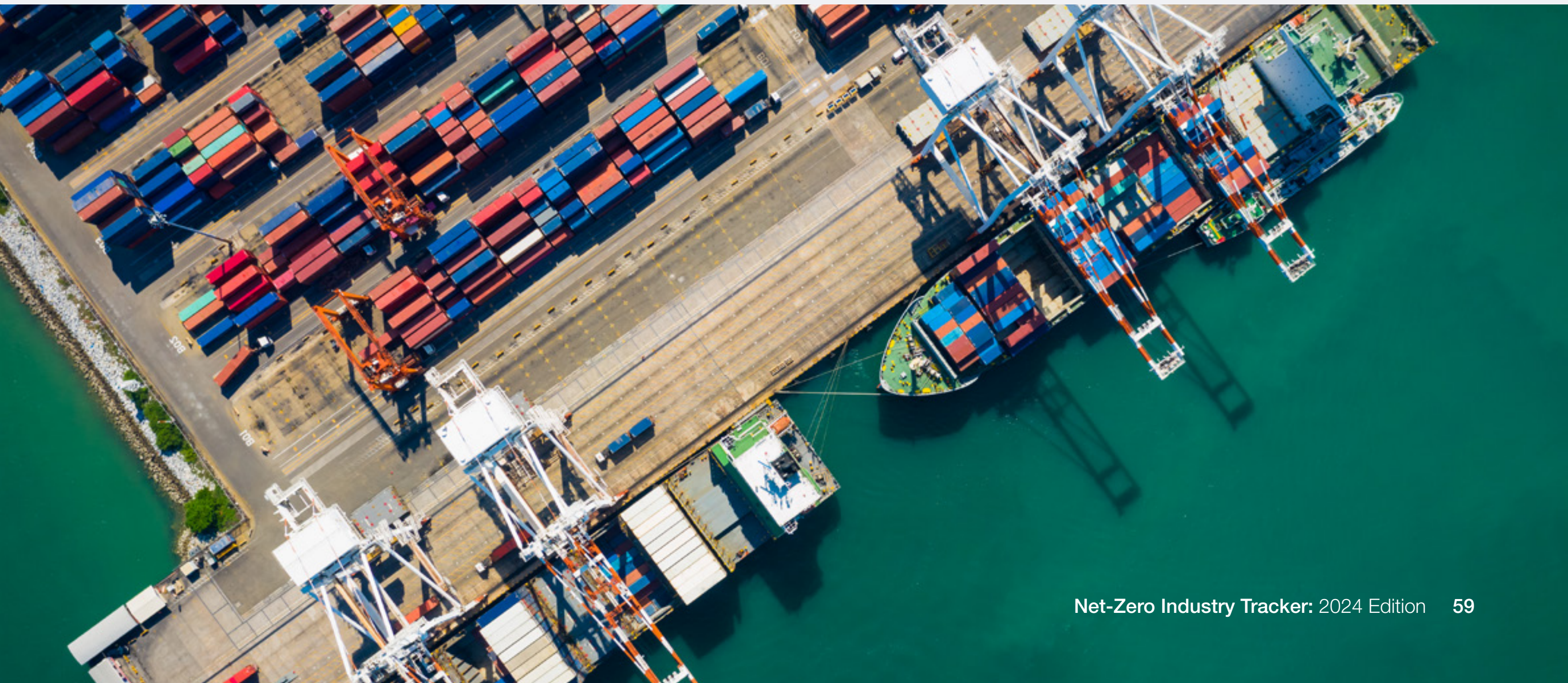
FIGURE 33

Top countries/regions for shipping trade volume (2022) and ships built (2023)

Percentage of overall sea trade volume		
1	China	32%
2	US	7%
3	Singapore	4%
4	South Korea	3%
5	Malaysia	3%

Percentage of total ships built		
1	China	51%
2	South Korea	28%
3	South Korea	15%
4	Philippines	1%
5	Vietnam	1%

Source: United Nations Trade and Development (UNCTAD).



1

SHIPPING

Capital

The shipping industry will need substantial capital investment to advance the production of ZEFs and development of a ZEF-compatible shipping fleet, with an estimated requirement of $2.6 trillion.[198] This comes to an additional annual capital investment of around $91 billion, which is more than double the existing annual CapEx of $44 billion[199] in the shipping sector. The majority of this additional investment must come from the ecosystem (and not only shipping companies) to build the enabling infrastructure. Shipping decarbonization requires a scale-up of clean hydrogen, CCUS and bunkering infrastructure. The shipping sector needs to invest in retrofitting the existing fleet with dual-fuel engines to support the use of low-emission fuels and ZEFs.

It is projected that out of the total additional investment required, about $2 trillion[200] is expected to go towards ZEF production infrastructure (the majority of which will be for setting up of clean hydrogen capacity) followed by bunkering and CCUS capacity. Retrofitting the existing fleet with dual-fuel engines will require approximately $0.6 trillion of the total additional investment, based on the average cost of retrofitting being between $5 million and $15 million per ship.[201]

FIGURE 34 **Investments required by the sector and enabled by the ecosystem**

$2.6 trillion

required in investment by 2050

Investments by the sector (around 22% of investments)

- 🟢 Adopt new ZEFs (ammonia, methanol)
- 🟢 Partner with fuel providers to deliver ZEFs
- 🟠 Adopt low-emission transition fuels (LNG, biofuels)
- 🟠 Partner with fuel providers to deliver transition fuels
- 🔵 Develop new ZEF-compatible vessels
- 🔵 Develop dual-fuel engines to retrofit existing shipping fleet
- 🔵 Adopt battery-electric ships using PEM fuel cells

Enabled by the ecosystem (around 78% of total investments)

- 🟢 Develop clean hydrogen production capacity
- 🟢 Expand production of ZEFs (ammonia, methanol)
- 🟠 Expand production of low-emission transition fuels (LNG, biofuels)
- 🔵 Develop bunkering infrastructure for ZEFs
- 🔵 Develop battery charging stations at ports

🟢 Zero-emission fuels 🟠 Low-emission fuels 🔵 Propulsion technologies

Source: Accenture analysis based on data from S&P and DNV.

The shipping industry's return on invested capital (ROIC) is at 13%[202] and its WACC is at 8.4%.[203] This narrow margin means that without additional support from external factors (such as technological advancements, policy incentives and industry collaboration), the industry may struggle to afford and implement the significant changes needed for effective decarbonization.

2

SHIPPING

Policy

The global shipping industry is governed by the IMO's regulations. In 2023, the IMO updated its GHG strategy to aim for net-zero emissions by or around 2050, as well as 2030 and 2040 mid-term targets and a goal for uptake of zero or near-zero emission fuels to be 5% (striving for 10%) by 2030.[204] In addition to the IMO strategy, there are several key regional policies playing a critical role in supporting the decarbonization of the shipping industry. The EU's Emissions Trading System for shipping, which sets limits on GHG emissions and requires shipping companies to purchase carbon credits for their emissions in voyages involving EU ports, has been extended in 2024 to cover all large ships (of 5,000 gross tonnage and above) entering EU ports.[205] The FuelEU Maritime regulation, which will be effective in the EU from January 2025, has set a GHG emission-reduction target of 2% in 2025 (vs. 2020), increasing to 6% in 2030 to reach 80% in 2050.[206]

As part of the ongoing meetings and negotiations of the IMO's Marine Environment Protection Committee (MEPC), several countries and organizations, including two prominent shipping trade associations, have submitted proposals. One of these is from the World Shipping Council, which represents members primarily in the container shipping segment. It has proposed a green balance mechanism to help close the gap between low-carbon fuels and fossil fuels. The mechanism would apply a fee to ships using fossil fuels and allocate credits to those using low-carbon fuels, ensuring that the average cost of fuel is equal.[207] The next significant step on the policy lever will be the Spring MEPC83 meeting in the IMO.

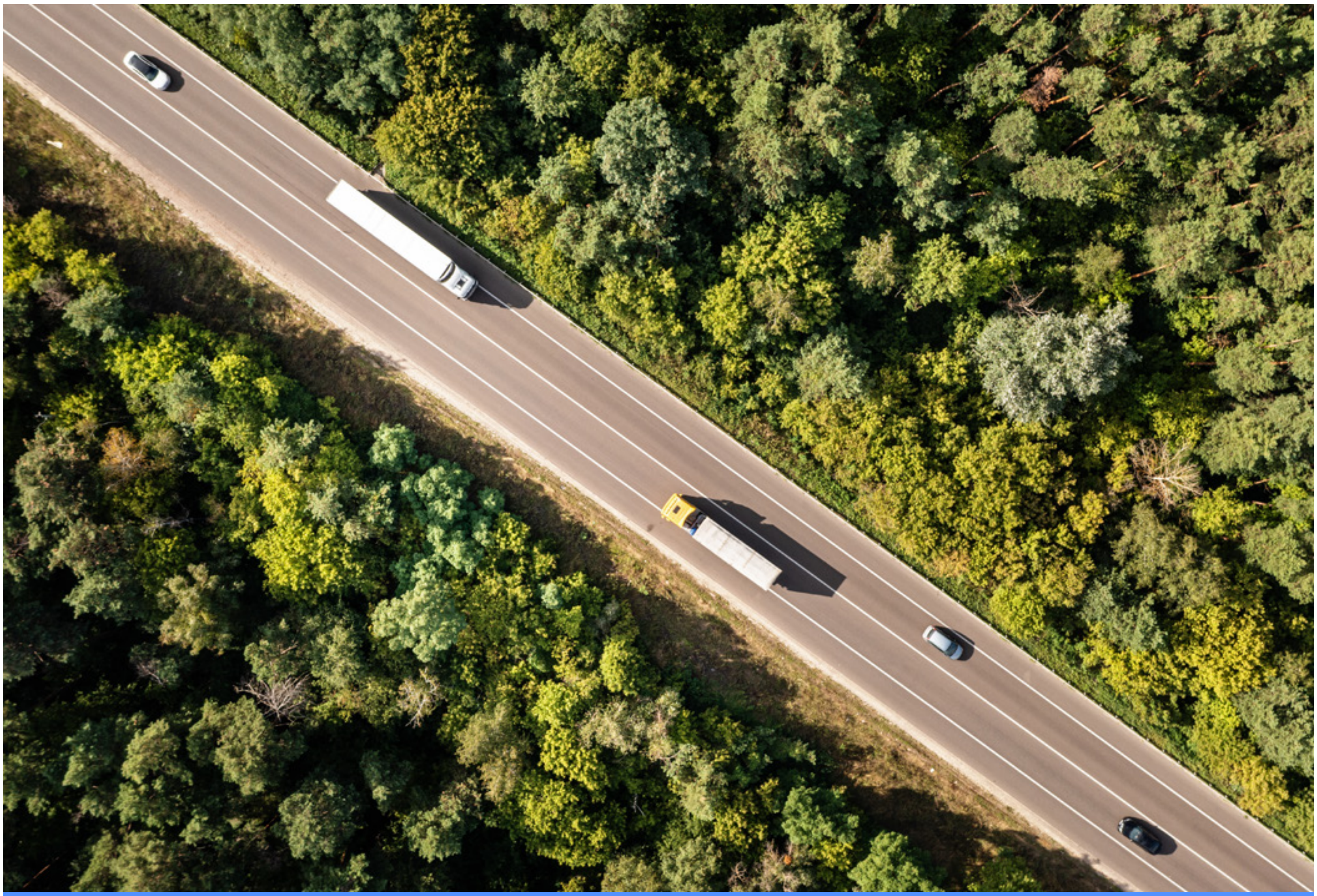
TABLE 7

Shipping industry policy summary

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	– EU-ETS[208] – US International Maritime Pollution Accountability Act: $150 per tonne of CO_2 emissions proposed[209] – IMO economic measure, 2023 strategy[210]	Up to $10 billion a year of additional costs for the industry due to the need to acquire carbon credits once the EU-ETS is fully implemented in 2026.[211] The proposed US carbon pricing is projected to bring in $250 billion in low-emission funding over the next 10 years.[212] Carbon pricing under IMO is still under discussion and will not be in effect before 2027.
Mandate-based	**Performance standards and certification**	– Energy Efficiency Design Index (EEXI)[213] – Carbon Intensity Indicator (CI)[214]	Ships must comply with these mandatory standards, which are intended to drive continuous technical and operational improvements.
	Direct regulation	– EU Alternative Fuels Infrastructure Regulation	These are mandates for major EU ports to provide shore-side electricity to vessels. They reduce emissions at ports by providing cleaner electricity as an alternative, with a specific timeline for ports to act upon (by 2030).
	Fuel standards	– FuelEU Maritime regulation[215] – US Clean Shipping Act[216] – IMO technical measure, 2023 strategy[217]	These are predictable pathways for low-emission fuels that encourage adoption and drive demand.
Incentive-based	**Taxes and subsidies**	– IRA clean power and green hydrogen production tax credits[218]	These credits have encouraged a 50% reduction in green hydrogen production costs, which can boost scaling of green hydrogen capacity required for low-emission fuels.[219] The feasibility of such subsidy-driven policies for developing economies is uncertain.
	Green corridors	– Green corridor pledge at COP28 between the US and UK[220]	This pledge reduces the risks of adopting low-emission fuels by deploying at a local scale and mobilizing demand. So far, 44 green corridor initiatives have been announced, involving over 171 stakeholders.[221]
	Direct funding	– Public funding for converting diesel plants to hydrogen and setting up charging stations in Croatia[222]	This provides new funds for hydrogen projects, the retrofitting of diesel plants to hydrogen and the establishment of charging stations for maritime transport.

6 Trucking industry net-zero tracker

The industry must advance electric and hydrogen trucks for long-term emissions cuts, while prioritizing biofuels, synfuels and efficiency improvements for near-term impact.



- Global trucking demand is expected to double by 2050, making decarbonization of the trucking sector critical, as it remains a major source of CO_2e emissions due to continued fossil fuel reliance.
- Hydrogen- and battery-powered electric trucks are expected to be key pathways to net-zero emissions trucking by 2050.

1.3%	1.1%	2.4%
Increase in absolute CO_2 emissions (2022-2023)	Decrease in emission intensity (2022-2023)	Increase in demand (2022-2023)

TRUCKING

Key performance data 2023[223,224,225,226]

5%	Contribution to global CO_2e emissions
1.9 Gt CO_2e	Scope 1 and 2 emissions
6%	Emissions increase (2019-2023)
58 gCO_2/tkm	Emissions intensity
14%	Decrease in emission intensity (2019-2023)
2 times	Demand increase in NZE scenario by 2050, compared to 2023
<1%	Current low-emission infrastructure
~$9 trillion	Additional investment required for net zero by 2050

Performance summary

- The direct emissions[227] were 1.89 Gt CO_2e[228] in 2023, a 6% reduction from 1.78 Gt CO_2e[229] in 2019.
- The industry has decreased emission intensity by 14%[230] in the last five years, driven by improvements in fuel efficiency.
- Activity is at all-time high, at 32.8 trillion ton-km[231] in 2023 as sector recovers from the COVID-19 pandemic, compared to 26.6 trillion ton-km in 2019.
- Low-emission fuel consumption contributed 4%[232] to the total fuel share of the heavy-duty trucking sector.
- Energy intensity was reduced by 15% from 1.24 MJ/ton-km in 2019 to 1.05 MJ/ton-km in 2022.[233]

Future emissions trajectory

- The industry is forecast to reduce emissions intensity by 28% by 2030 and 94% by 2050, compared to 2023 levels, according to the IEA.[234] The direct CO_2e emissions are expected to be 1.4 Gt in 2030 and 0.22 Gt in 2050.[235]
- According to MPP, 7 million[236] zero-emission trucks will be required by 2030 to align with net-zero emissions by 2050.

Readiness key takeaways

Technology	3	↑	– Compressed and liquified biogas and synfuels technologies (being the most mature) are in the early adoption stage (TRL 9).[237] – Hydrogen fuel cell technology is in the demonstration stage (TRL 8), and battery electric trucks are in commercial operation in the relevant environment stage (TRL 9). However, hydrogen internal combustion (hydrogen IC) trucks are in the prototype stage.[238]
Infrastructure	1	↓	– Current infrastructure capacities are insufficient, as less than 1% of the necessary infrastructure is in place. This falls short of what is needed to enable the adoption of battery-electric trucks (BETs) and hydrogen-electric trucks (HETs).[239] – Approximately 700 GW of clean power and 50 MTPA of hydrogen infrastructure is required for net-zero emissions by 2050.[240]
Demand	2	⊖	– Approximately 4% of current trucking fuel consumption comes from low-emissions sources.[241] – The green premium is estimated at 80% for manufacturers and original equipment manufacturers (OEMs), which translates to 1-3% for end consumers.[242]
Capital	1	⊖	– Up to $9 trillion[243] additional cumulative investments are required by 2050 to achieve net-zero emissions by 2050, translating to an additional $320 billion annually until 2050. – Currently, the trucking sector has an annual CapEx of $286 billion.[244]
Policy	3	⊖	– Stricter GHG standards and ambitious ZET targets are being announced by governments. There is an increasing set of policies for infrastructure deployment strategy, incentives, subsidies, weight and dimension allowance, and carbon tax.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Accelerate the adoption of drop-in biofuels and synfuels in the interim.
- Invest in the development of BETs and HETs.
- Make use of efficiency and design improvement opportunities at an accelerated pace.

Long-term (by 2050)

- Accelerate the development of hydrogen- and battery-electric technologies for long-haul applications.

Ecosystem-enabled solutions

Mid-term

- Invest in clean power infrastructure to increase access to renewable energy sources.

Long-term

- Invest in R&D to accelerate the deployment of ultra-fast charging infrastructure.
- Coordinate with other sectors to achieve economies of scale for biofuels, hydrogen and grid requirements.

Performance

The sector currently accounts for 5%[245] of global direct CO_2e emissions. Fossil fuels account for approximately 96%[246] of fuel consumption in the industry, making them a critical driver for emission intensity.

TABLE 8

Trucking industry performance

Performance metric	Change (2019-2023)
Industry activity (trillion ton-km)	+23%[247]
Emission intensity (gCO_2/ton-km)	-14%[248]
Total CO_2e emissions	-6%[249]

In 2023, the trucking sector produced 1.89 Gt CO_2e in direct emissions, marking a 6% increase from 1.78 Gt CO_2e in 2019.[250] Despite the growth in emissions, the industry has made significant strides in reducing emission intensity, achieving a 14%[251] reduction over the past five years due to improvements in fuel efficiency. Trucking activity reached an all-time high of 32.8 trillion ton-km in 2023, compared to 26.6 trillion ton-km in 2019, as the sector recovered from COVID-19 pandemic-related disruptions.[252]

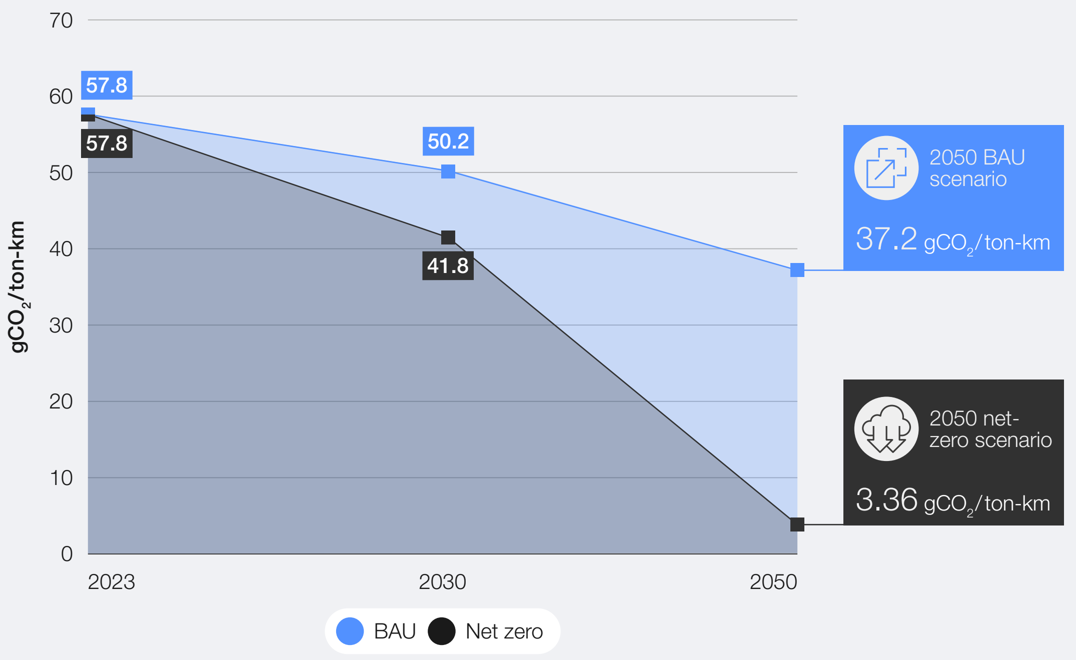
The sector's energy intensity dropped by 15%, from 1.24 MJ/ton-km in 2019 to 1.05 MJ/ton-km in 2022.[253] Low-emission fuels, while representing a small share of the total fuel used in the sector, highlight the growing (albeit slow) shift away from diesel. For example, Tesla delivered its highly anticipated Tesla Semi,[254] marking a major step towards the electrification of long-haul trucking. The electric trucks, delivered to PepsiCo, demonstrated a range of up to 500 miles on a single charge, pushing the boundaries of what electric trucks can achieve in long-haul operations.

However, with global trucking demand expected to double by 2050,[255] further innovation and policy actions are essential to accelerate the sector's transition to net zero.

Readiness

FIGURE 35

Emissions intensity trajectory for the trucking sector



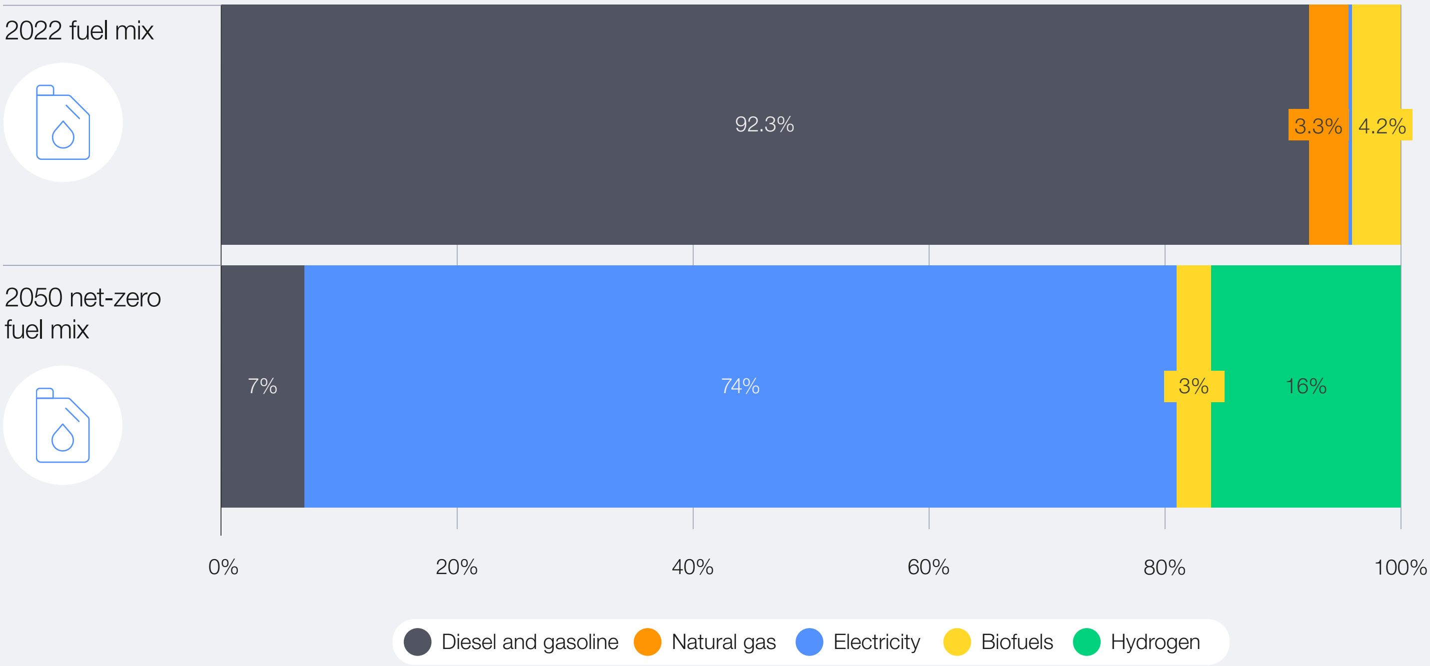
Source: IEA Net Zero Scenario.

The trucking industry is on a path to significantly reduce its carbon emissions, with the goal of cutting emissions intensity by 28% by 2030 and 94% by 2050, according to the IEA's Net-Zero Scenario.[256] By 2050, direct CO_2e emissions are expected to drop to just 0.22 Gt, down from 1.89 Gt in 2023.[257] Achieving this goal will require the deployment of 7 million zero-emission trucks by 2030, as outlined by the Mission Possible Partnership (MPP).[258] Currently, the adoption of alternative fuel technologies remains in the early stages: compressed and liquified biogas and synfuels are in their mature phase but still early in market penetration, while BETs and HETs are in the demonstration phase.

Infrastructure readiness is a critical challenge, with less than 1%[259] of the necessary infrastructure for BETs and HETs in place. Massive clean energy investments are needed, including 700 GW of renewable power and 50 million tons per annum of hydrogen capacity by 2050.[260]

The shift to zero-emission trucks comes with high costs; the green premium for manufacturers stands at 80%, which translates to a 1-3% price increase for consumers.[261] Up to $9 trillion[262] in additional investments are required by 2050, amounting to an extra $320 billion annually. Despite these challenges, governments are announcing stricter emissions standards and more ambitious zero-emission truck targets, with global collaboration on infrastructure expected to accelerate innovation and adoption.

FIGURE 36 **Fuel mix in 2022 and 2050 (NZE Scenario)**



Source: IEA Net Zero Scenario.

3

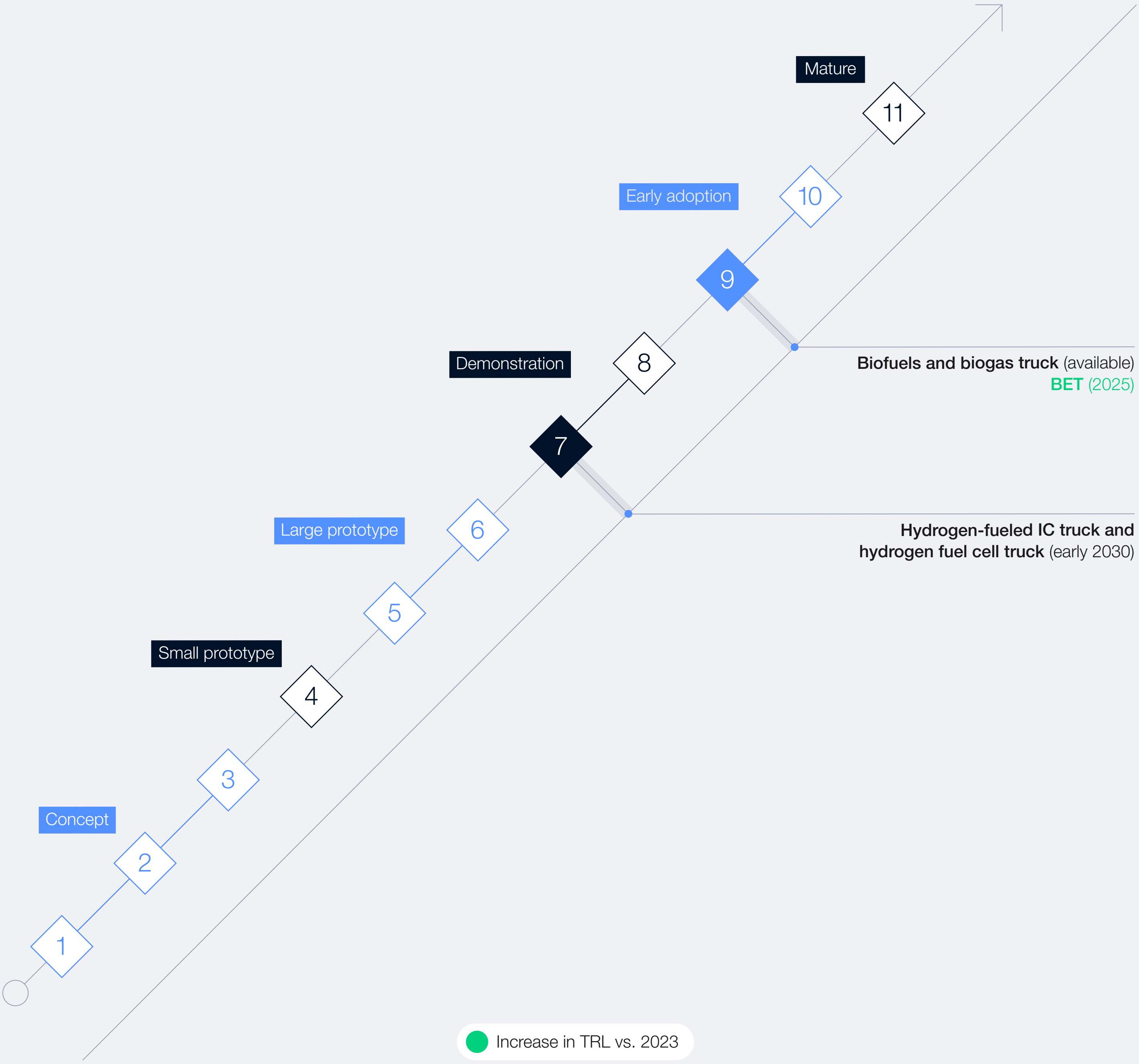
TRUCKING

Technology

Technologies to achieve net-zero emissions are at different readiness levels. Two leading levers have emerged: BETs and HETs.

FIGURE 37

Decarbonization TRLs and year of commercial availability



Biofuels and biogas truck (available)
BET (2025)

Hydrogen-fueled IC truck and hydrogen fuel cell truck (early 2030)

Source: Accenture analysis based on data from IEA ETP Clean Energy Technology Guide and MPP.

Technology lever 1: BETs

BETs are in the early adoption stage with a TRL at 8-9.[263] Electric trucks use batteries (today almost exclusively lithium-ion batteries) arranged in a battery pack. The battery pack is combined with inverters and an electric motor to convert electrical energy into mechanical energy. Heavy-duty trucks in particular require either devoted infrastructure (e.g. battery swapping) or high-energy density battery chemistries (e.g. solid-state batteries, as of 2023, are at the prototype level) to be competitive. Medium-duty trucks have similar (but less demanding) requirements.

Technology lever 2: HETs

HETs are based on two types of technology: hydrogen fuel cell trucks (TRL 8-9[264]) and direct hydrogen internal combustion trucks (TRL 7). Hydrogen fuel cell trucks have significant advantages for long-haul trucking. Compared to BETs, they offer longer driving ranges and faster refuelling times – typically within 10 to 15 minutes,[265] which is similar to conventional diesel trucks. In addition, fuel cells can consistently provide power without the need for large, heavy battery packs, making them a viable option for heavier freight transport.

Hydrogen internal combustion trucks involve combusting hydrogen directly in an engine that does not rely on fuel cells. Although less energy efficient than fuel cells today (40-50% efficiency for hydrogen engines vs. 50-60% for fuel cells[266]), the hydrogen engine does not require rare materials like platinum and could represent a cost-effective solution. Hydrogen internal combustion engines may also offer transient behaviour that performs more effectively and is easier to regulate than fuel cells. Over the longer term, it could also reach up to 55%[267] energy efficiency for trucks; as such, it could be particularly suitable for heavy-duty applications. R&D (at TRL 5-6[268]) is currently underway to improve fuel efficiency, which is another key area of future development for this technology.

1

TRUCKING

Infrastructure

The commercial deployment of BETs and HETs depends heavily on the availability of essential infrastructure. Currently, less than 1%[269] of the required infrastructure is in place, which is inadequate to support the widespread adoption of BETs and HETs. To meet the projected goal of having 53% BETs and 47% HETs on the road by 2050, the trucking industry will need a substantial increase in clean power and hydrogen production capacity to meet expected 700 GW of clean power and 50 MTPA of hydrogen infrastructure capacity by 2050.[270]

For BETs to become feasible for medium- and long-haul transport, they need access to charging infrastructure, both on-site and on the road. By 2050, an estimated 31 million EV public charging points will be required to meet the rising demand for BETs.[271] HETs require access to on-site hydrogen refuelling infrastructure. An estimated 46,000 hydrogen refuelling stations are required to meet the demand for HETs by 2050.[272]

FIGURE 38 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean power generation	Approximately 0 GW	Approximately 700 GW
Clean hydrogen production	Approximately 0 MTPA	50 MTPA
Charging and refueling infrastructure	Less than 1%	31 million public charging points 46,000 refuelling stations

Source: Accenture analysis based on data from IEA and MPP.

TRUCKING

Demand

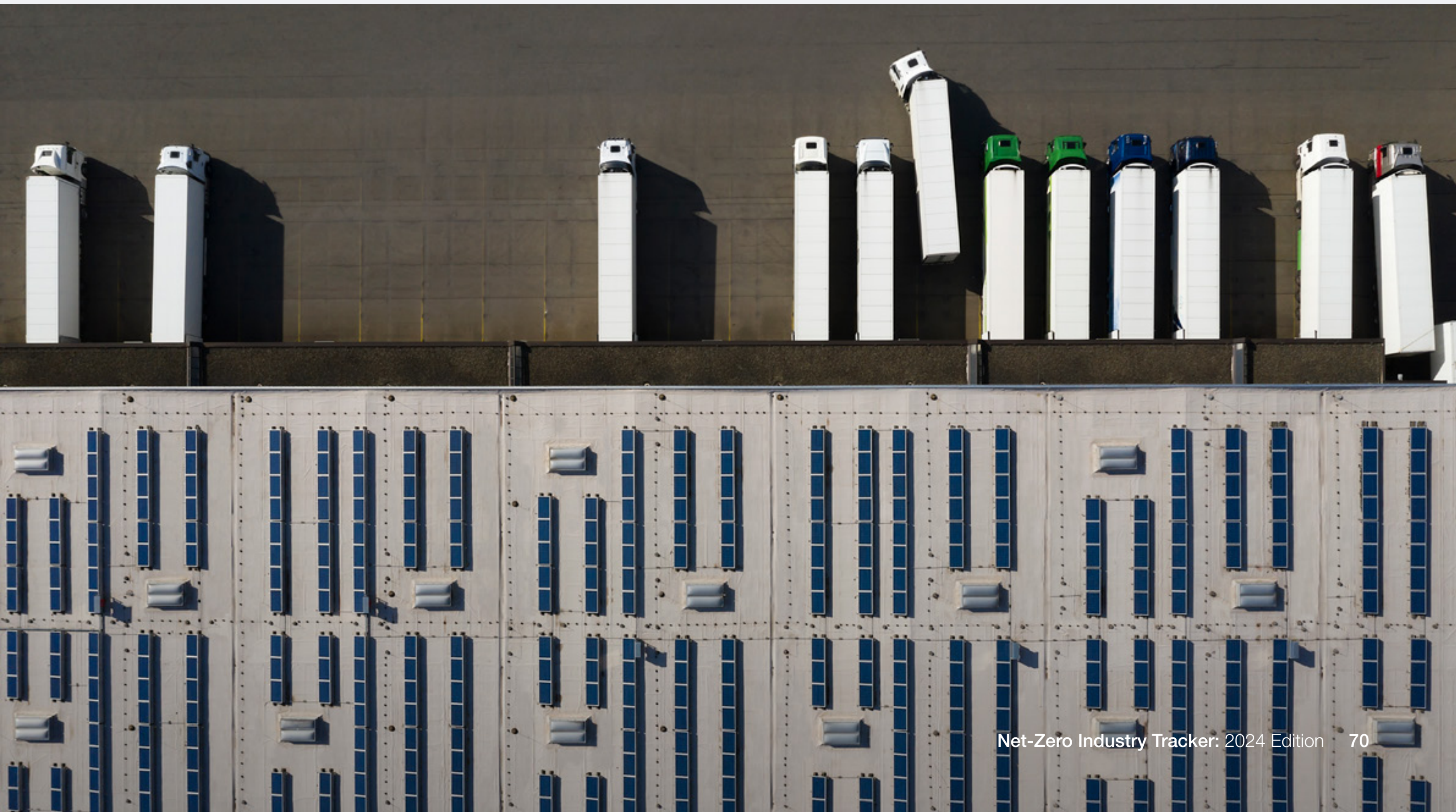
Sales share of plug-in hybrid, battery and fuel cell electric heavy trucks was less than 1% in 2022 and is expected to increase to 37% of total global sales by 2030.[273] This growth is driven by a combination of stricter emissions regulations, advancements in EV technology and increased demand. Leading truck manufacturers, such as Volvo, Daimler and Tesla, are launching new electric truck models, contributing to the anticipated surge in sales. China continues to lead on deployment of electric trucks, with over 70% of global electric truck sales in 2023.[274]

For manufacturers and OEMs, the green premium is estimated at 80%,[275] reflecting the higher costs of producing electric or hydrogen-powered trucks compared to conventional diesel models. However, for end consumers, this translates to a more manageable 1-3%[276] increase in the total cost of ownership, showing that while upfront manufacturing expenses are high, the impact on consumer prices is relatively modest. This green premium highlights the financial challenge the industry faces in scaling low-emission technologies.

FIGURE 39 **Global sales share of electric trucks[277] (2022) and hydrogen commercial vehicles[278] (2023)**

Electric truck registrations and sales share by region, 2022	
1 China	86%
2 US	5%
3 Europe	5%
4 Others	4%

Global sales of fuel cell commercial vehicles, 2023	
1 China	95%
2 US	3%
3 Europe	1%
4 Others	1%



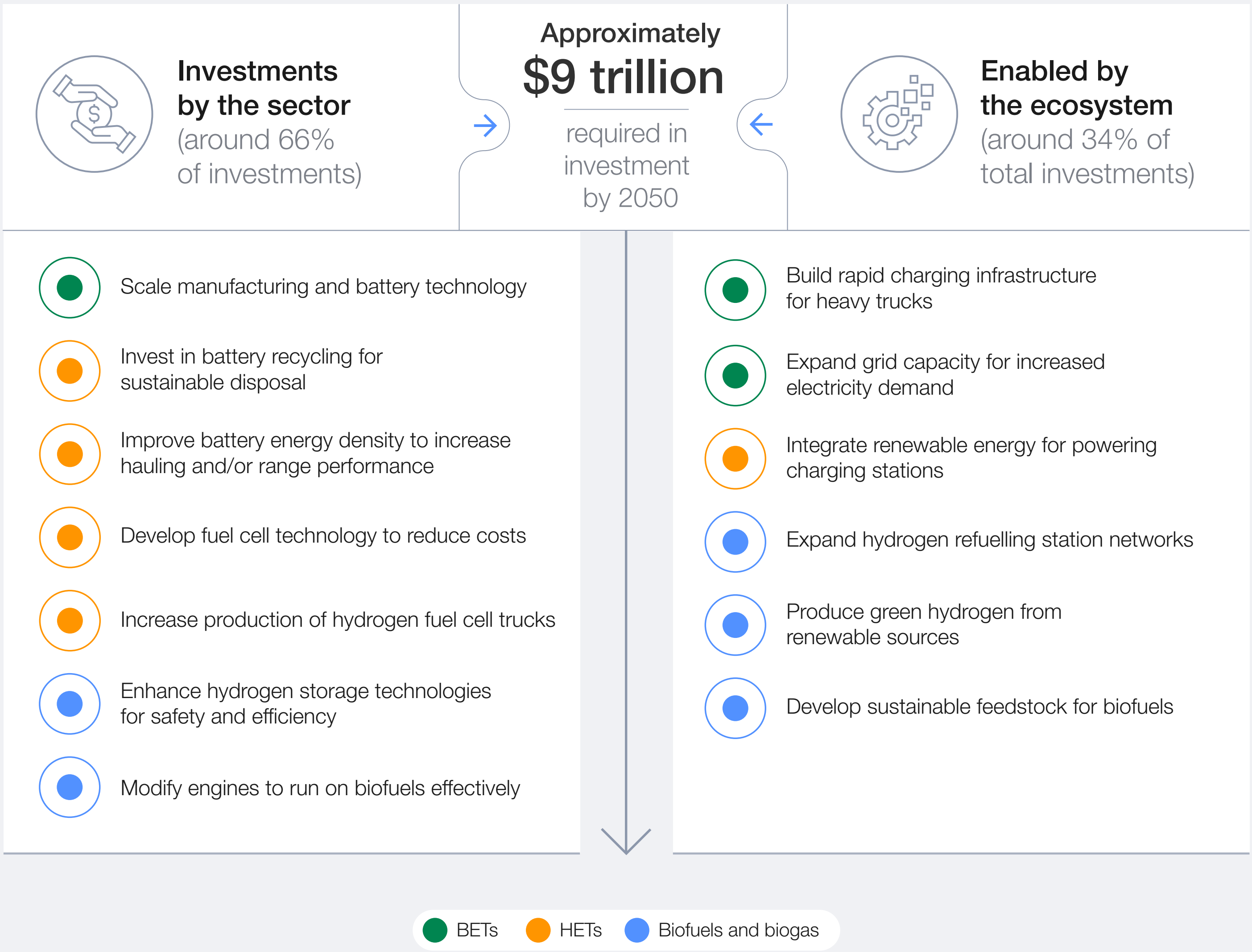
1

TRUCKING

Capital

Achieving net-zero emissions in the trucking industry by 2050 will require substantial financial investment. An estimated $9 trillion[279] in additional cumulative investments is needed by 2050, which translates to an annual investment of $320 billion until 2050. This is a significant increase from the current annual capital expenditure (CapEx) of $286 billion in the trucking sector. These investments will be crucial for scaling up clean energy infrastructure, developing zero-emission vehicle technologies, and transitioning to alternative fuels like hydrogen and electricity. This funding will support the expansion of BETs and hydrogen fuel cell trucks, and the development of refuelling and charging networks. Without this financial commitment, the industry will struggle to meet its emissions-reduction targets and the growing demand for sustainable transportation.

FIGURE 40 **Investments required by the sector and enabled by the ecosystem**



Investments by the sector
(around 66% of investments)

Approximately
$9 trillion
required in investment by 2050

Enabled by the ecosystem
(around 34% of total investments)

- 🟢 Scale manufacturing and battery technology
- 🟠 Invest in battery recycling for sustainable disposal
- 🟠 Improve battery energy density to increase hauling and/or range performance
- 🟠 Develop fuel cell technology to reduce costs
- 🟠 Increase production of hydrogen fuel cell trucks
- 🔵 Enhance hydrogen storage technologies for safety and efficiency
- 🔵 Modify engines to run on biofuels effectively

- 🟢 Build rapid charging infrastructure for heavy trucks
- 🟢 Expand grid capacity for increased electricity demand
- 🟠 Integrate renewable energy for powering charging stations
- 🔵 Expand hydrogen refuelling station networks
- 🔵 Produce green hydrogen from renewable sources
- 🔵 Develop sustainable feedstock for biofuels

🟢 BETs 🟠 HETs 🔵 Biofuels and biogas

Source: Accenture analysis based on data from MPP.

3

TRUCKING

Policy

Global trucking activity is highly concentrated in US, Europe, China and India. This underscores the importance of implementing effective and tangible policies to improve the adoption of zero-emission trucks in these regions.

In 2022, more than 70% of heavy-duty vehicles (HDVs) sold were subject to fuel economy or vehicle efficiency regulations, an increase from 60% in 2017 – though this figure is down from a peak of 80% in 2020 due to rising sales in countries without such policies.[280] While many countries are setting ambitious emissions targets, advanced economies could take cues from the European Union, the US and China by implementing a mix of regulations and incentives to effectively address CO_2 emissions from HDVs.

TABLE 9 **Trucking industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	UK Carbon Pricing Mechanism[281]	Establishes a financial cost for carbon emissions, incentivizing trucking companies to adopt cleaner technologies and reduce emissions.
	Border adjustment tariff	EU Carbon Border Adjustment Mechanism (CBAM)[282]	Imposes tariffs on imports based on carbon emissions, encouraging domestic trucking companies to lower their emissions and compete effectively against foreign firms.
	Product standard	California's Low-Emission Vehicle Program[283]	Sets strict emissions standards for HDVs, promoting the development and sale of cleaner trucks and driving manufacturers towards zero-emission vehicles.
Mandate-based	**Direct regulations**	EU Revised CO_2 emission standards for Heavy-Duty Vehicles[284]	The revised CO_2 emission standards for HDVs will be key to drive down emissions in the road transport sector and ensure the increasing supply of new zero-emission vehicles (ZEVs) to the market.
	Direct regulations	EU Alternative fuels infrastructure[285]	More recharging and refuelling stations for alternative fuels will be deployed in the coming years across Europe. This will enable the transport sector to significantly reduce its carbon footprint following the adoption of the alternative fuel infrastructure regulation (AFIR).
	Government targets	EU Emissions Trading Scheme for transport[286]	Revised CO_2 standards for HDVs and the Alternative Fuels Infrastructure Regulation will aid heavy-duty ZEV deployment.
Incentive-based	**Incentives**	EU Eurovignette Directive[287]	The directive is expected to incentivize the use of cleaner trucks, discourage the use of less-efficient trucks and reduce diesel consumption and emissions.
	Incentive-based subsidies	US Federal Electric Vehicle Tax Credit[288]	Provides financial incentives for purchasing electric trucks, lowering the upfront costs for fleet operators and accelerating the transition to zero-emission vehicles.
	Incentives	California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project[289]	Offers vouchers to fleet operators for purchasing clean trucks, incentivizing the shift to low-emission vehicles and helping offset initial costs.
	Direct R&D funds/grants	US Department of Energy's Vehicle Technologies Office[290]	Funds R&D projects focused on advanced vehicle technologies, including electric and hydrogen fuel cell trucks, encouraging innovation and reducing costs over time.

7 Steel industry net-zero tracker

Long-term emissions reduction solutions include direct reduced iron in electric arc furnaces and increased scrap steel use; short-term solutions include the use of carbon capture.

- The steel industry has seen a rise in emissions, driven by an increase in production share from China and India, where production is highly emission-intensive.
- Progress is being made in electrifying secondary steel production, but more investment in renewable energy and cleaner technologies is essential for lowering emissions.

3%

Increase in absolute CO_2 emissions (2022-2023)

3%

Increase in emission intensity (2022-2023)

0.1%

Increase in demand (2022-2023)

STEEL

Key performance data 2023[291,292,293]

7%

Contribution to global CO_2e emissions

2.8 Gt CO_2e

Scope 1 and 2 emissions

1.8%

Emissions increase (2019-2023)

1.5 tCO_2e/t

Emissions intensity
(per tonne of steel, 2023)

83%

Fossil fuels in the fuel mix (2022)

1.3 times

Demand in NZE scenario by 2050, compared to 2023

Performance summary

- The industry has seen an increase in emission intensity by 0.6%[294] in the 2019-2023 period. This is mainly driven by an increase in production in regions that heavily rely on blast furnaces, which are high in emissions intensity.
- Steel production saw a marginal increase by 0.1% in 2023 vs. 2022.[295]
- In 2022, the energy mix for steel production consisted of 73% coal, 14% electricity, 8% natural gas, 1% oil and 3% others, including bioenergy.[296]
- The planned capacity of BF-BOF went from 64.5% to 64%,[297] and EAF from 32% to 43%, from 2022 to 2023, indicating a move towards cleaner technology.[298]

Future emissions trajectory

- The industry targets a 45% reduction in intensity for primary steel and a 65% reduction for secondary steel by 2030, and net-zero emissions by 2050.[299]
- In total, 77% of large publicly traded steel companies consider climate change in their decision-making processes.[300]

Readiness key takeaways

Technology	2	⊖	– Scrap-based EAF with green power and BF-BOF with BECCS are the most advanced technologies. – BF-BOF with CCS and CCU are in the prototype stage, while direct reduced iron EAF (DRI-EAF) with CCS is at the demonstration stage and is expected to be commercially available by 2028.[301]
Infrastructure	1	⊖	– Of the 2050 fuel mix, clean power is expected to comprise 26%, hydrogen 29% and bioenergy 6%.[302] This will require 833 GW of clean power, 48 MTPA of clean hydrogen and 460 MTPA of biofuels capacity.[303] CCUS will also play a key role in reducing emissions. – Significant efforts in building clean power, hydrogen and bioenergy capacity are required to meet the 2050 net-zero requirements, as the current energy mix is dominated by fossil fuels.
Demand	3	⊖	– As of 2022, less than 10% of steel was produced using low-emission processes, with nearly all progress occurring in low-emission secondary production (e.g. recycling).[304] – Demand from the automotive industry has been on the rise, with the announcement of green supply agreements. There is especially high demand for use in EVs.
Capital	1	⊖	– The steel sector currently has an annual CapEx of $111 billion.[305] – The steel sector will require over $129 billion[306] in annual investments by 2050. Almost 70% of this investment must come from the ecosystem in the form of low-emission energy capacity investments. – Significant additional investment requirement, low industry margins and ease of increasing capital are leading to the low capital readiness score.
Policy	2	⊖	– The EU's Carbon Border Adjustment Mechanism (CBAM) will end free ETS allowances for steel by 2034 and impose tariffs on emissions-intensive imports.[307] – By 2025, China will prioritize the creation of a circular economy, seeking an increase in the use of scrap steel to 255 Mt by 2025 and peak steel production and sectoral emissions before 2030.[308]

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Switch from BF-BOF to EAFs.
- Use renewable electricity in EAFs to cut carbon intensity for secondary steel.

Long-term (by 2050)

- Explore green hydrogen as a replacement for fossil fuels to be used in EAF.

Ecosystem-enabled solutions

Mid-term (by 2030)

- Standardize green steel and hydrogen, setting consistent standards for producing steel and hydrogen from low-carbon sources.
- Increase scrap collection to enable more scrap-based production.

Long-term (by 2050)

- Develop infrastructure for producing and distributing green hydrogen.

Performance

The sector currently accounts for 7% of global CO_2e emissions. Emissions are mainly driven by the heavy use of fossil fuels in the energy-intensive production process, which account for around 75% of the current fuel mix.

TABLE 10

Steel industry performance

Performance metric	Change (2019-2023)
Industry output	+1.2%[309]
Emission intensity	+0.6%[310]
Total CO_2e emissions	+1.8%[311]

In the 2019-2023 period, demand increased by 1.2% while emission intensity increased by 0.6%. The increase in emission intensity is primarily due to the increase in steel production in high-emission regions. For example, steel production saw an increase in China, which continues to rely heavily on the more emission-intensive BF-BOF processes. India also saw an increase in steel production, where coal is the primary source of energy, leading to higher emissions per unit of steel produced.

There are three established methods of steel production currently in use, with varying levels of energy intensity (and hence emissions intensity). The most common production route is BF-BOF, which is used for 72% of global steel production, followed by scrap steel-EAF (scrap-EAF), which constitutes 21% of global steel production, and DRI-EAF, which constitutes 7% of global steel production.

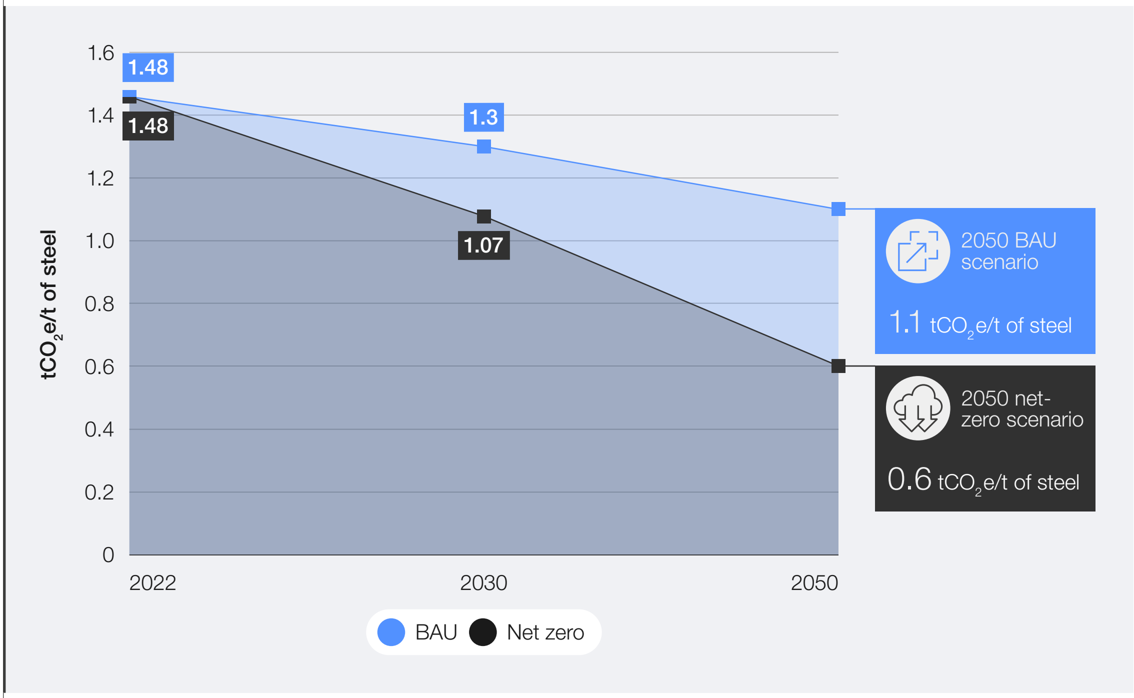
The energy intensity of BF-BOF and DRI-EAF processes is around 22-2023 gigajoules per tonne (GJ/t) of steel, while for scrap-EAF it is less than half (around 10 GJ/t), which is a key reason for its lower emissions intensity.[312] The BF-BOF process emits 2.3 tonnes of CO_2 per tonne of steel, whereas the scrap-EAF process emits only 0.7 tonnes and the DRI-EAF process emits 1.4 tonnes.[313] The steelmaking process varies across regions, with China and India mainly using the BF-BOF process with coal as primary fuel, the EU using BF-BOF with advanced BF technologies to lower emissions intensity, and the US having the highest share of scrap-EAF steel production and thus the lowest emissions intensity globally.

Coal has been the dominant fuel used in the steel production process and has consistently contributed to around 75% of the fuel mix for the last five years. Thus, there is a need for technologies that can replace coal power with renewable and low-emission fuels. For example, blast furnaces could be coupled with bioenergy and carbon capture and storage, which is known as BF-BOF with BECCS.

Readiness

FIGURE 41

Emission intensity trajectory for the steel sector



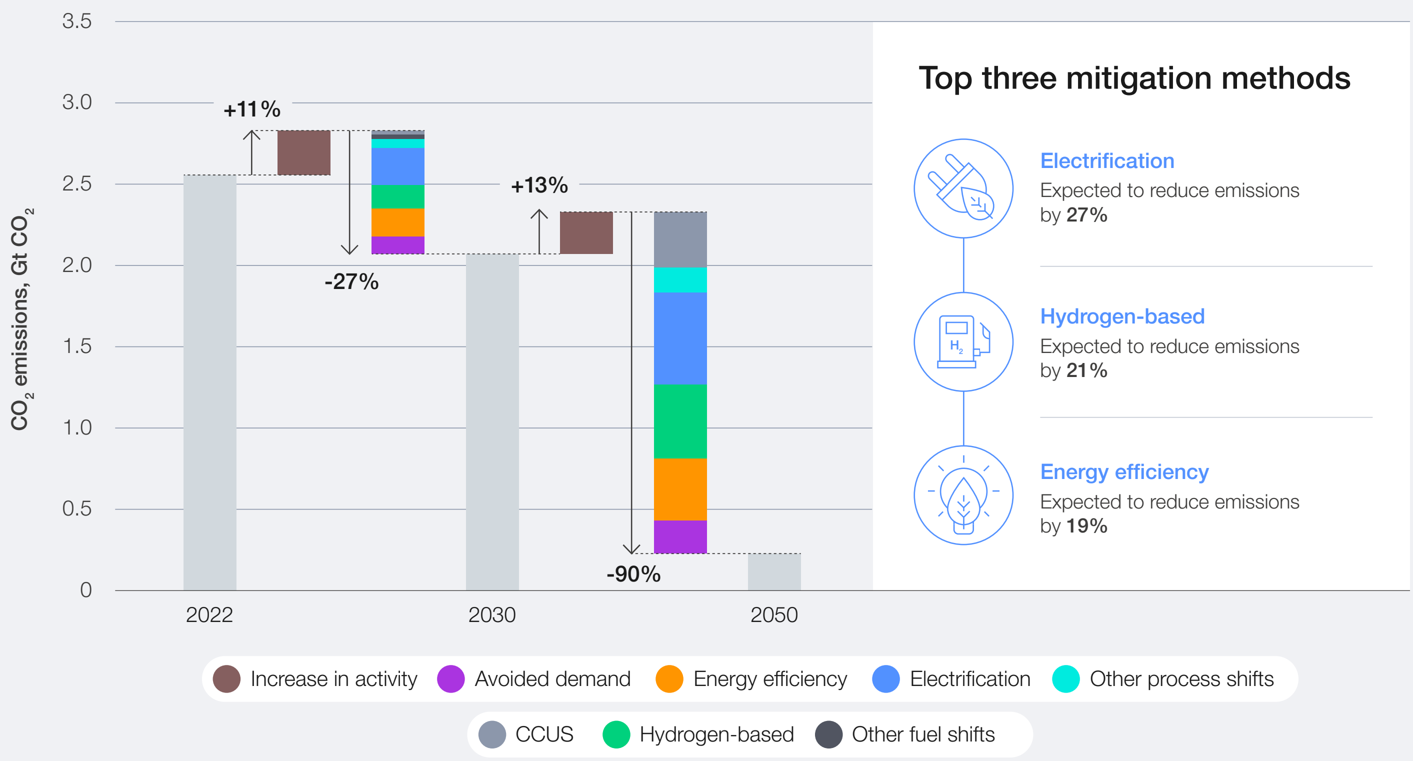
Source: IEA and STEPS Scenario (BAU).

The demand for steel is expected to grow by 32% by 2050. This increase will primarily be driven by rising urbanization and industrialization in emerging economies, and the growth of green energy infrastructure due to the energy transition, which will require significant amounts of steel.

Thus, the industry must act quickly to reduce emission intensity and offset the increase in demand. The top three decarbonization levers for steel are electrification, use of hydrogen in production and energy efficiency.

FIGURE 42

Decarbonization levers and top mitigation methods (NZE Scenario)



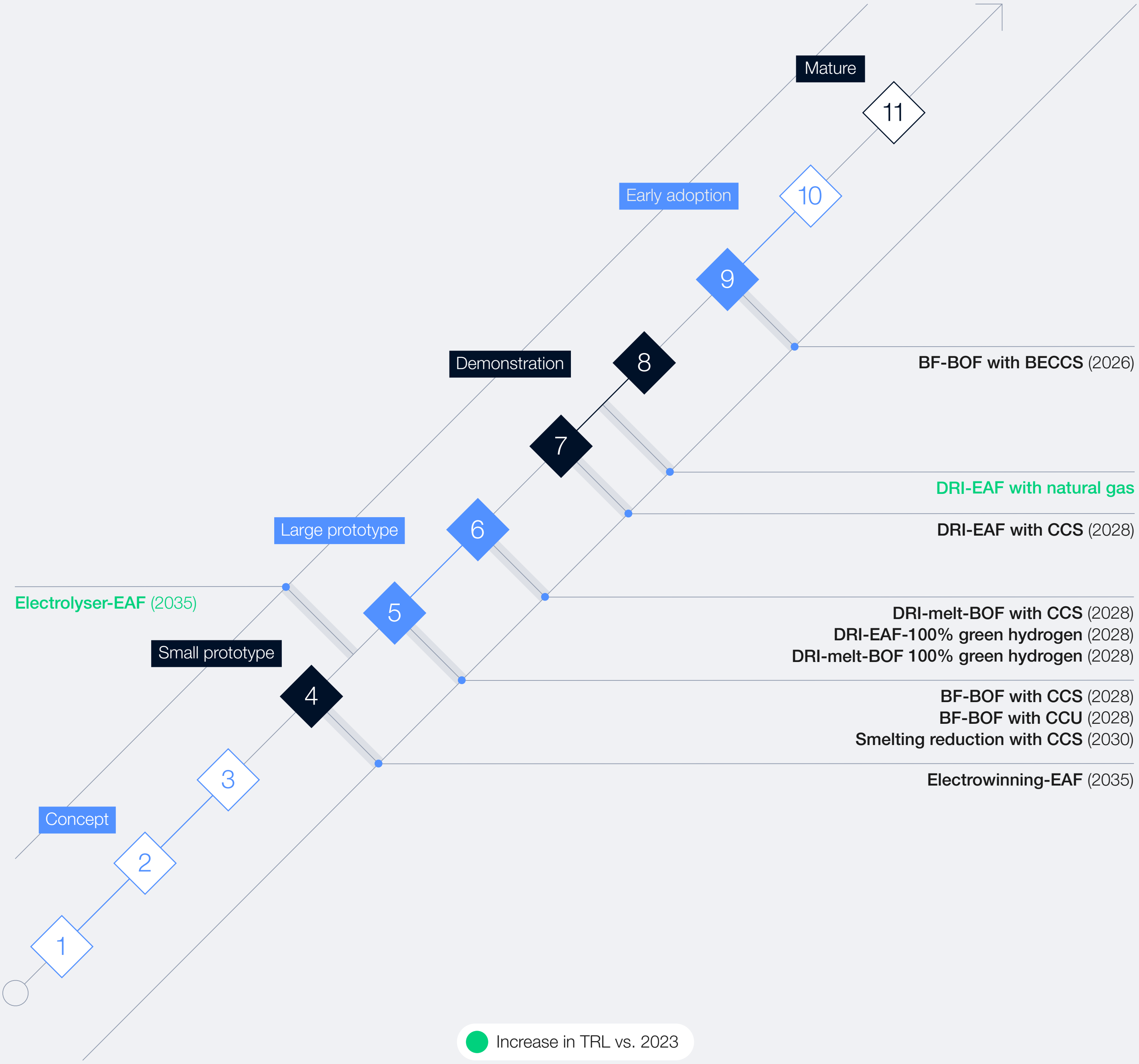
Source: IEA.

STEEL

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Three key pathways are currently available: increased use of scrap, use of clean hydrogen for primary steel production and CCUS technology for primary steel production.

FIGURE 43 **Decarbonization TRLs and year of commercial availability**



BF-BOF with BECCS (2026)

DRI-EAF with natural gas

DRI-EAF with CCS (2028)

Electrolyser-EAF (2035)

DRI-melt-BOF with CCS (2028)
DRI-EAF-100% green hydrogen (2028)
DRI-melt-BOF 100% green hydrogen (2028)

BF-BOF with CCS (2028)
BF-BOF with CCU (2028)
Smelting reduction with CCS (2030)

Electrowinning-EAF (2035)

Source: Accenture analysis based on data from IEA ETP Clean Energy Technology Guide and MPP.

Technology pathway 1: Increased use of scrap

The increased use of scrap is an important decarbonization lever for steel production, since scrap-based (secondary) production through the scrap-EAF process currently emits less than one-third of emissions compared to primary production through the BF-BOF process. This is because it eliminates the need for the processing of iron-ore, which is an emissions-intensive step. Furthermore, if renewable energy is used in the scrap-EAF process, the emissions from this process can be lowered to near-zero levels. The IEA projects that the share of scrap in metallic inputs for steel production will reach 48% by 2050.

Technology pathway 2: Clean hydrogen-based primary production

One of the most promising developments in steelmaking technology is the use of hydrogen-based direct reduced iron (DRI with H_2) production, which emits water vapor instead of CO_2, instead of traditional blast furnaces. Several pilot projects, particularly in Europe (e.g. Sweden's HYBRIT project), are exploring this technology with the aim of achieving large-scale commercial viability in the coming years.

Technology pathway 3: CCUS technology for primary production

The adoption of CCUS in the BF-BOF process is expected to reduce CO_2e emissions by up to 90%.[314] Most CCUS technologies for steel production are expected to become commercially available after 2028. Another key technology that has seen progress recently is the injection of biomass in place of coal in the blast furnace, which, when coupled with CCS, can lead to further emissions reduction. The use of CCUS is expected to reduce steel emissions by 13% by 2050.

1

STEEL

Infrastructure

According to MPP, the steel sector currently relies primarily on fossil fuels, with 106 GW of coal power and 45 MTPA of natural gas capacity available, while the clean power and hydrogen capacity available is negligible.[315]

To meet the 2050 net-zero targets, the 2050 fuel mix for steel will need to look significantly different. Clean power will need to supply 26% of the energy required for production, necessitating 833 GW of installed clean power capacity. Hydrogen will need to provide 29% of the energy required, supported by advancements in hydrogen-powered production processes, requiring 48 MTPA of hydrogen capacity. To further reduce emissions, 853 MTPA of CCUS capacity will be required. Biofuels are expected to contribute to 6% of the 2050 fuel mix and will require a capacity of 458 MTPA. However, it is expected that 15% of the energy mix in 2050 will still come from unabated fossil fuels, due to the emission-intensive nature of steel production.

FIGURE 44 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean power generation	Less than 1 GW	833 GW
Clean hydrogen production	Less than 1 MTPA	48 MTPA
CO_2 transport and storage	Less than 1 MTPA	853 MTPA

Source: Accenture analysis based on data from MPP.

3

STEEL

Demand

Currently, less than 1% of steel meets the industry's net-zero thresholds. The estimated B2B green premium of steel remains high, at 40%, but is expected to fall by 2050 with the drop in energy prices for renewable energy and hydrogen.

The demand for low-emission steel is expected to increase, especially from the automotive industry, since the B2C green premium for cars is less than 1%. Many companies (including BMW, Volkswagen and Volvo) have announced plans to use low-emission steel in the production of EVs. There has also been an increase in green steel supply agreements announced, with the transport sector constituting nearly half of them. The most prominent of these agreements are Volvo Trucks' purchase of SSAB's first batch of fossil-free steel and the Mercedes Benz agreement with Stegra (formerly known as H_2 Green Steel) for 50,000 tonnes of steel made with hydrogen.[316]

Access to scrap steel is not evenly distributed globally, and hence poses a challenge in increasing share of secondary steel production. There is a need to improve supply chain efficiency to ensure consistent flow of recyclable materials. To further reduce emissions, steel producers should adopt a circular economy model and recycle and reuse their steel scrap to increase secondary steel production.

FIGURE 45 **Top countries/regions in steel production and demand**

	Percentage of overall production	
1	China	54%
2	Europe	7%
3	India	7%
4	North America	6%
5	Japan	5%

	Percentage of overall demand (2022)	
1	China	52%
2	Europe	8%
3	North America	8%
4	India	6%
5	Japan	3%

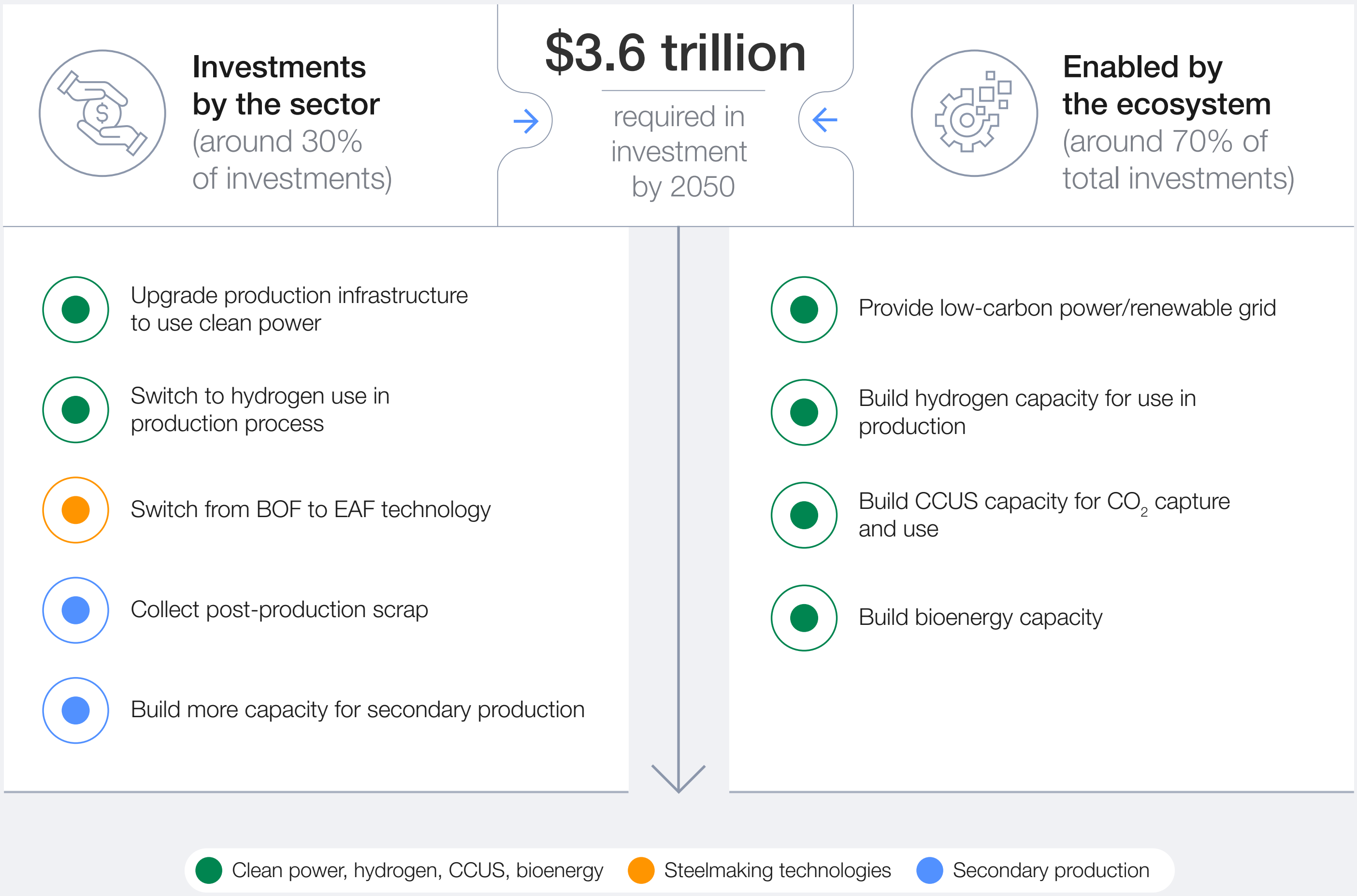
Source: World Steel.

STEEL

1 Capital

The steel industry will need substantial capital investment to advance low-emission production technologies. To support these technologies, a significant investment towards low-emission energy capacity will also be required. Overall, the estimated additional investment required is $3.6 trillion, out of which almost 70% must be invested by the ecosystem, while only around 30% must be invested by the sector companies. Ecosystem investments will include those needed to build capacity for hydrogen, clean power, CCUS and bioenergy, while investments by companies will be mainly focused on transitioning to net-zero compliant production technologies.

FIGURE 46 **Investments required by the sector and enabled by the ecosystem**



$3.6 trillion

required in investment by 2050

Investments by the sector (around 30% of investments)

- 🟢 Upgrade production infrastructure to use clean power
- 🟢 Switch to hydrogen use in production process
- 🟠 Switch from BOF to EAF technology
- 🔵 Collect post-production scrap
- 🔵 Build more capacity for secondary production

Enabled by the ecosystem (around 70% of total investments)

- 🟢 Provide low-carbon power/renewable grid
- 🟢 Build hydrogen capacity for use in production
- 🟢 Build CCUS capacity for CO_2 capture and use
- 🟢 Build bioenergy capacity

🟢 Clean power, hydrogen, CCUS, bioenergy 🟠 Steelmaking technologies 🔵 Secondary production

Source: Accenture analysis based on data from MPP.

With the steel industry's ROIC at 10%[317] and its WACC at 9.4%,[318] the industry's profits are only slightly higher than its costs of financing. This narrow margin means that without additional support from external factors (such as technological advancements, policy incentives and industry collaboration), the industry may struggle to afford and implement the significant changes needed for effective decarbonization. The availability of scrap will influence investments in EAF infrastructure across different countries, with the EU and China having the highest potential to expand their EAF-based production.

Approximately 77% of large publicly traded steel companies view climate change as a key consideration for their strategic assessment and integrate it into their operational decision-making. Meanwhile, 15% of companies are building basic emissions management systems and process capabilities. Finally, 8% of companies acknowledge climate change as a business issue.

2

STEEL

Policy

The production of steel is highly concentrated globally, with China and India contributing to over 60% of the total output, and future demand from these countries is expected to be significant. However, key policies aimed at emissions reduction are currently being developed primarily in the US and Europe. Hence, it is critical to develop and enforce supportive policies in regions where most of the demand and production comes from.

To support the journey towards net-zero emissions, the key focus areas of policy in the steel sector should be:

- Investment in the development of new steelmaking technologies that are less emission and energy intensive compared to existing processes (e.g. EAF technologies with the use of low-emission fuels)
- Direct funding/incentives for increasing capacity for renewable energy, hydrogen, CCUS and biofuels required to power the new steelmaking processes
- Demand-side interventions for green public procurement (as an example) to stimulate the demand for green steel

Furthermore, international collaboration must align emissions-accounting methodologies for steel to effectively track and monitor progress towards net-zero targets, especially in major producing countries like China and India.

TABLE 11 **Steel industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	– EU-ETS[319] – California ETS[320] – South Korea ETS[321] – China ETS[322]	Incentivizes steel producers to reduce emissions, but impact is limited by free emission allowances and lower carbon prices.
	Border adjustment tariff	EU CBAM[323]	Emission-intensive steel exporters to the EU face increased costs of compliance. Currently, 30% of steel consumed is imported from non-EU countries. The policy needs to be complemented by transparent and fair carbon accounting standards.
	Carbon price	India's Carbon Credits Trading Scheme (pending launch in 2026)	India's domestic voluntary carbon market will include the iron and steel sector, and is expected to launch in 2026.
Mandate-based	**Product standards**	China's Action Plan for Industrial Carbon Peaking[324]	By 2025, steel suppliers are expected to achieve an annual recycling capacity of 180 million tonnes.
Incentive-based	**Direct funding**	UK Green Steel Fund[325]	£2.1-3.5 billion clean steel fund, with the aim of establishing up to 3.78 Mt of additional secondary steel capacity, 4.44 Mt of low-emissions primary steel capacity and 5 Mt of domestic hydrogen-DRI capacity.
	Tax credits and subsidies	IRA tax-credits to clean power, green hydrogen and CCUS[326]	These can potentially reduce the cost of near-zero-emission steel by up to 35%. With limited funding available in developing economies, international funding collaboration mechanisms are an option to raise the required capital.
	Direct funding	EU Clean Steel Partnership[327]	Funding to support research and innovation for carbon neutral steel production.

8

Cement industry net-zero tracker

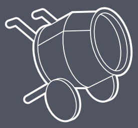
The industry must prioritize supplementary cementitious materials, efficiency strategies and bioenergy now, while advancing CCUS, electrification and fuel shifts for long-term reductions.

- The emission intensity has remained relatively stable over the past five years, largely due to slow adoption of supplementary cementitious materials (SCMs). However, large industrial-scale projects are in the pipeline, and there is momentum across the entire sector to cut emissions.
- CCUS and material-efficiency strategies are expected to reduce around 75% of the cement sector's emissions. However, significant investments are needed to scale them effectively.

2%	0.2%	2%
Decrease in absolute CO_2 emissions (2022-2023)	Decrease in emission intensity (2022-2023)	Decrease in demand (2022-2023)

CEMENT

Key performance data 2023 [328,329,330,331]



6%

Contribution to global CO_2e emissions

2.4 Gt CO_2e

Scope 1 and 2 emissions

4%

Emissions decrease (2019-2023)

0.58 tCO_2e/t

Emissions intensity

~0%

Change in emission intensity (2018-2022)

6%

Reduction in expected demand in NZE scenario by 2050, compared to 2023

<1%

Current low-emission clinker production

$1.42 trillion

Additional investment required for net zero by 2050

Performance summary

- The emission intensity has been relatively stable[332] for the last five years, primarily due to the slow adoption of supplementary cementitious materials (SCMs).
- The cement industry's absolute emissions have seen a 4%[333] decline in from 2019 to 2023, driven by a 3%[334] decline in demand for cement.
- Low-emission clinker production accounted for less than 1%[335] of total production worldwide in 2022. The share of low-emissions fuel in thermal energy use currently accounts for only 5%[336] of total production.
- The energy mix for cement consisted of 77% coal and petroleum coke, 15% natural gas, 4% non-renewable waste and 4% renewable waste.[337]
- Current infrastructure stands at less than 1%[338] for CCUS, clean power and hydrogen of the required infrastructure capacity by 2050 for net-zero emissions.

Future emissions trajectory

- The industry is forecast to reduce emissions intensity by 22%[339] by 2030 compared to 2023 levels (according to the IEA's Net Zero Scenario), and absolute CO_2e emissions are expected to be 1.91 Gt[340] in 2030.
- A total of 61%[341] of publicly traded companies in the cement industry consider climate change in their operational decision-making processes.

Readiness key takeaways

Technology	2	⊖	– CCUS, the major decarbonization lever, is still in the prototype stage (TRL 6).[342] – Material-recycling technologies are in the demonstration stage (TRL 7) and electrification and hydrogen are at the prototype stage (TRL 5).[343]
Infrastructure	1	↓	– CCUS infrastructure capacity required by 2050 is between 1.2-1.6 Gt[344] of CO_2 per year, with less than 1% currently available for the production of low-carbon cement. – By 2050, 624 GW of clean power and 6 Mt of hydrogen infrastructure is required.[345] Limited progress in incorporating hydrogen, clean power and CCUS led to a decline in score this year.
Demand	2	⊖	– The share of current near-zero emissions clinker production for cement is less than 1%.[346] – The green premium is estimated at 50-70% for B2B and 1.5-3% for B2C.[347]
Capital	2	↑	– Over $51 billion[348] in additional annual investments are required by 2050 by the cement sector, mainly for the installation of CCUS equipment. – Currently, the cement sector has an annual CapEx of $147 billion.[349] – The score increased from last year, as current capital levels increased, leading to an additional 35% of annual CapEx needed, compared to 71% previously.[350]
Policy	3	⊖	– The policies focus on reducing emissions through carbon pricing mechanisms and energy efficiency improvements. Several governments are also introducing roadmaps to guide the industry towards cleaner practices.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Use SCMs and low-carbon fuels to replace traditional fossil fuels in kilns.
- Enhance production processes and promote resource-efficient manufacturing and material efficiency.

Long-term (by 2050)

- Upgrade equipment and processes to improve energy efficiency.
- Implement CCUS systems at kiln facilities to capture CO_2 emissions.

Ecosystem-enabled solutions

Mid-term

- Build supply chains of SCMs and low-carbon fuel and facilitate their adoption.

Long-term

- Invest in the development of infrastructure for clean hydrogen and CCUS.
- Invest in material recycling technologies.

Performance

Currently, the cement industry accounts for approximately 6%[351] of global CO_2e emissions, primarily due to the energy-intensive process of clinker production. Fossil fuels account for over 95%[352] of thermal energy use in the industry, making them a critical driver for emission intensity. The primary challenge for the cement industry is balancing the reduction of CO_2 emissions with meeting rising global demand.

TABLE 12

Cement industry performance

Performance metric	Change (2019-2023)
Industry output	-3.4%[353]
Emission intensity (tCO_2/t cement)	~0%[354]
Total CO_2e emissions	-4%[355]

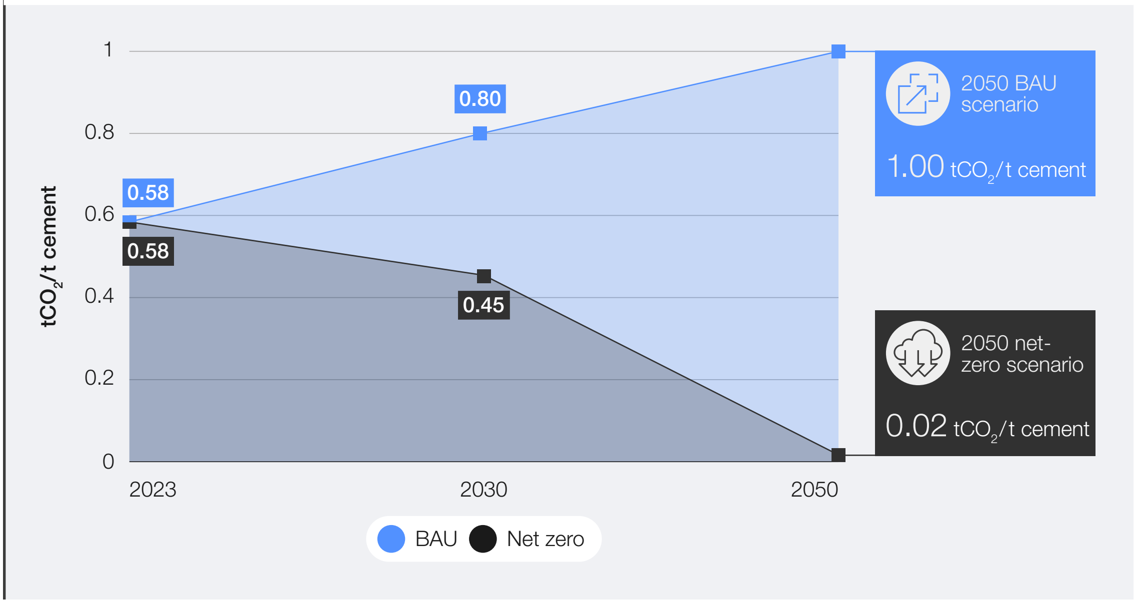
Low-emission clinker production accounted for less than 1%[356] of global production in 2022, while low-emission fuels comprised only 5%[357] of the total thermal energy used in cement production. The energy mix remains heavily reliant on carbon-intensive sources, with 77% coming from coal and petroleum coke, 15% from natural gas and just 4% from both non-renewable and renewable waste.[358] Additionally, the current infrastructure for critical decarbonization technologies such as CCUS, clean power and hydrogen sits at less than 1%[359] of the capacity needed by 2050 to meet net-zero emissions targets.

Key initiatives in the cement sector (including the adoption of circular-economy principles, enhancement of energy efficiency and exploration of alternative materials such as low-carbon clinker substitutes) are essential to achieving long-term emissions reductions. Innovations such as CCUS and the development of novel materials like geopolymer cement offer potential pathways to lower emissions. Companies like Holcim[360] (a global leader in innovative and sustainable building solutions) are investing in companies like Sublime Systems (a leading low-carbon cement technology startup) to help scale up their low-carbon cement technology. Many cement companies are integrating CCUS technologies – for instance, projects like Norcem[361] in Norway and CEMEX and Carbon Clean project[362] aim to implement carbon capture at scale.

Readiness

FIGURE 47

Emissions intensity trajectory for the cement sector

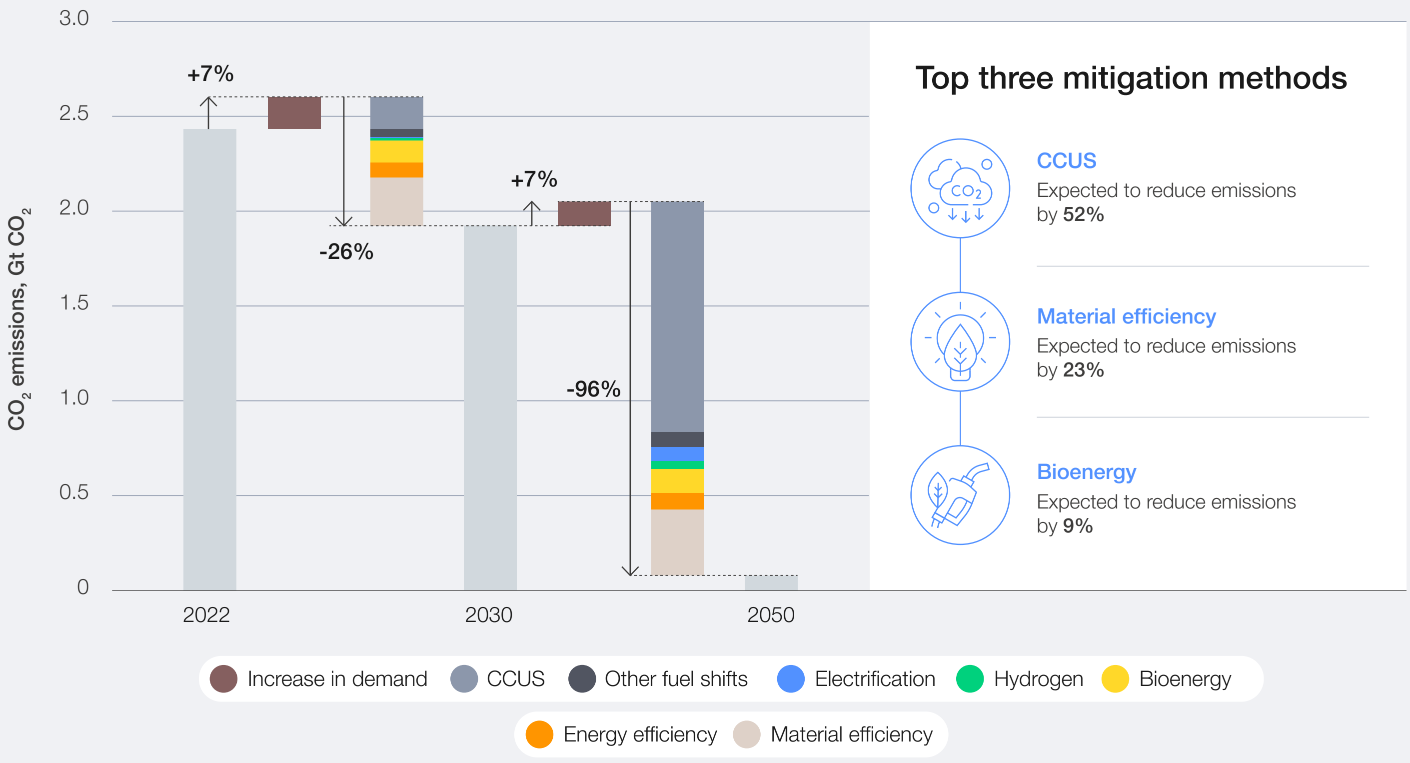


Source: IEA Net Zero Scenario.

The cement sector faces significant challenges in decarbonization, with key technologies still in early stages. CCUS, a major decarbonization tool, remains in the prototype stage (TRL 6),[363] while material recycling is at TRL 7[364] and electrification and hydrogen solutions are in the prototype phase (TRL 5).[365] By 2050, the sector will need infrastructure capable of capturing 1.2-1.6 Gt[366] of CO_2 annually, but current capacity is less than 1%.[367] Additionally, 624 GW of clean power and 6 Mt of hydrogen infrastructure will be required.[368] Green premiums are high, with a 50-70% premium for CCUS cement sold to concrete producers and 1.5-3% for end consumer such as homeowners.[369] Policy efforts focus on carbon pricing and energy efficiency, while roadmaps guide cleaner practices. The industry needs over $51 billion[370] in additional annual investments by 2050 (primarily for CCUS), though the current CapEx of $147 billion has improved, with only 35% now needed for these investments (down from 71% previously).[371] Overall cement demand is expected to reduce by 5%[372] by 2050, whereas demand share will increase in regions that encounter difficulties in decarbonizing cement.

To achieve net-zero emissions by 2050, the cement sector must adopt a multi-faceted approach to emissions reduction. Key drivers include improving material efficiency, enhancing energy efficiency and shifting towards cleaner fuels such as bioenergy, hydrogen and electrification. The two most critical levers for significant emissions reduction are the adoption of CCUS and the use of SCMs. CCUS has the potential to capture the vast CO_2 emissions from cement production, which is particularly crucial for this energy-intensive industry. SCMs, on the other hand, can reduce the reliance on clinker (the most carbon-intensive component of cement) by incorporating lower-carbon alternatives. Together, these technologies, supported by other fuel shifts and efficiency improvements, will be essential to driving deep decarbonization in the cement sector.

FIGURE 48 **Decarbonization levers and top mitigation methods (NZE Scenario)**



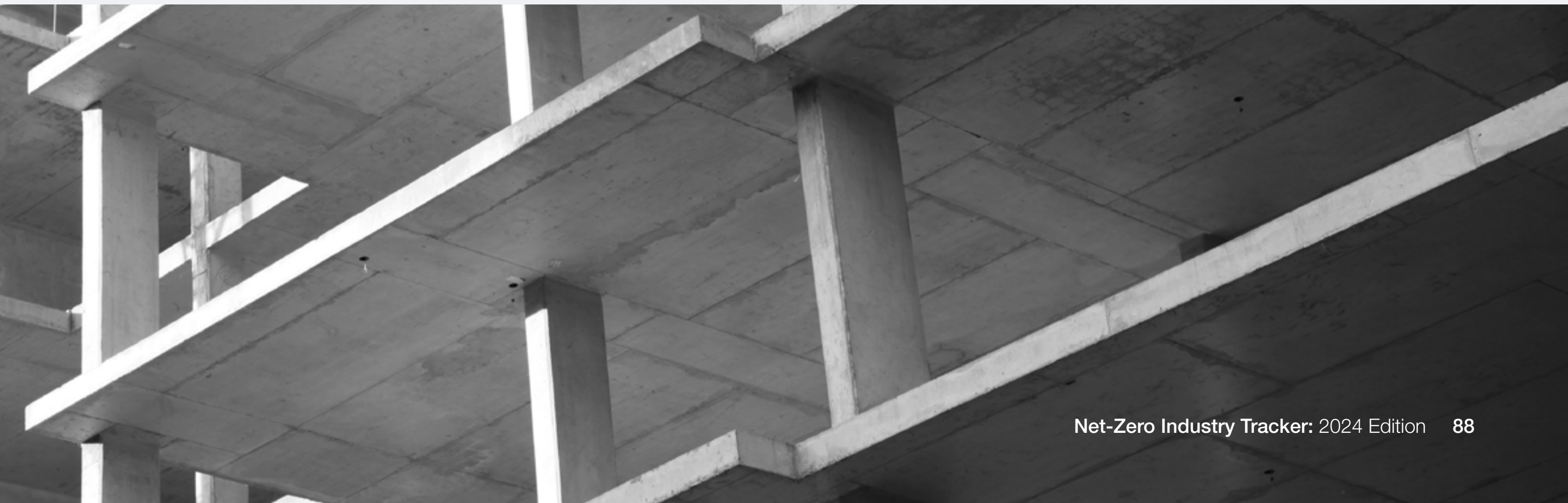
Top three mitigation methods

CCUS
Expected to reduce emissions by **52%**

Material efficiency
Expected to reduce emissions by **23%**

Bioenergy
Expected to reduce emissions by **9%**

Source: Accenture analysis based on data from IEA.



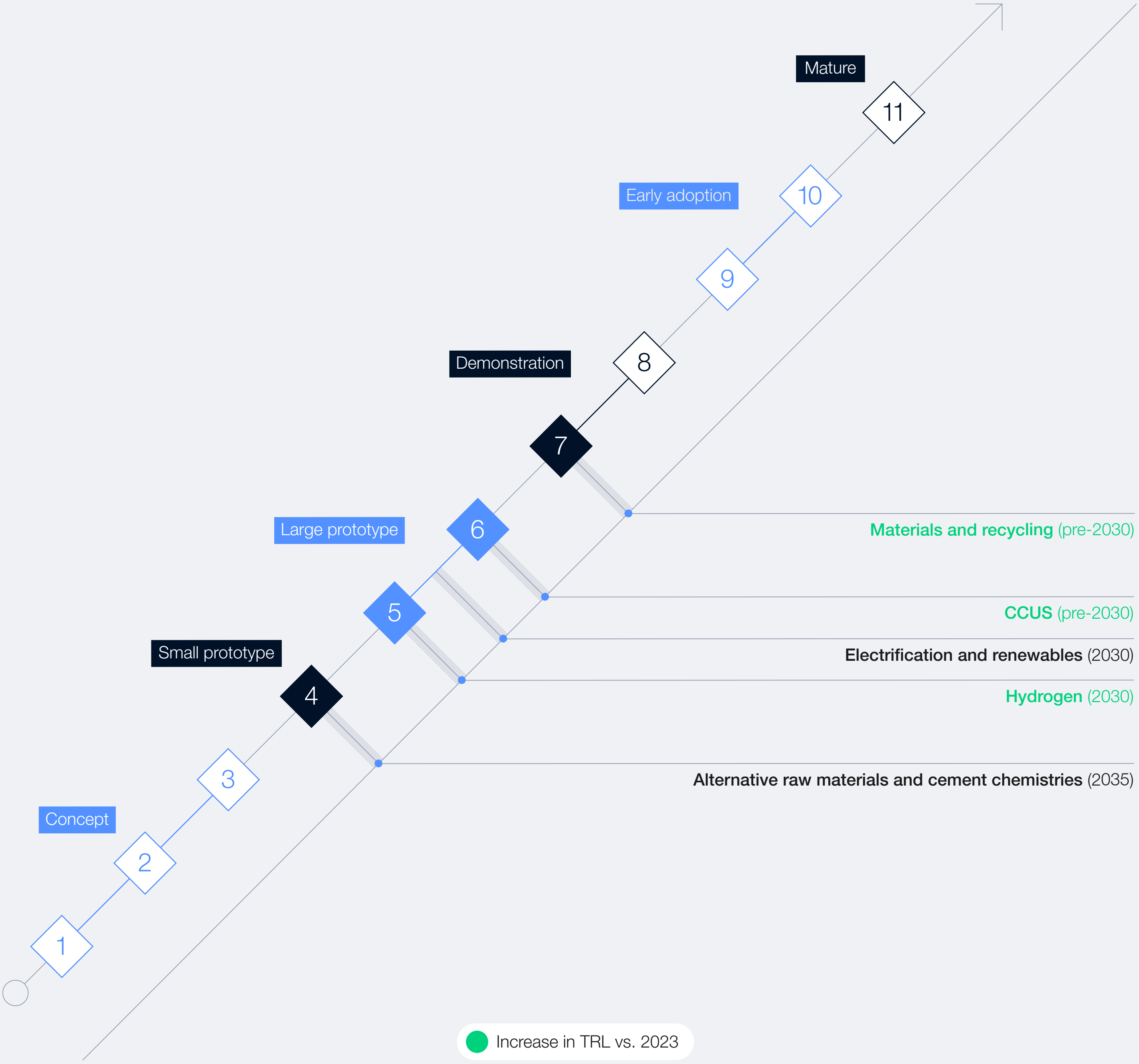
CEMENT

2

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Three leading pathways have emerged: CCUS, SCMs and bioenergy.

FIGURE 49 **Decarbonization TRLs and year of commercial availability**



Source: Accenture analysis based on data from IEA ETP Clean Energy Technology Guide.

Technology pathway 1: CCUS

The calcination process in cement production, responsible for 60-65% of its CO_2 emissions, is an unavoidable chemical reaction, making CCUS essential to capture these emissions at the source. In the cement industry, CCUS is progressing through varying stages of maturity, with post-combustion capture technologies being the closest to commercialization (TRL 7-8).[373] These technologies (e.g. amine-based solvents) have been demonstrated at pilot and large-scale levels, though challenges remain in cost and scalability. Oxy-fuel combustion (TRL 6-7) and direct separation technologies (TRL 4-6) are still under development, while CO_2 utilization pathways (TRL 3-7) are progressing, particularly in concrete curing.[374] Sequestration, already commercially viable (TRL 8-9), provides an immediate storage solution. However, broad adoption will depend on overcoming technical, financial and regulatory challenges.[375] Furthermore, recarbonation in cement allows concrete to absorb 5-10% of the CO_2 emitted during production, and an additional 5-10% may be taken up during the secondary or recycled lifetime, offering a modest reduction in the material's overall carbon footprint.[376]

Technology pathway 2: SCMs and material efficiency

Material efficiency and SCMs in the cement industry focus on reducing the amount of clinker (the primary source of CO_2 emissions) by using alternative materials like fly ash, slag and natural pozzolans. These technologies are relatively mature, with SCMs having a high TRL (TRL 7-9),[377] and are already commercially available in many markets. Material efficiency strategies, such as optimizing mix designs and improving process efficiency, are also well-established (TRL 7-9).[378] While SCM technologies are commercially viable, their broader adoption is constrained by limited availability of high-quality SCMs, especially as demand increases, and the need for standardized performance testing.

Technology pathway 3: Bioenergy and renewables

Bioenergy and renewable energy technology in the cement industry focuses on integrating sustainable energy sources, such as biomass and waste-derived fuels, to reduce fossil-fuel consumption and lower carbon emissions. The TRL for these solutions is generally around TRL 5-6,[379] indicating that while the technologies are in the development and testing phases, they are not yet widely commercially available. Biomass co-firing and the use of waste fuels are being piloted in some cement plants, demonstrating their feasibility but requiring further validation and optimization for broader application. Similarly, integrating renewable energy sources like solar and wind power is still in the early stages, with limited deployment and ongoing research to assess their full potential for cement manufacturing.

1

CEMENT

Infrastructure

To achieve net-zero emissions in the cement industry by 2050, a comprehensive overhaul of existing infrastructure is essential. This overhaul must focus on CCUS, material and energy efficiency, and bioenergy development. The current CCUS infrastructure available to cement industry is less than 1%[380] of infrastructure capacity required for net zero by 2050. The implementation of large-scale CCUS is critical. This involves capturing CO_2 emissions from cement plants and either using them in other processes or storing them underground. By 2050, a pan-European CO_2 transport and storage network[381] will be necessary to facilitate this process. Norway's Brevik[382] project is a notable example of how CCUS can be integrated into cement production.

The thermal energy intensity of clinker production must decrease by 2050. This transition involves increasing the share of bioenergy and renewable sources, which is projected to rise to 16%[383] of total thermal energy. The integration of hydrogen as a fuel source is also expected to play a vital role, necessitating new energy infrastructure to support this shift. The expansion of bioenergy infrastructure will be crucial for reducing reliance on fossil fuels. This includes the use of biomass and waste-to-energy processes to supply thermal energy for cement production.

FIGURE 50 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean power generation	Approximately 0 GW	624 GW
Clean hydrogen production	Approximately 0 MTPA	6 MTPA
CO_2 transport and storage	Approximately 0 MTPA	1,400 MTPA

Source: Accenture analysis based on data from IEA and MPP.

CEMENT

2

Demand

Overall cement demand is expected to reduce by 6%[384] by 2050. Cement production saw a significant decline in 2023, dropping by 2%[385] to 4,072 Mt, although this overall figure conceals varying regional trends. China, despite experiencing a 10.5% year-on-year decrease in production due to its real estate crisis and COVID-19 pandemic-related policies, remains the world's largest cement producer, accounting for 51% of global output.[386] India is the second-largest producer, with its share of global cement production increasing from 8% in 2021 to 9% in 2022.[387] In the medium-term, China's share is expected to decline, while growth in cement output is expected from South-East Asia, Latin America and Africa, driven by these regions' expanding infrastructure needs and development initiatives.

Despite the significant 50-70%[388] green premium for B2B transactions in the cement sector (stemming from the higher costs associated with producing low-carbon materials) the actual impact on the cost of end-user products is relatively modest, averaging around 3%.[389] This discrepancy occurs because cement typically represents a small portion of the total cost of most final products, such as buildings or infrastructure projects.

FIGURE 51 **Top countries/regions in cement production and consumption**

Percentage of overall production (2022)	
1 China	51%
2 India	9%
3 EU	7%
4 Vietnam	3%
5 US	2%

Percentage of overall consumption (2019)	
1 China	56%
2 India	8%
3 US	2%
4 Brazil	1.4%
5 Russia	1.3%

Source: United States Geological Survey (USGS) and Indexbox.

2

CEMENT

Capital

The cement industry will require additional capital investment of $1.42 trillion[390] by 2050 to develop and implement low-emission technologies and infrastructure. Plant owners are responsible for the majority of this investment, with 69% of the total funding required for net-zero efforts coming from within the sector.[391] Cement-making equipment is expected to account for 39% of the cumulative investment, followed by SCMs at 27%, underscoring the importance of reducing clinker use in cement production to lower emissions.[392] Carbon capture equipment, a key technology for decarbonization, represents 22%[393] of the capital outlay, illustrating its critical role in mitigating the sector's substantial CO_2 emissions.

Outside the direct control of cement plant owners, other stakeholders will need to invest in infrastructure to support net-zero goals. This includes 18% of the investment going towards zero-emissions electricity generation, 13% for carbon capture, storage and transport infrastructure, and 1% for green hydrogen electrolysis capacity.[394] These external investments are vital to enabling the cement industry's transition, as clean energy and hydrogen will help reduce reliance on carbon-intensive fuels, while CCS technology will capture and store residual emissions. This highlights the collaborative effort required across the value chain to achieve net-zero in the cement sector.

FIGURE 52 **Investments required by the sector and enabled by the ecosystem**

$1.42 trillion

required in investment by 2050

Investments by the sector
(around 69% of investments)

- 🟢 Switch production from fossil to renewable feedstock sources
- 🟢 Invest in R&D for low-TRL technologies
- 🟢 Retrofit legacy infrastructure
- 🟠 Invest in CCUS and DAC technology
- 🔵 Adopt SCMs for reducing clinker use production
- 🔵 Scale circularity and materials recycling
- 🔵 Adopt resource-efficient manufacturing

Enabled by the ecosystem
(around 31% of total investments)

- 🟢 Digitize the value chain and disclose key environmental system data
- 🟢 Renewable electricity production
- 🟢 Demand creation via offtake agreements
- 🟠 Build CO_2 capture plants
- 🔵 Fast track critical innovations to commercial scale
- 🔵 De-risk large-scale financial investment

🟢 Hydrogen, bioenergy and renewables 🟠 CCUS 🔵 Circularity and material efficiency

Source: Accenture analysis based on data from MPP.

3

CEMENT

Policy

Global cement production is concentrated, with China accounting for 51%[395] of the total output in 2022, followed by India, the EU and the US. This highlights the critical need for targeted and effective policies to curb emissions in major cement-producing regions. Given the sector's significant contribution to global CO_2 emissions, a robust policy framework is essential to drive decarbonization and support the transition to low-carbon production methods, such as allowing certain SCMs to be used in building codes.

The adoption of standardized carbon accounting frameworks, clear scope definitions and consistent system boundaries will play a crucial role in promoting transparency and accountability across the cement industry. These measures ensure accurate emissions reporting and compliance with industry-wide sustainability targets. Initiatives from global industry bodies, like the Global Cement and Concrete Association (GCCA),[396] emphasize the importance of collaboration and the sharing of best practices in decarbonization efforts. Additionally, initiatives on standards harmonization like the Industrial Deep Decarbonisation Initiative (IDDI)[397] aim to spur early demand for low- and near-zero-emission products through green public procurement commitments.

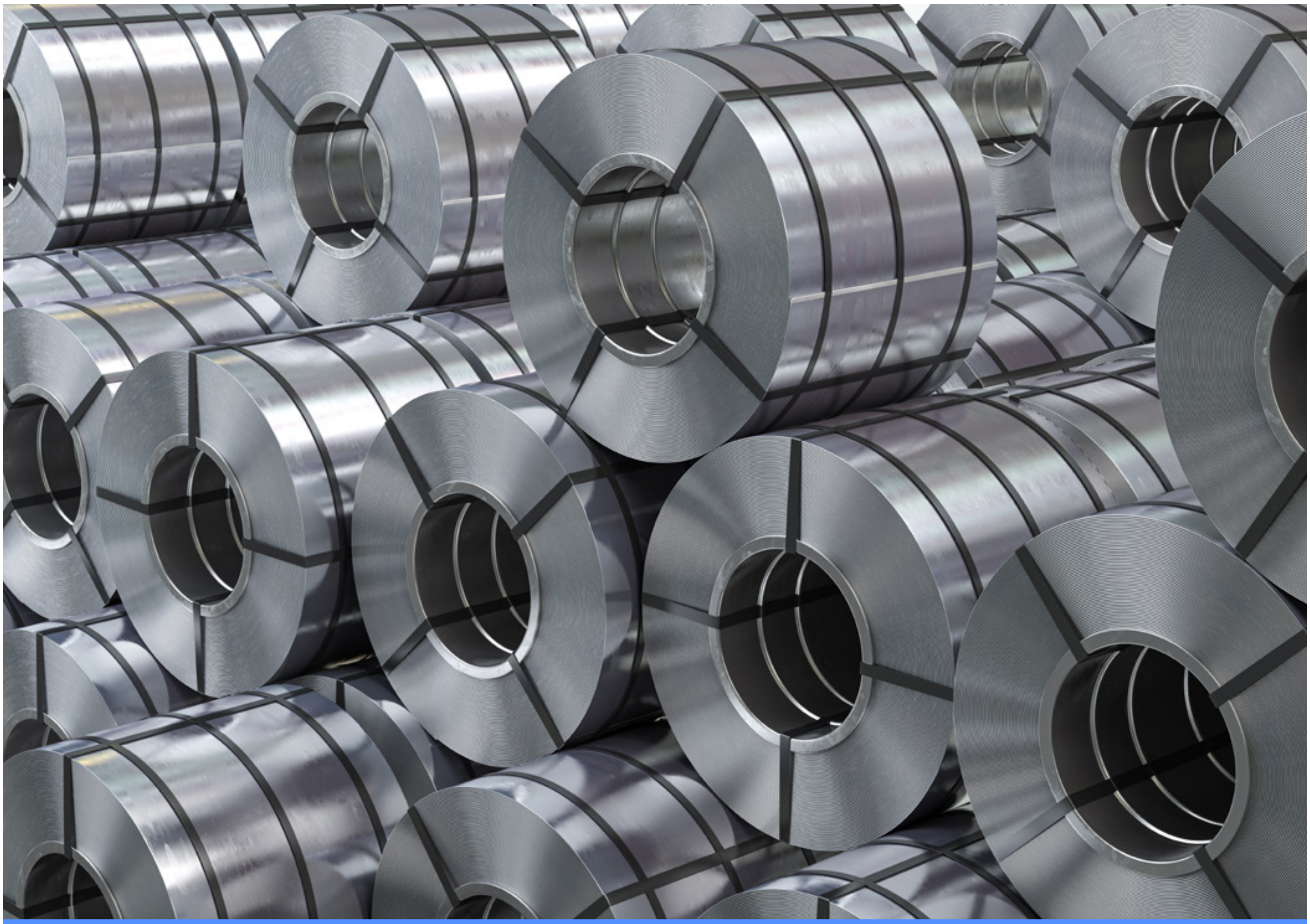
TABLE 13 **Cement industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	Canada's Output-Based Pricing System (OBPS)[398]	Large industrial facilities like cement plants are required to pay a price on carbon pollution, but receive output-based allocations to protect against competitiveness impacts, encouraging them to reduce emissions while remaining economically viable.
	Border adjustment tariff	EU Carbon Border Adjustment Mechanism (CBAM)[399]	To prevent carbon leakage (the relocation of cement production to countries with less stringent climate policies), the EU is implementing a CBAM.
	Product standard	India's BIS 1489 Standard[400]	The Bureau of Indian Standards (BIS) regulates the quality of blended cement in India, promoting the use of Pozzolana and other supplementary materials to lower the carbon intensity of cement.
Mandate-based	**Direct regulations**	EU Industrial Emissions Directive (IED)[401]	The cement sector is subject to stringent emissions limits set by the IED, which controls pollutants such as nitric oxides (NO_x), sulfur oxides (SO_x) and particulate matter.
	Direct regulations	China's National Standard on Air Pollutants for the Cement Industry[402]	China enforces regulations that limit the emissions of dust, SO_x and NO_x from cement plants. Non-compliance results in fines and possible plant closures.
	Government targets	India's 2070 Net-Zero Pledge[403]	India has set long-term targets for reducing the carbon intensity of its economy, which includes initiatives to decarbonize the cement industry by transitioning to more efficient processes, renewable energy and CO_2 capture technologies.
Incentive-based	**Subsidies**	Germany's decarbonization in industry programme[404]	The programme provides financial assistance to implement innovative decarbonization technologies, supporting industries' transition to net-zero emissions.
	Direct R&D funds/grants	US Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E)[405]	ARPA-E has allocated funds specifically for developing carbon-reducing innovations in industrial sectors such as cement. Grants support cutting-edge research in process innovation, energy efficiency and carbon capture.
	Direct R&D funds/grants	US Department of Energy's Industrial Demonstrations Program[406]	By funding large-scale projects that demonstrate the feasibility of cutting GHG emissions, the programme incentivizes the adoption of cleaner technologies, such as carbon capture, low-carbon fuels and advanced manufacturing methods.

9

Aluminium industry net-zero tracker

The industry must prioritize low-carbon electricity, recycling and efficiency now, while advancing electrification, fuel switching, inert anodes and CCUS for aluminium emissions cuts.



- Emission intensity has decreased in the last five years due to reduced dependence on coal, enhanced energy efficiency and increased production of secondary aluminium.
- Renewable energy adoption in smelting has seen progress, but substantial infrastructure investments are still necessary to fully decarbonize the industry.

0.4%

Increase in absolute CO_2 emissions (2022-2023)

2.3%

Decrease in emission intensity (2022-2023)

2.7%

Increase in demand (2022-2023)

ALUMINIUM

Key performance data 2023[407,408,409,410]

2%

Contribution to global GHG emissions

1.12 Gt CO_2e

Scope 1 and 2 emissions (2023)

1.3%

Emissions decrease (2019-2023)

10.04 tCO_{2eq}

Emissions intensity (per tonne of aluminium, 2023)

61%

Fossil fuels in the smelting power mix (2022)

1.8 times

Demand increase in NZE scenario by 2050, compared to 2023

Performance summary

- The industry has reduced emission intensity by 13.6% from 2019 to 2023.[411] This is mainly driven by improvements in reduced reliance on coal, increased secondary production and energy efficiencies.
- The absolute emission for aluminium (primary and secondary combined) was 1.13 Gt of CO_2e in 2019, decreasing to 1.12 Gt of CO_2e in 2023.[412]
- Hydropower and renewable energy contribute to 39% of the electricity used in smelting.[413]
- Secondary aluminium, which requires significantly less energy, contributes to 36% of total production.

Future emissions trajectory

- The industry will need to reduce emissions intensity by 30% by 2030 and 97% by 2050, compared to 2022 levels, to be compatible with the IAI's 1.5 degrees scenario. The absolute CO_2 emissions for aluminium (primary and secondary combined) will need to be 810 Mt in 2030 and 53 Mt in 2050.[414]

Readiness key takeaways

Technology	3	⊖	– Electricity decarbonization for secondary aluminium smelting is available, with material and process efficiency at the demonstration stage (TRL 8).[415] – Inert anodes are at the demonstration stage (TRL 7) and CCUS is at the concept stage (TRL 3), both targeting commercial readiness by 2030.[416]
Infrastructure	3	⊖	– 9.5 MTPA of clean hydrogen and 86 MTPA of CCUS are required by 2050.[417] – 223 GW of clean power is required by 2050.[418] – Power purchase agreements (PPA) are increasing for use of clean power for production, with China harnessing hydropower.
Demand	3	↓	– Approximately 30% of the total primary aluminium produced emitted less than 5 t of CO_2e/t of aluminium in 2021.[419] – The green premium for B2B is estimated at 40%.[420] – Momentum in offtake agreements and announced projects has slowed down over the last year.
Capital	1	⊖	– Currently, the aluminium sector has an annual CapEx of $23 billion. – Over $19 billion in additional annual investments are required by 2050 by the aluminium sector and by infrastructure buildout companies. – Significant additional investment requirement, low industry margins and ease of increasing capital are leading to the low capital readiness score.
Policy	2	⊖	– The EU has introduced CBAM, covering aluminium, with certificate purchases starting in January 2026.[421] – By 2025, 30% of China's aluminium capacity must meet efficiency benchmarks, 25% of energy must be renewable and recycled output should reach 11.5 million tons.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Source low-carbon grid power to reduce carbon intensity.
- Retrofit existing fossil-fuel-based captive power assets with CCUS, where access to clean power grids is not economical.
- Develop and deploy low-emission refining technologies like electric boilers, mechanical vapour recompression, etc.
- Accelerate market readiness for low-emission smelting technologies like inert anodes.
- Improve efficiencies and end-user scrap collection rate to maximize secondary production.
- Ensure product-level emissions reporting.

Long-term (by 2050)

- Scale up the use of electric boilers for low and mid-heat processes.
- Scale up the use of low-emission clean technologies (e.g. inert anodes).

Ecosystem-enabled solutions

Mid-term (by 2030)

- Invest in clean power infrastructure and grid capacity supported by energy storage systems to support the net-zero transition.
- Implement policies that further support the development and commercialization of low-emission clean technologies.
- Encourage scrap use and transparent declaration.
- Introduce and enforce industry-level standards (e.g. ASI's chain of custody[422]).

Long-term (by 2050)

- Reduce production cost premiums through an increased number of low-emission projects.
- Enable shared infrastructure and supply-chain stability through strategic partnerships.
- Develop infrastructure and market for green hydrogen to decarbonize boilers and calcination.

Performance

The sector currently accounts for 2% of global CO_2e emissions. As much as 60% of process emissions stem from electricity consumption, while 16% come from the fossil fuels used for thermal energy.[423] Thus, the electricity mix used, especially for smelting, is a critical driver for emission intensity.

TABLE 14 **Aluminium industry performance**

Performance metric	Change (2019-2023)
Industry output	+14.2%[424]
Emission intensity	-13.6%[425]
Total CO_2e emissions	-1.3%[426]

In the 2019-2023 period, demand increased by 14.2% while emission intensity decreased by 13.6%. The reduction in emission intensity is primarily due to:

1. **Reduced coal consumption**: Coal remains the largest contributor to the power mix used for aluminium, but the sector has seen a steady decrease in recent years, especially in China, where over half of global aluminium is produced. As major manufacturing countries reduce coal reliance and switch to renewable energy and less carbon-intense fuels, this will continue be a key driver in reducing emissions intensity.

2. **Higher rates of recycling**: Secondary aluminium production is steadily increasing in the industry, which uses less energy than primary aluminium. Scrap recycling rates are at an all-time high and are expected to continue to rise.

The smelting power mix still relies on fossil fuels for 61% of the power used and 39% from renewable sources (including hydropower). Coal represented 50% of the power mix in 2023, down from 57% in 2021, with the displaced coal primarily replaced by renewable energy.[427] The smelting power mix trajectory has been promising and is expected to eliminate the majority of Scope 2 emissions.

However, Scope 1 emissions are primarily in refining and process-related emissions, which have been relatively stable in recent years since the technologies required to decarbonize these processes remain nascent (e.g. hydrogen and CCUS).

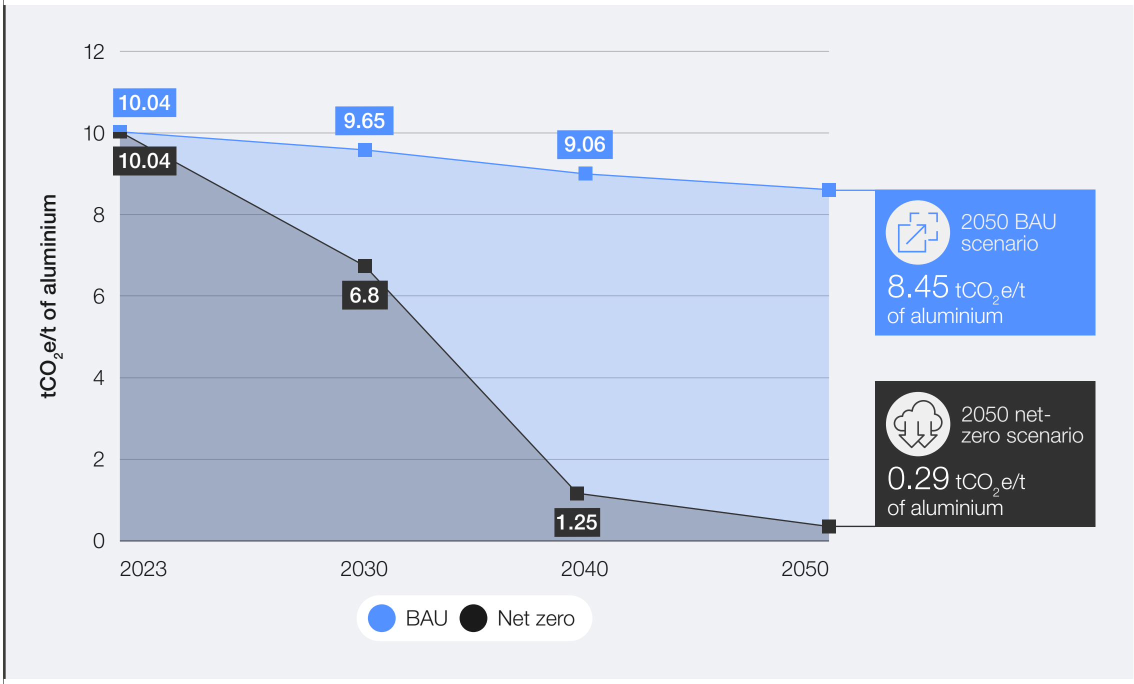
Several leading aluminium producers are testing breakthrough technologies, often in partnership. Examples include the Rio Tinto and Alcoa collaboration on inert anodes in Canada with support from Innovation, Science and Economic Development Canada (ISED); pilot tests on the use of hydrogen instead of fuels in alumina refining funded by the Australian Renewable Energy Agency (ARENA); and Norway-based company Hydro's attempts to use the carbochlorination process to produce zero-carbon aluminium, which is supported by the Norwegian government via state enterprise Enova.

Primary production has an energy intensity of 70 GJ per tonne, making it more energy-demanding than steel and cement. In contrast, secondary aluminium uses only 5% of the energy required in primary production.[428] Additionally, secondary aluminium is often cheaper from a process perspective – the challenge remains twofold: increasing scrap rate collection, which is currently at 70%, and removing impurities or alloying elements. Obvious limitations to growing secondary production are limited scrap availability, quality and segregation, and the fact that primary production is superior in technical specifications critical for certain industrial applications of aluminium.

Readiness

FIGURE 53

Emission intensity trajectory for the aluminium sector



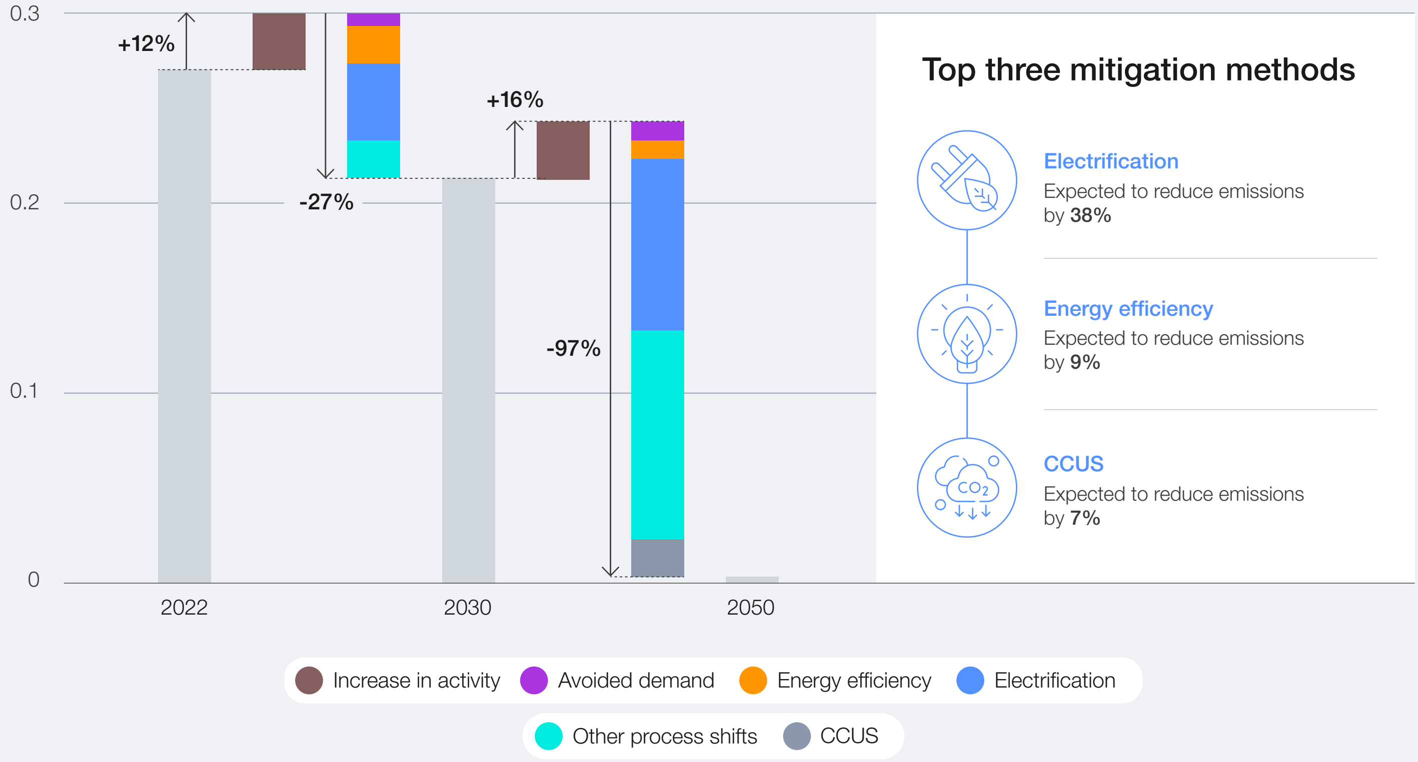
Source: IAI.

Overall aluminium demand is expected to grow by 80%[429] by 2050. The transport, construction, packaging and electrical sectors will account for most of the growth in aluminium demand. Increasing industrialization in emerging markets and global growth in transmission and distribution infrastructure are expected to be the main drivers for demand growth. Most of the demand growth is expected to be in the secondary aluminium market.

Thus, the industry needs to act fast on decarbonization to continue reduction in emission intensity and to offset the increase in demand.

FIGURE 54

Decarbonization levers and top mitigation methods (NZE Scenario)



Source: Accenture analysis based on IEA data.

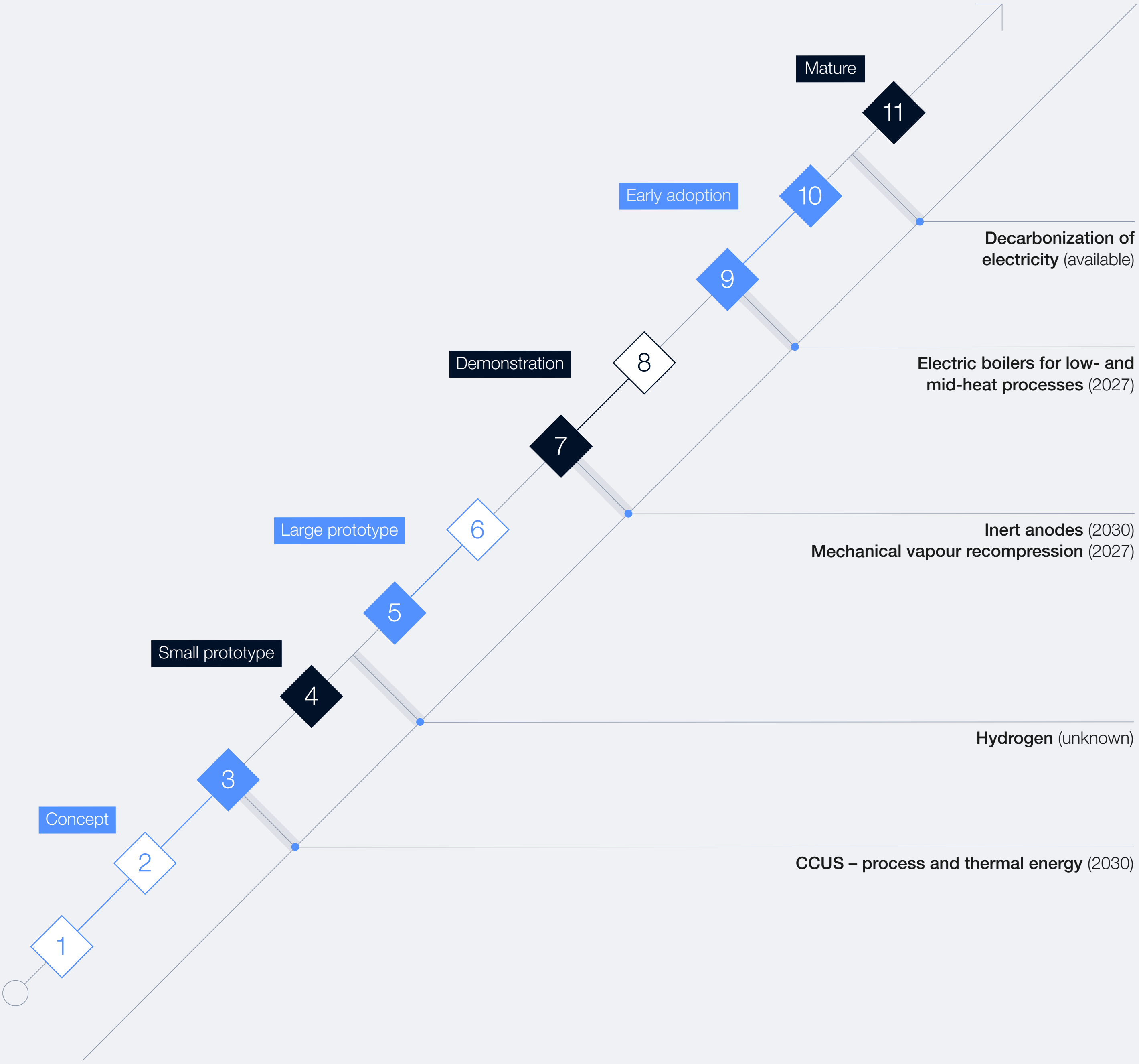
3

ALUMINIUM

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Three key pathways are currently available: electricity decarbonization, reduction of direct emissions, and recycling and resource efficiency.

FIGURE 55 **Decarbonization TRLs and year of commercial availability**



Source: Accenture analysis based on data from IEA ETP Clean Energy Technology Guide and MPP.

Technology pathway 1:
Electricity decarbonization

Renewable grids and electricity power agreements, combined with storage technologies to manage capacity volatility, offer a promising path for cleaner smelting and secondary production. However, these solutions are likely to incur additional costs in the short term. Another approach is the use of CCUS with captive power plants that rely on fossil fuels where renewable energy sources are not available. This method currently carries a cost premium of up to 30% in certain regions.[430] Additionally, nuclear-powered small modular reactors (SMRs) present an alternative, though this technology is still in the early stages of development.

Technology pathway 2:
Reduction of direct emissions

Process emissions contribute around 15% of the industry's emissions. Inert anodes and CCUS are pivotal technologies for low-emission smelting. Inert anodes are projected to become commercially viable after 2030, although they may lead to a 9% increase in production costs. CCUS applications in smelting are still in the early stages, and due to the low CO_2 concentrations in smelting flue gas, this approach is expected to involve higher costs for carbon capture.

Emissions from fuel combustion contribute another 15% of the industry's emissions. Thus, implementing low-emission refining technologies is essential for reducing thermal energy emissions in the refining process. Technologies such as electric boilers and mechanical vapour recompression (MVR) are vital for this purpose. MVR technology, which addresses the digestion process responsible for 70% of refining energy consumption, is anticipated to become available after 2027.[431] For the remaining 30% of energy used in the calcination process, emerging technologies like hydrogen calciners and electrified calciners have the potential to lower emissions.

Technology pathway 3:
Recycling and resource efficiency

Increased recycling can lead to a significant reduction in annual emissions, since secondary production emissions are much lower than primary production emissions. To achieve this, the availability of post-consumer scrap (which currently stands at 70%) needs to approach 100% by 2050.[432] The development and implementation of technologies that enhance scrap quality, such as advanced scrap sorting and purification methods, will be crucial in making this transition successful.

3

ALUMINIUM

Infrastructure

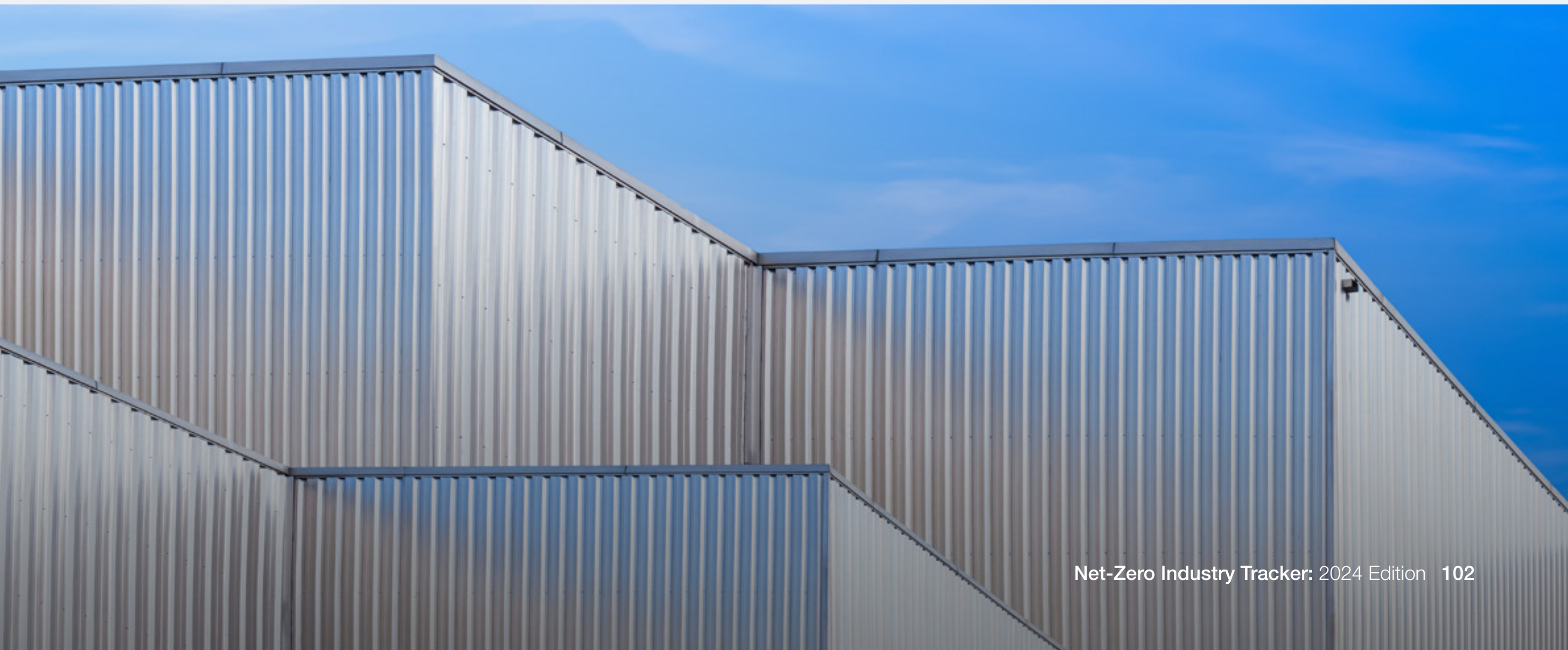
According to the MPP's Aluminium Transition Strategy, the aluminium sector currently has 14.3 GW of clean power available, primarily from hydropower. Low-carbon power capacity requirements are forecast to rise to 223 GW by 2050. The additional power demand is expected to be met through nuclear, renewables and captive power with CCUS.[433]

The aluminium sector needs to substantially expand its capacity for power from CCS or low-carbon grids to stay on a 1.5°C pathway. Currently, less than 1% of the CCUS capacity required by 2050 is operational. Progress in nuclear power has been slow due to the extensive R&D needed for SMRs, which are not anticipated to be commercially available to the aluminium industry until around 2035, with cost competitiveness potentially being achieved by 2040. Furthermore, the slow advancement of CCUS in smelting applications is attributed to its nascent stage and the challenge of capturing CO_2 from smelting flue gases, which are characterized by low CO_2 concentrations and higher capture costs.

FIGURE 56 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean power generation	14.3 GW	223 GW
Clean hydrogen production	0 MTPA	9.5 MTPA
CO_2 transport and storage	0 MTPA	86 MTPA

Source: Accenture analysis based on MPP.



3

ALUMINIUM

Demand

In 2021, approximately 30% of the total primary aluminium produced emitted less than 5 tCO_2e/t of aluminium.[434] The main final uses for aluminium are for cost-sensitive industries such as aircraft, cars, construction and electric cables. This strains the ability of the ecosystem to absorb the B2B green premium for aluminium, which is estimated at 40%, with current technologies.[435] However, offtake agreements provide early signals for low-emissions aluminium demand growth. Additionally, major companies in consumer electronics, including Apple or Ball Corporation, already use low-carbon aluminium. It is important to note that a 40% B2B green premium translates to a 1% increase for end consumers of cars, which shows that the cost of decarbonization is primarily borne by aluminium producers and is not trickling down to end consumers.

For the industry to align with net-zero targets and strengthen demand signals, adherence to globally accepted definitions of low-emission and net-zero aluminium are necessary. Standards for carbon content remain opaque, regional and voluntary. Beginning in 2023, the China Green Metal Certification Centre began issuing certifications for green-power aluminium to qualifying smelters nationwide. This is a notable milestone, considering that China currently dominates aluminium production, with over 50% of the market share.[436] These certifications allow for clear differentiation between aluminium produced with green power and that made with thermal power, addressing the needs of downstream producers who require environmentally friendly raw materials.

Further commitment is evident as industry leaders ramp up their efforts to accelerate low-carbon product transparency and demand with a suite of new initiatives. Rio Tinto's "START" programme[437] intends to inform consumer choices, and the London Metal Exchange (LME) launched digital passports to store certificates of analysis and sustainability for listed metals.[438] Additionally, leading aluminium industry lenders (Citi, ING and Societe Generale) are working with the RMI, (formerly Rocky Mountain Institute) to develop a climate-aligned financing framework. For comparability reasons, the unified use of sector-specific carbon footprint methodology with cradle-to-gate boundaries that are inclusive of Scope 1, 2 and 3 upstream emissions would add to transparency and market creation.

Expanding the range of industrial customers beyond traditional uses is essential. Aluminium plays a crucial role in technologies that are anticipated to underpin a net-zero future, including EVs, wind turbines, photovoltaics and energy storage systems. Consequently, regions like China, which are projected to see increased demand for these technologies, will require more low-emission aluminium compared to other areas.

FIGURE 57 **Top countries/regions in aluminium production and demand**

	Percentage of overall production	
1	China	59%
2	India	6%
3	Russia	5%
4	Canada	4%
5	United Arab Emirates	4%

	Percentage of overall demand (2022)	
1	China	57.5%
2	Europe	14.2%
3	Asia (excluding China)	11.4%
4	North America	9.9%
5	Middle East	2.5%

Source: Nasdaq and Statista.

1

ALUMINIUM

Capital

The aluminium industry will need substantial capital investment to advance low-emission smelting and refining technologies beyond merely decarbonizing power sources, with an estimated requirement of $543 billion.[439] The majority of this investment must be invested by the ecosystem, and not only by aluminium companies, to build the enabling infrastructure. Aluminium decarbonization requires a scale-up of low-carbon power, hydrogen and CCUS. The aluminium sector must invest in retrofitting smelting and refining to enable electrification and reduce emissions.

It is projected that out of the total additional investment required, about 42% is expected to go towards electricity infrastructure (grid/PPAs), 24% towards captive power generation, 3% towards green hydrogen electrolyser capacity, less than 1% towards CCS infrastructure, 5% towards refineries and 27% towards smelters.[440] Overall, 32% of the total additional investment is expected to come from the sector companies, while the remaining 68% is expected to come from the ecosystem.

FIGURE 58 **Investments required by the sector and enabled by the ecosystem**

$543 billion

required in investment by 2050

Investments by the sector (around 25% of investments)

- 🟢 Upgrade smelters for electrification
- 🟢 Purchase power agreements
- 🟠 Build more capacity for secondary production
- 🔵 Inert anodes for low-emission smelting
- 🔵 CCUS
- 🔵 Electric boilers and mechanical vapour compression
- 🔵 Hydrogen calciners and electrified calciners

Enabled by the ecosystem (around 75% of total investments)

- 🟢 Provide low-carbon power/renewable grid
- 🟢 Develop nuclear-powered small modular reactors
- 🟠 Collect post-consumer scrap
- 🟠 Enhance scrap quality
- 🔵 Supply low-carbon hydrogen

🟢 Clean power for smelting 🟠 Secondary production 🔵 Low-emissions refining and smelting

Source: Accenture analysis based on data from MPP.

With the aluminium industry's ROIC at 11%[441] and its WACC at 9.6%,[442] the industry's profits are just slightly higher than its costs of financing. This narrow margin means that without additional support from external factors (such as technological advancements, policy incentives and industry collaboration) the industry may struggle to afford and implement the significant changes needed for effective decarbonization. Nevertheless, the recent progress of the industry to reduce emissions intensity is promising and should encourage the ecosystem to help the sector progress.

2

ALUMINIUM

Policy

Global aluminium production is highly regionalized, with China contributing 60% of the total output. This underscores the importance of implementing effective and tangible policies to improve access to clean energy in key production regions. Domestic and international regulations aimed at encouraging low-emission aluminium production are still in development. To address this, priorities should include facilitating the adoption of clean power; supporting R&D alongside market-based approaches to advance early-stage low-emission smelting and refining technologies; and enhancing recycling rates through improved collection policies and infrastructure for sorting and purifying aluminium scrap. Given that policy measures to support decarbonization are still emerging, it is crucial to establish concrete policy actions in major producing regions.

Furthermore, policies and regulations to standardize carbon accounting frameworks, scope and system boundaries are pivotal to strengthening product-level reporting. Additional trust in decarbonized products, paired with stringent specifications and benchmarks, is likely to facilitate a market-based approach for decarbonized aluminium. Improved carbon accounting will conversely inform policy compliance and provide critical transparency to inform the consumer and hold producers accountable.

TABLE 15 **Aluminium industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	EU-ETS[443]	Incentivizes aluminium producers to reduce emissions.
	Border adjustment tariff	CBAM[444]	Emission-intensive aluminium exporters to the EU face increased costs of compliance. Currently, 50% of aluminium consumed is imported from non-EU countries. This policy needs to be complemented by transparent and fair carbon accounting standards.
	Product standard	Aluminium Stewardship Initiative's Performance Standard 3, recognized by Green Building Council of Australia	Provides transparency and standardization to the environmental performance of aluminium products.[445]
Mandate-based	**Direct regulations**	Inclusion of aluminium in the EU's Critical Raw Material Act[446]	This act improves the circularity and sustainability of critical raw materials like aluminium but is still in the proposal stage.
	Government targets	China's renewable energy use targets for aluminium	Doubles the share of renewables in the aluminium energy mix by 2030.[447]
Incentive-based	**Subsidies**	China: provincial level subsidy	Public support to smelters to move to incentivize energy-efficiency technologies.[448]
	Direct R&D funds/grants	Canada's investment in ELYSIS' inert anode technology	A direct funding investment of $60 million positions ELYSIS to support further R&D and achieve commercial scale.[449] Additionally, funding support for R&D to accelerate innovative technologies should be reinforced by policies that enable technology access and transfer to developing countries.

10

Primary chemicals industry net-zero tracker

To reduce emissions, the industry must prioritize CCUS, energy efficiency and plastics recycling now, while advancing electrification, fuel shifts, bio-based feedstocks and hydrogen for lasting impact.

- The increase in demand for primary chemicals over the past five years has driven a rise in emissions, as this energy-intensive industry relies heavily on fossil fuels for both feedstock and process energy, substantially contributing to CO_2 emissions.
- CCUS and chemicals recycling, along with electrification and energy efficiency measures, are expected to reduce around half of the emissions in the primary chemicals sector by 2050.

0.1%	2%	2%
Decrease in absolute CO_2 emissions (2022-2023)	Decrease in emission intensity (2022-2023)	Increase in demand (2022-2023)

*Primary chemicals include ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol

PRIMARY CHEMICALS

Key performance data 2023[450,451,452,453,454]

2.5%
Contribution to global CO_2e emissions

0.94 Gt CO_2e
Scope 1 and 2 emissions

6%
Emissions increase (2019-2023)

1.27 Mt CO_2e/Mt
Emissions intensity

2.2%
Decrease in emission intensity (2019-2023)

2.3 times
Demand increase in NZE scenario by 2050, compared to 2023

2%
Current low-emission production

$6.5 trillion
Additional investment required for net zero by 2050

Performance summary

- The emission intensity has been stable at approximately 1.3 Mt CO_2e /Mt chemicals[455] for the last five years. This is primarily due to the industry prioritizing addressing supply chain disruptions and commodity price volatility.
- The absolute emissions[456] for primary chemicals has seen 6%[457] rise in the 2019-2023 period, driven by an increase in demand for ammonia by 4%, methanol by 19% and high-value chemicals by 9%.[458]
- Low emission production accounted for only 2%[459] of the total emission production worldwide in 2022. Only 8% of current plastic production is through recycling.[460]
- In 2022, the energy mix for primary chemicals was composed of 55% natural gas, 36% coal, 7% electricity, 1% oil and 0.6% biofuels.[461]
- Current infrastructure stands at less than 1% for CCUS, clean power and hydrogen of the required infrastructure capacity by 2050 for net-zero emissions.[462]

Future emissions trajectory

- The industry is forecasted to reduce emissions intensity by 28%[463] by 2030 compared to 2023 levels, according to IEA Net Zero Scenario. Absolute CO_2e emissions are expected to be 0.77 Gt in 2030.[464]
- 90%[465] of publicly traded companies in primary chemicals industry consider climate change in their operational decision-making processes, and 58%[466] of companies have approved Science Based Targets initiative (SBTi) targets.

Readiness key takeaways

Technology	3	– CCUS, chemicals recycling, bioenergy, renewables and hydrogen usage are all in the demonstration stage (TRL 7) with CCUS and chemicals recycling being the most mature (TRL 8).[467] – Electrification is in the prototype stage (TRL 5).[468]
Infrastructure	2	– CO_2 capture capacity is projected to grow to 52 Mt by 2030, a significant increase from 4 Mt in 2022.[469] – Current capacities are insufficient, as less than 1% of CCUS infrastructure and clean power infrastructure required by 2050 is available for the industry.
Demand	2	– Less than 2% of low-emission primary chemicals are currently being produced.[470] – The green premium for primary chemicals is estimated at 55%[471] for manufacturers on average and 1-3%[472] for end user products.
Capital	2	– Over $6.5 trillion[473,474] additional cumulative investments are required by 2050, out of which 60% are expected towards green ammonia, 27% towards green methanol and 9% towards waste management. – Currently, the chemicals sector has an annual CapEx of $86 billion.[475]
Policy	2	– Policies promote the increased use of clean hydrogen to replace fossil fuels in chemical production, mitigate chemical pollution risks, set emissions reduction targets, minimize plastic waste and enhance recycling technologies.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Implement material efficiency measures.
- Retrofit existing facilities to use clean hydrogen for ammonia and methanol production.

Long-term (by 2050)

- Execute major retrofits to ethylene and polyethylene production plants to increase capacity and reduce emissions.
- Create facilities that convert captured CO_2 into methanol.

Ecosystem-enabled solutions

Mid-term

- Work on waste market access and waste flow orchestration.
- Develop the infrastructure needed to produce and distribute clean hydrogen and other clean fuels.

Long-term

- Invest in dedicated CO_2 capture and storage capacity.
- Digitize the value chain and disclose key environmental system data.
- De-risk large-scale financial investment.

Performance

The primary chemicals sector currently accounts for 2.5%[476] of global direct CO_2e emissions. Fossil fuels account for over 98%[477] of energy and feedstock consumption in the industry, making them a critical driver for emission intensity. The chemical sector is the largest industrial energy consumer and the third largest industry subsector[487] in terms of direct CO_2e emissions. The chemical industry has a multifaceted opportunity to lower their Scope 1 and Scope 2 emissions and downstream end-market Scope 3 emissions. Scope 3 represents the majority, at 64%, while Scopes 1 and 2 only represent 36%.

TABLE 16 **Primary chemicals industry performance**

Performance metric	Change (2019-2023)
Industry output	+37%[478]
Emission intensity (Mt CO_2/Mt chemicals)	-2.2%[479]
Total CO_2e emissions	+5.8%[480]

In the 2019-2023 period, industry output increased by 37%,[481] while total emissions increased by 5.8%.[482] The increase in emissions is primarily due to:

1. **Increased production demand**: Global demand for chemicals (such as plastics, fertilizers and industrial chemicals) grew due to expanding economies, especially in emerging markets. This led to increased production, which in turn raised emissions.

2. **Supply chain and operational disruptions**: Global events, such as the COVID-19 pandemic and geopolitical tensions, led to temporary shifts in supply chains and operations. Higher gas prices, which resulted in less efficient production processes, delayed efficiency improvements and raised emissions.

In 2022, the energy mix for primary chemicals consisted of 55% gas, 36% coal (mostly used by China), 7% electricity, 1% oil and 0.6% biofuels in 2022.[483] Key initiatives, including efforts to integrate circular economy principles, improve energy efficiency and explore alternative feedstocks such as bio-based chemicals, which are critical to achieving long-term emissions reductions. Currently, only 8%[484] of total plastics production comes from recycling. The development of advanced chemical recycling technologies, such as depolymerization and pyrolysis, offers a potential solution by enabling the recycling of mixed or contaminated plastics that are not currently recyclable via traditional mechanical methods. Companies like BASF[485] and SABIC[486] are investing in these technologies to create a closed-loop system for plastics. However, the challenge remains that plastics are typically difficult to collect efficiently, and the quality of recycled plastics often falls short of the standards required for certain high-safety applications, such as food packaging or medical use.

Leading companies such as Shell and ExxonMobil,[487] supported by both public and private investment, are developing scalable CCUS systems that aim to capture and repurpose the industry's emissions. In parallel, hydrogen-based chemical production processes are gaining traction as potential long-term solutions for reducing carbon intensity, though their adoption remains in early stages due to high costs and infrastructure limitations.

Readiness

FIGURE 59

Emissions intensity trajectory for the primary chemicals sector

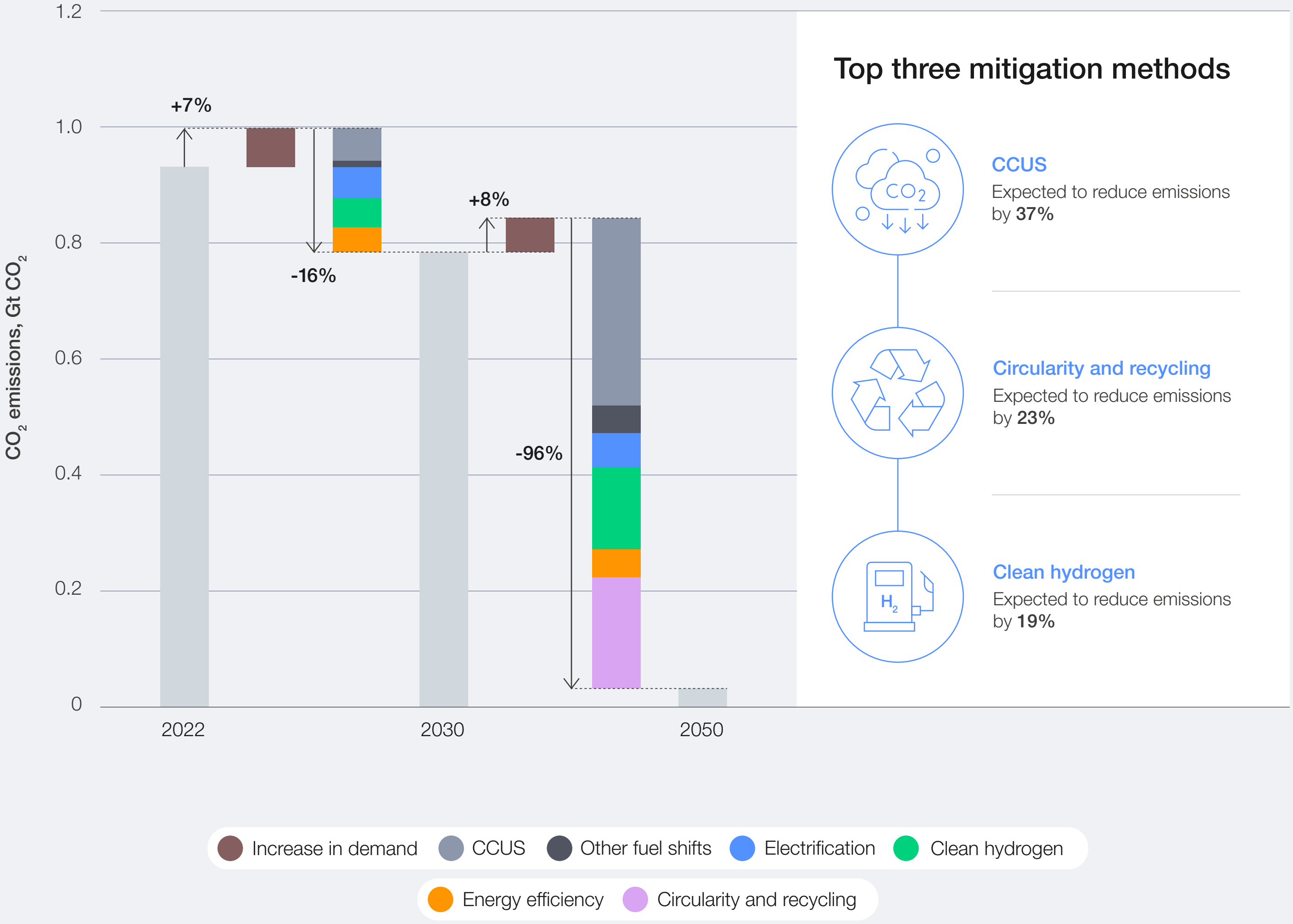
Source: IEA Net Zero Scenario.

Overall primary chemicals demand is expected to increase by 2.3 times[488] by 2050. By this time, green ammonia will represent 60% of demand (a fivefold increase from 2022) and methanol 20% (a fourfold increase from 2022).[489] Circularity can reduce demand by approximately 20%, saving $1 trillion[490] of CapEx needed to abate the system. Production volumes will more than double[491] overall by 2050, driven by new net-zero enabling chemical applications in other industries. Reducing demand is also essential to ensure that CCUS requirements remain manageable within current scaling limitations. The chemicals sector needs to decouple from fossil fuels and switch to renewable carbon feedstocks. As a feedstock, CO_2 is another decarbonization lever for the primary chemicals industry. Capturing CO_2 from industrial processes or the atmosphere and using it as a raw material to produce chemicals, fuels and materials (rather than simply storing it) aligns with the broader goals of carbon circularity, reducing reliance on fossil-based carbon sources. Its abundant availability, potential to close carbon loops and versatility in producing various chemicals make it an attractive alternative to both bio- and waste-based feedstocks.

Scaling circularity, switching production from fossil fuels to renewable feedstock sources, retrofitting legacy infrastructure and abating end-of-life chemicals are key operational pathways for achieving net-zero goals.

Clearer prioritization for deployment involves establishing a sequence of needs, starting with consistent global regulations to enable large-scale transformative investments. Next, political support for necessary infrastructure is essential, followed by customer willingness to pay, which helps secure the business case. Finally, case-by-case funding is needed to support implementation and manage associated risks effectively. Industry can start with the most cost-effective measures, using abatement cost calculations to ensure the transformation is feasible for society and customers. Energy transformation, being less expensive than material transformation in the chemical industry, is suggested to take priority. Additionally, using existing assets with renewable or recycled feedstock can accelerate deployment, as it is both cost-effective and less capital-intensive. While electrolytic hydrogen is costly for chemical use, blue hydrogen is a viable alternative, potentially reducing CO_2 emissions by up to 90%, with minimal additional cost.

FIGURE 60 | **Decarbonization levers and top mitigation methods (NZE Scenario)**



Top three mitigation methods

CCUS
Expected to reduce emissions by **37%**

Circularity and recycling
Expected to reduce emissions by **23%**

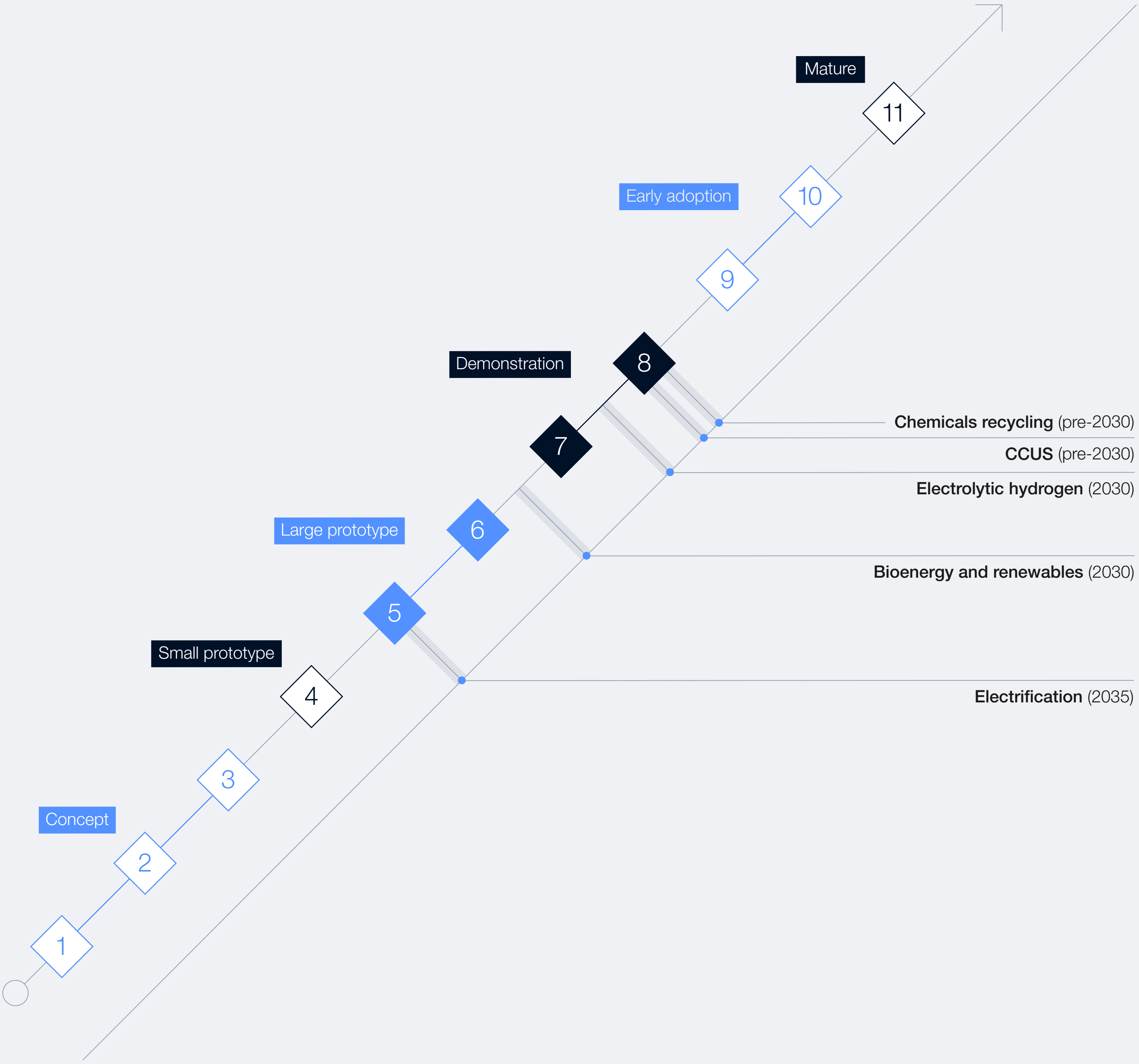
Clean hydrogen
Expected to reduce emissions by **19%**

Source: Accenture analysis based on data from IEA.

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Three leading pathways have emerged: CCUS, electrolytic hydrogen and circularity.

FIGURE 61 **Decarbonization TRLs and year of commercial availability**



Source: Accenture analysis based on data from IEA ETP Clean Energy Technology Guide.

Technology pathway 1: CCUS

In the primary chemicals industry, many capture technologies – particularly post-combustion capture using solvents (e.g. amines) – are nearing TRL 8-9,[492] indicating they are fully developed and have been demonstrated at industrial scale. However, novel capture methods (e.g. membrane-based or direct air capture) are at TRL 5-7,[493] indicating pilot-scale testing and demonstration projects have taken place, but not widespread commercial deployment.

Utilization technologies, where captured CO_2 is converted into value-added chemicals, are more advanced due to their integration with carbon-intensive processes and the potential to use captured CO_2 as a feedstock for products like methanol and urea.

Technology pathway 2: Electrolytic hydrogen

Alkaline electrolysis (ALK) is the most mature electrolysis technology, reaching TRL 8-9,[494] meaning it is commercially available and operating in industrial settings. Alkaline electrolysers have been demonstrated at large scale and are considered a mature technology for producing green hydrogen. Green hydrogen production using ALK and PEM electrolysers is already commercially available for specific applications within the chemicals industry, such as the production of ammonia and methanol, and energy use. However, current installations are often small-scale demonstration projects or pilot plants, as the cost of electrolytic hydrogen is still higher than hydrogen produced from fossil fuels. Clean hydrogen is playing a new role as an energy vector (new market) compared to its current role in chemical industry as material vector.

Technology pathway 3: Circularity and recycling

The concept of circularity in the primary chemicals industry includes strategies such as recycling, waste valorization, material efficiency, and substituting conventional materials with alternative or bio-based chemicals. Mechanical recycling (e.g. plastics recycling) is a mature technology with a TRL of 9,[495] meaning it is commercially available and widely implemented. The mechanical recycling of certain polymers, like polyethylene terephthalate (PET) and high-density polyethylene (HDPE), is already scaled. Advanced chemical recycling (e.g. pyrolysis and depolymerization), which breaks down plastics and other materials into chemical building blocks for reuse, are at TRL 5-7.[496] They are undergoing pilot and early-stage commercial trials but have not yet reached widespread commercialization. Key challenges include high energy requirements, scalability issues and economic viability. Waste-to-chemicals conversion, bio-based feedstocks, and material efficiency and substitution are pathways that can reduce demand and emissions.

2

PRIMARY CHEMICALS

Infrastructure

Transitioning to a net-zero chemicals industry by 2050 will require concerted investment and infrastructure development in CCUS, hydrogen production and clean energy generation. Presently, there are limited operational CCUS facilities, with most focusing on fossil fuel processing and industrial applications. Current capacities are insufficient, as less than 1%[497] of CCUS infrastructure and clean power infrastructure required by 2050 is available for the industry. The chemical sector can use CCU in ways that most other industries cannot, creating products such as synthetic fuels (e.g. methanol and aviation fuels), polymers and plastics (e.g. CO_2-based polyols for polyurethane production), chemical intermediates (e.g. formic acid and formaldehyde), and mineralized building materials (e.g. carbonates for construction). Unlike CCS, which primarily incurs costs, CCU allows the chemical industry to use CO_2 to create marketable products.

Renewable energy sources are increasingly being integrated into the power grid, but much more is needed to meet the projected demand. Current renewable capacity is 7 GW, and around 2200 GW of new renewable generation capacity will be required by 2050. Developing advanced energy storage technologies is essential to manage the intermittent nature of renewables and ensure a stable energy supply.

The existing hydrogen infrastructure primarily involves the production of grey hydrogen, which is derived from fossil fuels. There are only a handful of large-scale projects for clean hydrogen (green or blue hydrogen) that are currently operational. Companies like air products[498] are developing multiple hydrogen production facilities in the Netherlands, coupling steam methane reforming with CCUS to produce blue hydrogen while capturing and storing significant amounts of CO_2.

FIGURE 62 **Infrastructure for decarbonization capacity**

	Current capacity used	Capacity required (2050)
Clean power generation	**7** GW	**2,200** GW
Clean hydrogen production	**0** MTPA	**60** MTPA
CO_2 transport and storage	**4** MTPA	**640** MTPA

Source: Accenture analysis based on data from CGC.

2

PRIMARY CHEMICALS

Demand

Overall, by 2050, primary chemicals demand is expected to increase by 2.3 times.[499] By this time, green ammonia will represent 60% of demand and methanol will account for 20%.[500] Ammonia saw modest annual increases of around 1% and methanol of approximately 6.5% over the past decade.[501] However, production stagnation was noted in 2022, due to external factors like the energy crisis. While ammonia will grow significantly to full new net-zero applications such as shipping and power, non-ammonia chemicals will experience the greatest impacts of circularity.

To align with net-zero goals, the industry must pivot from fossil fuel-based feedstocks to more sustainable options. This includes increasing the use of electricity and bioenergy and enhancing recycling and material efficiency. Current reliance on coal, particularly in regions like China, is being scrutinized due to its high emission intensity, with expectations of a 30% reduction in coal use by 2030.[502]

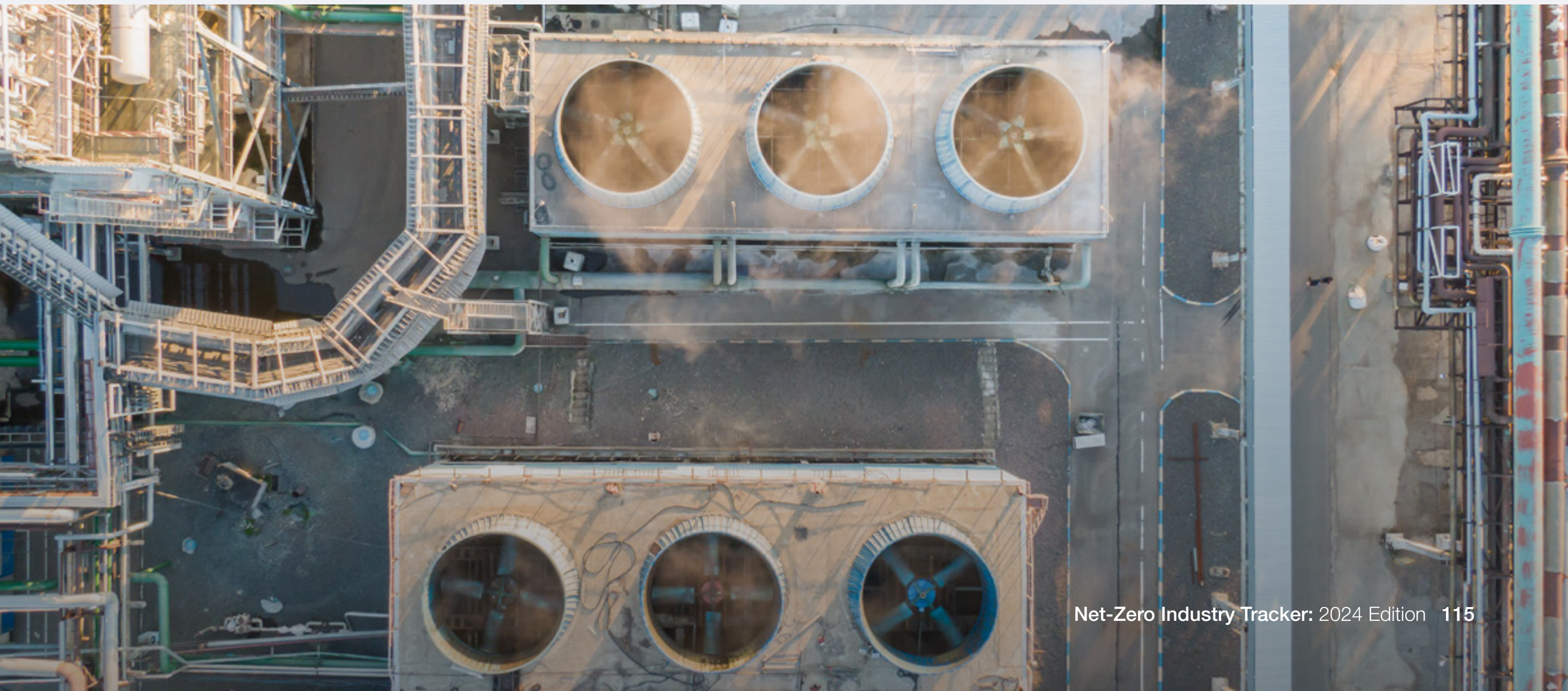
Despite the B2B green premium of 55%[503] on average, the impact of the increased manufacturing cost to end user products is limited to low single-digit percentages.

FIGURE 63 **Top countries/regions in primary chemical production and demand**

Chemical sales worldwide (2023)	
1 China	54.9%
2 US	11.2%
3 Germany	4%
4 India	2.3%
5 All other countries	27.6%

Percentage of overall consumption (2023)	
1 China	30.6%
2 US	6.9%
3 Germany	2.5%
4 India	2.4%
5 Japan	1.7%

Source: Statista.[504,505]



2

PRIMARY CHEMICALS

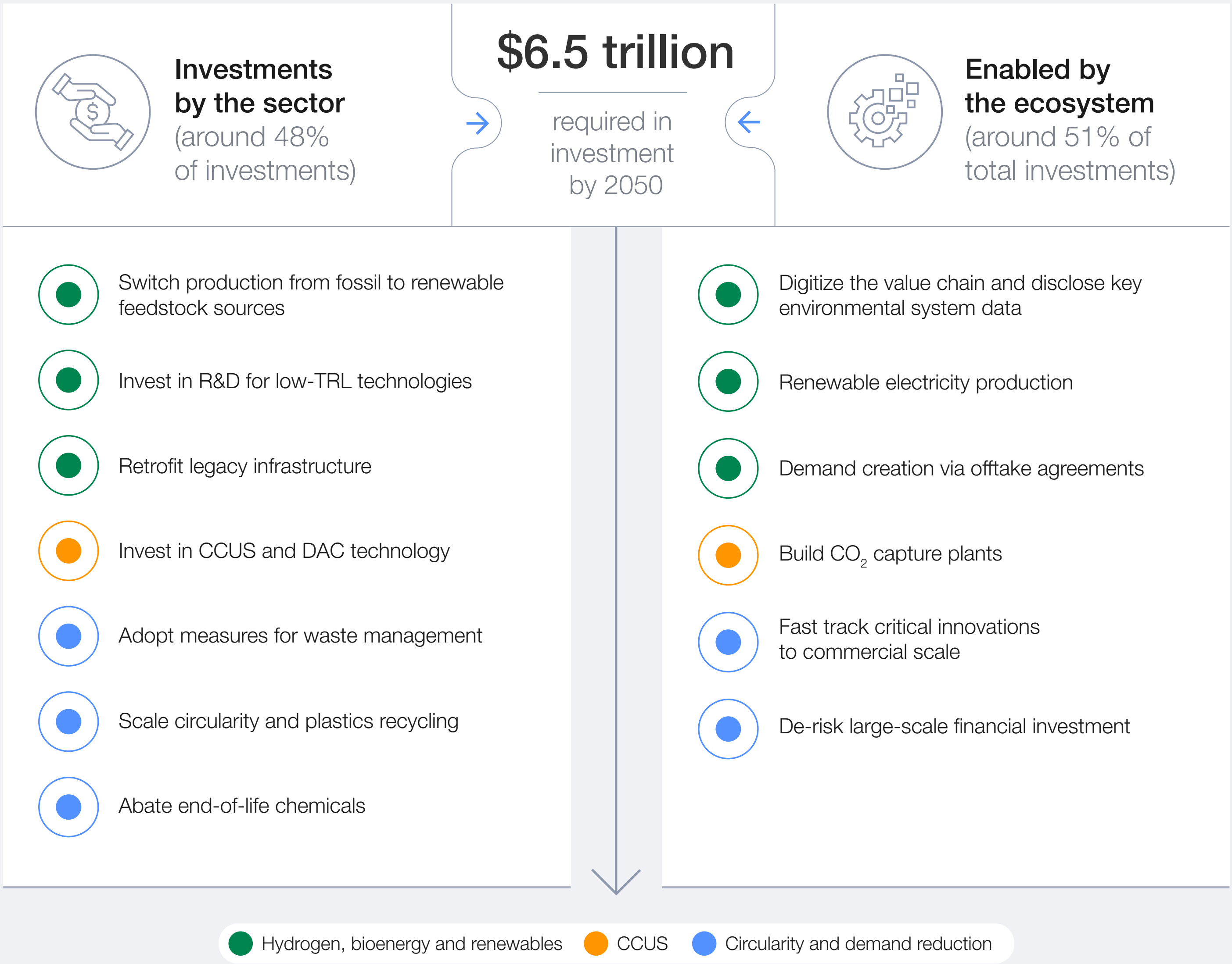
Capital

The primary chemicals industry will require additional capital investment of \$6.5 trillion[506,507] by 2050 to develop and implement low-emission technologies and infrastructure, 60% of which is for ammonia. Maximizing the efficiency of existing infrastructure will remain the most practical approach in the near term, which involves retrofitting existing plants and increasing circularity. However, the majority of future investments will focus on expanding capacity, necessitating the construction of new facilities. While optimizing current assets can yield immediate returns, long-term growth will rely heavily on better returns and low B2B premiums for the manufacturers.

The product carbon footprint (PCF) for each chemical product can vary significantly based on its production process, raw material sourcing and energy use. Transitioning to greener products often hinges on both the willingness of consumers and industries to invest in these sustainable options, as they typically involve higher costs.

A flexible allocation model like mass balance is an excellent approach in such cases. It allows manufacturers to balance renewable and non-renewable inputs without having to fully retool production for every single product. By using mass balance, companies can allocate a portion of their sustainable resources to specific products, effectively supporting the market shift towards greener products without making drastic, immediate changes to all production lines. This approach can accelerate the transition while remaining adaptable to evolving demand and willingness to pay for sustainable options.

FIGURE 64 **Investments required by the sector and enabled by the ecosystem**



\$6.5 trillion required in investment by 2050

Investments by the sector (around 48% of investments)

- 🟢 Switch production from fossil to renewable feedstock sources
- 🟢 Invest in R&D for low-TRL technologies
- 🟢 Retrofit legacy infrastructure
- 🟠 Invest in CCUS and DAC technology
- 🔵 Adopt measures for waste management
- 🔵 Scale circularity and plastics recycling
- 🔵 Abate end-of-life chemicals

Enabled by the ecosystem (around 51% of total investments)

- 🟢 Digitize the value chain and disclose key environmental system data
- 🟢 Renewable electricity production
- 🟢 Demand creation via offtake agreements
- 🟠 Build CO_2 capture plants
- 🔵 Fast track critical innovations to commercial scale
- 🔵 De-risk large-scale financial investment

🟢 Hydrogen, bioenergy and renewables 🟠 CCUS 🔵 Circularity and demand reduction

PRIMARY CHEMICALS

Policy

Global chemicals production is highly concentrated, with China contributing 44%[508] of the total production worldwide in 2023, followed by the EU and US. This underscores the importance of implementing effective and tangible policies to advance a comprehensive policy framework aimed at reducing industry emissions in key production regions.

Implementing standardized carbon accounting frameworks, clear scope definitions and consistent system boundaries is essential for promoting transparency and accountability. These measures are key to ensuring accurate emissions reporting and adherence to industry-wide guidelines.

Initiatives such as the International Council of Chemical Associations' (ICCA)[509] sustainability programmes emphasize the importance of standardization and collaboration among industry players to share best practices, particularly in adopting low-carbon technologies and alternative feedstocks. The ICCA, representing more than 90% of global chemical sales, recently announced the launch of three high-level ambitions on the sound management of chemicals and waste for the industry. By 2030, the industry aims to provide access to product safety and sustainability data, support chemical management systems in 30 countries, and guide product portfolios towards sustainable solutions.

TABLE 17 **Primary chemicals industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	Canada's Carbon Pricing[510]	Firms are incentivized to adopt energy-efficient practices to minimize carbon tax payments. This leads to increased operational efficiency and potential cost savings over time.
	Border adjustment tariff	Proposed US Border Carbon Adjustment[511]	US chemical companies will benefit from a more level playing field, as foreign competitors will face similar carbon costs. This may spur US firms to invest more in decarbonization to maintain their export competitiveness.
	Product standard	California Safer Consumer Products Regulations[512]	The regulation encourages the chemical industry to phase out harmful substances and develop safer, greener alternatives in products.
Mandate-based	**Direct regulations**	REACH Regulation in the EU[513]	Chemical companies are required to evaluate and reduce the risks of substances they produce or import. This leads to better safety and environmental practices in chemical production, significantly reducing hazardous chemicals.
	Direct regulations	Toxic Substances Control Act (TSCA) in the US[514]	By regulating the manufacturing and use of toxic chemicals, the TSCA leads to a reduction in harmful chemical releases into the environment. It protects ecosystems and public health.
	Government targets	Germany's Climate Action Plan 2050[515]	The ambitious emission-reduction targets (61-62% by 2030) compel the chemical industry to adopt low-carbon processes such as electrification, hydrogen use and circular economy models. This accelerates industry-wide decarbonization.
Incentive-based	**Subsidies**	Germany's Carbon Contracts for Difference (CCfD)[516]	The CCfD helps cover the cost difference between conventional chemical production and low-carbon alternatives like green hydrogen or carbon capture. This incentivizes companies to make investments in these expensive but essential technologies.
	Direct R&D funds/grants	EU's Horizon Europe Program[517]	Funds from this programme encourage the development of sustainable technologies, such as recycling of chemical waste and energy-efficient processes.

11

Oil and gas industry net-zero tracker

To reduce emissions, fugitive methane capture, zero flaring technologies, and upstream electrification are effective in the short term. Long-term solutions include CCUS, downstream electrification and clean hydrogen.

- Reductions in methane and flaring emissions and an increase in renewable sourcing have led to a decrease in emission intensity in the sector.
- While progress is being made in developing CCUS, clean power and hydrogen technologies, increased investment is needed to scale them effectively.

6%

Decrease in absolute CO_2 emissions (2021-2022)

2.9%

Decrease in demand (2022-2023)

OIL AND GAS

Key performance data 2022[518,519,520]

5.1 Gt CO_2e

Scope 1 and 2 emissions

100%

Fossil fuels in the fuel mix (2019)

80%

Reduction in expected demand in NZE scenario by 2050, compared to 2023

3.3%

Emissions intensity decrease (2018-2022)

87 kg CO_2/boe

Emissions intensity in 2022

$1.1 trillion

Additional investment required for net zero by 2050

Performance summary

- The industry has reduced emissions by 3% 2018 and 2022.[521,522] This is mainly driven by reductions in methane and flaring emissions, increased electrification of operations and improved operational efficiency.
- The absolute emissions for oil and gas were 5.45 Gt CO_2e in 2021, which decreased to 5.1 Gt CO_2e in 2022.[523]
- The production, transport and processing of oil and gas in 2022 resulted in just under 15% of global energy-related GHG emissions.[524]
- In 2022, global consumption reached 97 million barrels per day (mb/d) of oil and 4,150 billion cubic metres (bcm) of natural gas.[525]

Future emissions trajectory

- As per the IEA NZE Scenario, the oil and gas industry aims to reduce emission intensity by 55% by 2030 and 91% by 2050.[526]
- The projected absolute CO_2e emissions (Scope 1 and 2 emissions) for the sector are 2 Gt in 2030, 0.45 Gt in 2040 and 0.15 Gt in 2050.[527]
- The industry aims to reduce methane emissions by over 75% by 2030 and eliminate all non-emergency flaring worldwide by the same year, leading to a nearly 95% reduction in flared volumes, according to the IEA's Net Zero Scenario.[528]

Readiness key takeaways

Technology	4	⊖	– Fugitive methane capture technologies, zero flaring technologies, and upstream electrification are mature and available solutions (TRL 10). – Upstream CCUS is in the early adoption stage (TRL 9). – Steam cracker electrification (TRL 5), clean hydrogen (TRL 3-5) and use of CCUS in cracking and process heater (TRL 3-5) are in the prototype stage.
Infrastructure	2	⊖	– 178 GW of clean power is required by 2030, out of which 34 GW is currently available. – 10 MTPA of clean hydrogen is required by 2030. Currently, none of the capacity is available. – 390 MTPA of CCUS is required by 2030, out of which 33 MTPA are currently available for natural gas processing and LNG operations.
Demand	3	⊖	– The oil and gas sector contributes to 1% of the total clean energy investments globally. – The green premium in the oil sector is estimated at 10% for B2B, while in the gas sector, it is estimated at 7%.
Capital	3	⊖	– Over $1.1 trillion in investments are required by 2050, out of which around $780 billion is for electrification and efficiency, $110 is for CCUS, $102 billion is for methane reduction, $83 billion is for clean hydrogen and $70 billion is for flaring reduction.[529] – Currently, the industry has an annual CapEx of $409 billion.
Policy	3	⊖	– Policies are introduced to reduce emissions from existing fossil fuel infrastructure, scale up the deployment of clean energy technologies and boost the deployment of CCUS.

Sector priorities

Company-led solutions

Mid-term (by 2030)

- Increase investments in renewable energy sources to provide the energy required for operations.
- Scale methane abatement and flaring reduction technologies.
- Improve energy efficiency in extraction, refining and distribution processes.

Long-term (by 2050)

- Capture CO_2 with CCUS technology and use it to enhance methanol production.
- Transition towards sustainable business models that focus on renewables.

Ecosystem-enabled solutions

Mid-term

- Expand the production and availability of renewable energy sources.
- Encourage the implementation of programmes and technologies aimed at reducing methane emissions.

Long-term

- Invest in the development of infrastructure for clean hydrogen, renewable energy generation and CCUS.
- Introduce policies to support the increase in demand for low-carbon materials to stimulate low-carbon hydrogen uptake.

Performance

The sector currently accounts for 14% of global CO_2e emissions. Methane emissions account for nearly half of all GHG emissions from oil and gas operations.

TABLE 18

Oil and gas industry performance

Performance metric	Change (2018-2022)
Industry output	-3% for oil +8% for gas
CO_2e emission intensity	-3%
Total CO_2e emissions	-4%

Despite a temporary decline in oil volume in 2020 due to COVID-19 pandemic restrictions, demand almost recovered to 2018 levels by 2022. As for natural gas, from 2018 to 2021, demand grew steadily, driven by industrial activity and power generation, particularly in Asia. In 2022, the Russia-Ukraine conflict led to a 1% global decline, with Europe seeing a sharper 13% drop due to supply disruptions and price spikes. Despite these challenges, overall demand remained stable across key sectors.[530] Absolute CO_2e emissions saw a decline of 4%, while CO_2e emission intensity saw a reduction of 3%. Which can be attributed to several key factors:

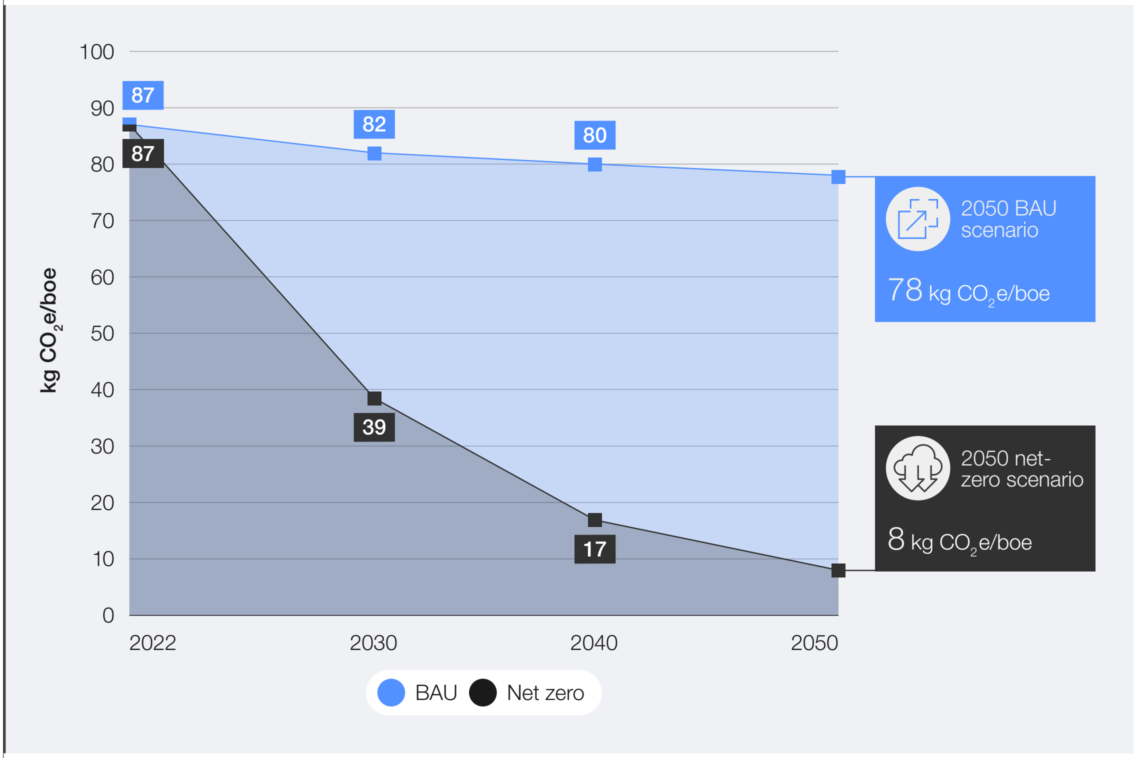
1. **Methane reductions**: Targeted initiatives (e.g. OCGI Satellite Monitoring Campaign[531]) aimed at detecting and eliminating methane leaks have decreased the overall GHG emissions of oil and gas operations.
2. **Reduced flaring**: Efforts to minimize the flaring of excess gas have led to significant reductions in CO_2 emissions, particularly from oil production sites.
3. **Improved operational efficiency**: Enhanced practices in extraction and processing have lowered energy consumption, further reducing emissions.
4. **Shift to cleaner sources**: The industry has increasingly focused on producing lighter oil and natural gas liquids, which have lower emissions intensity compared to heavier alternatives.

The Zero Routine Flaring by 2030 Initiative, launched by the World Bank and the UN in 2015, commits governments and companies to ending routine flaring by 2030. There has been some progress since its launch (the amount of gas flared per barrel of oil produced fell by approximately 10% in 2022 from 2021) but the total gas flared globally is still very high.[532]

Readiness

FIGURE 65

Emission intensity trajectory for the oil and gas sector

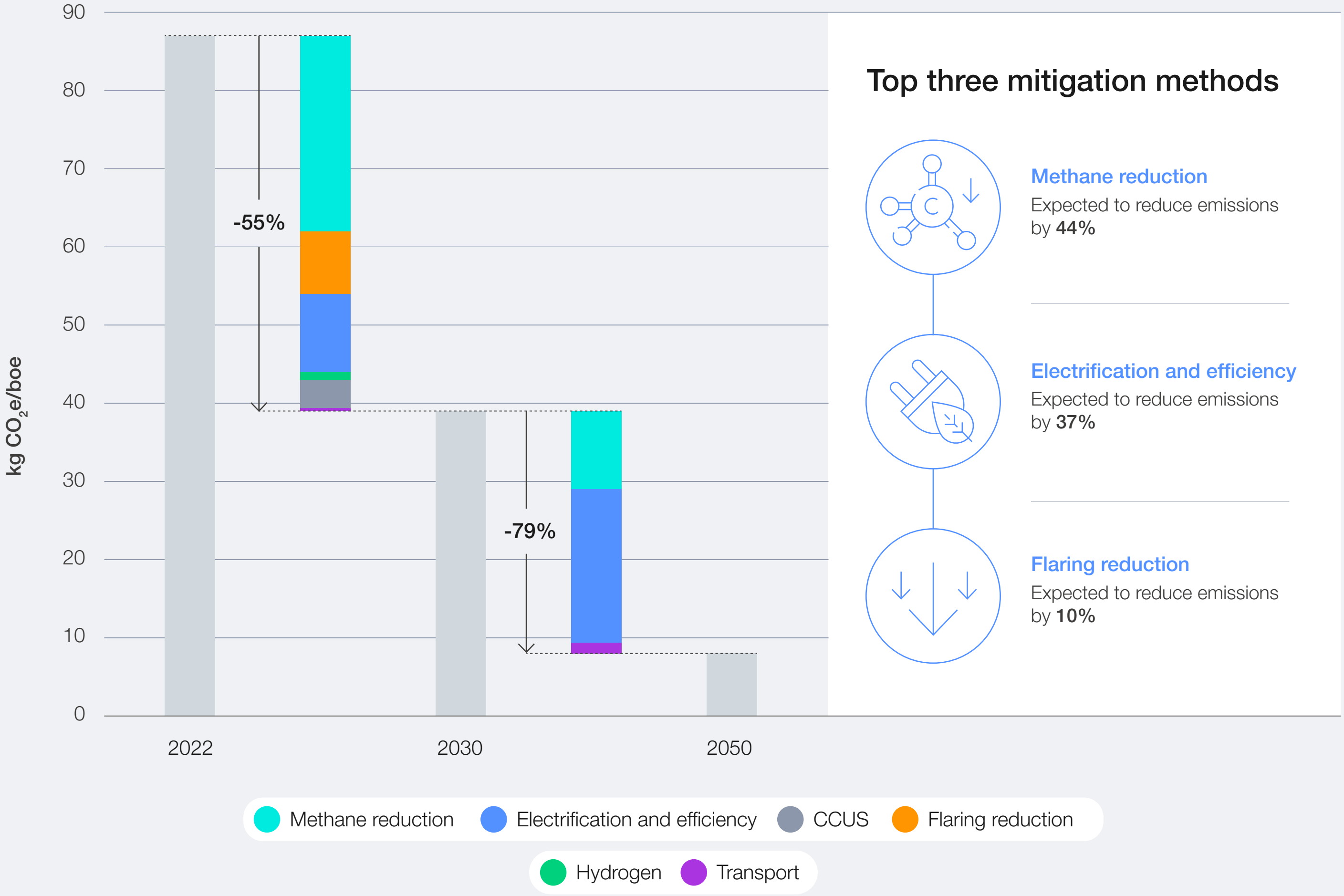


Source: Accenture analysis based on IEA NZE and STEPS Scenario.[533]

The oil and gas industry has advanced significantly in technology, particularly in methane capture and zero-flaring techniques, which are now fully developed (TRL 10). Meanwhile, electrification and energy efficiency measures are still in the demonstration phase and serve as important decarbonization levers. By 2050, the sector will need approximately 0.7 EJ of hydrogen, as per the IEA NZE scenario.[534] Currently, green premiums are relatively low, with natural gas at 7% and oil at 10%.[535] Policies are required to scale up the deployment of clean energy technologies and boost the deployment of CCUS. The industry requires over $600 billion in annual investments by 2030, primarily directed towards electrification, CCUS and low-emission hydrogen initiatives.[536] Overall, forecasts indicate a 74% decline in oil demand and a 78% drop in gas demand will be required by 2050 to meet the IEA NZE scenario.[537]

To achieve net-zero emissions by 2050, the oil and gas sector must focus on five key levers: addressing methane emissions, eliminating non-emergency flaring, electrifying upstream facilities with low-emission electricity, integrating CCUS and expanding the use of low-emission hydrogen in refineries. Reducing methane emissions is the most critical step for lowering overall emissions by 2030 given that it is a short-lived climate pollutant (SLCP), followed by improvements in electrification and efficiency. In net-zero scenarios, scaling up CCUS and adopting low-emission fuels for shipping will also play a significant role.

FIGURE 66 **Decarbonization levers and top mitigation methods (NZE Scenario)**



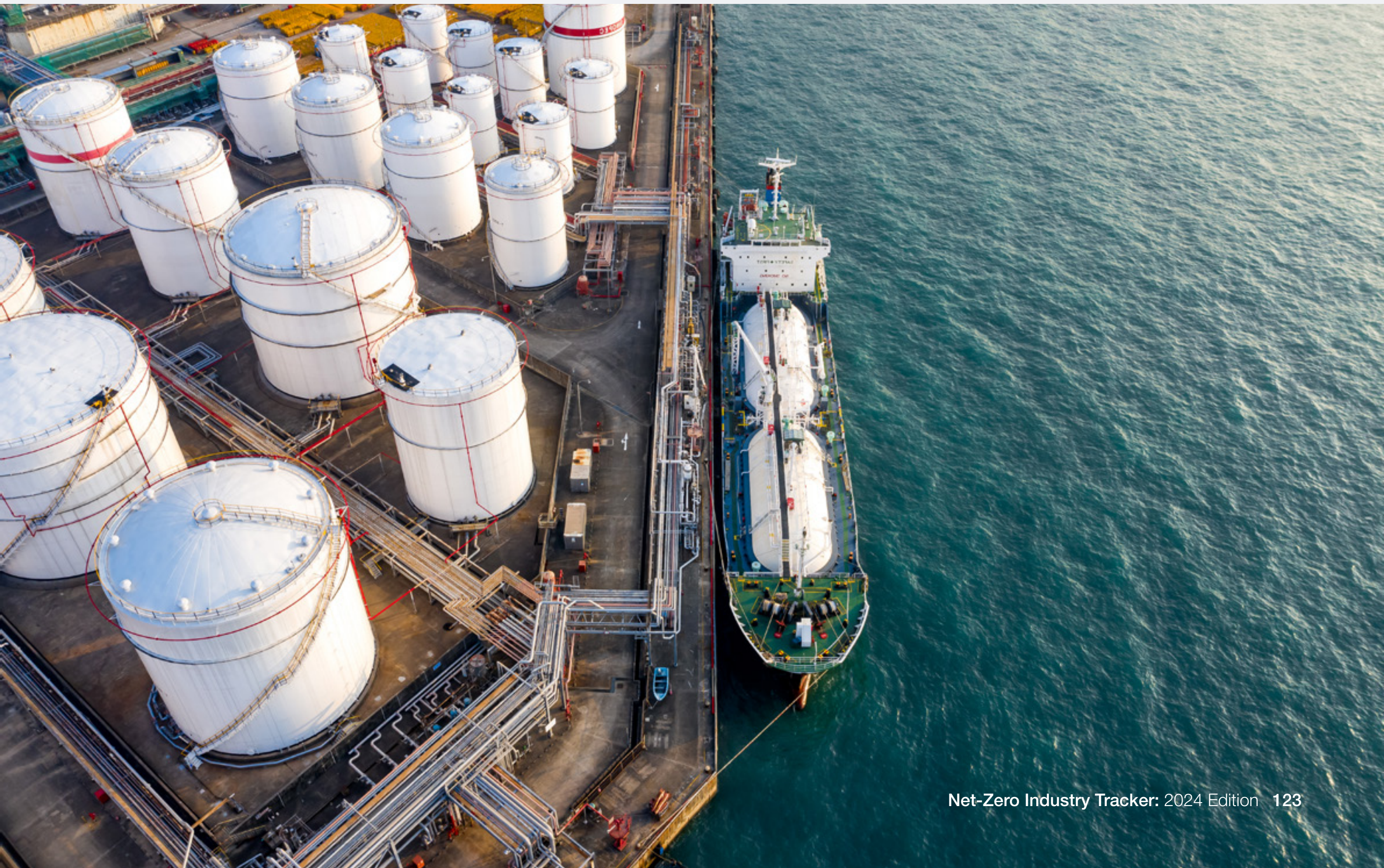
Top three mitigation methods

Methane reduction
Expected to reduce emissions by **44%**

Electrification and efficiency
Expected to reduce emissions by **37%**

Flaring reduction
Expected to reduce emissions by **10%**

Source: IEA.



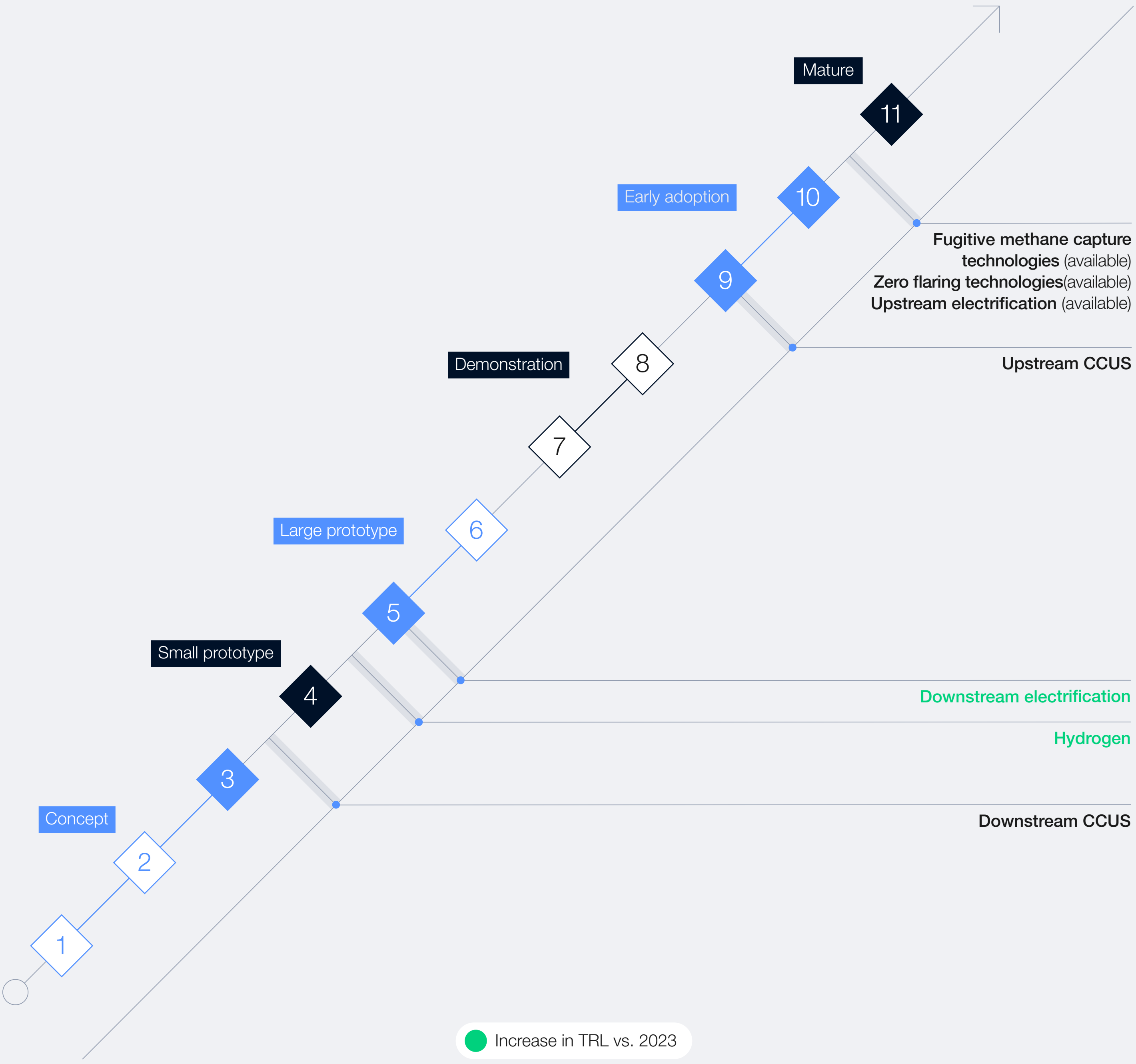
4

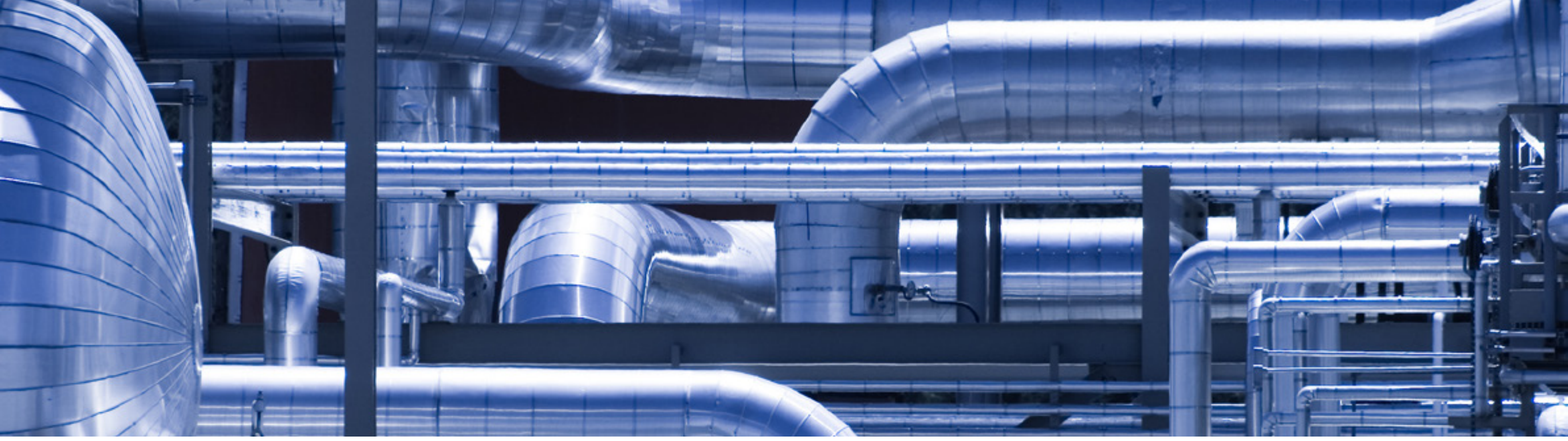
OIL AND GAS

Technology

Technologies to implement the decarbonization levers are at different readiness levels. Four pathways have emerged: methane abatement and zero-gas flaring, electrification, CCUS and clean hydrogen.

FIGURE 67 **Decarbonization TRLs**





Technology pathway 1: Methane abatement and zero-gas flaring

Methane abatement in the oil and gas industry is a cost-effective strategy for reducing GHG emissions, due to methane's potency and the potential to monetize captured gas. It is estimated that 40% of global methane emissions from oil and gas operations could be eliminated at no net cost. Addressing large leaks is a priority, with initiatives like the Methane Alert and Response System (MARS) using satellite technology to detect significant leaks and notify operators. The Oil and Gas Climate Initiative is piloting satellite monitoring in Iraq, Kazakhstan, Algeria and Egypt, with plans for expansion.[538]

Companies are employing various technologies to reduce or eliminate flaring. For instance, ExxonMobil announced in January 2023 that it had ceased routine gas flaring in the Permian Basin, aligning with its goal of net-zero emissions in the region by 2030. Portable compressed natural gas (CNG) and mini-LNG facilities can compress gas on-site for transport, potentially eliminating up to 89% of flaring, according to the US EPA in the Bakken field. Additionally, small-scale gas-to-methanol or gas-to-liquids plants are being developed with modular equipment. Upgrading flare tips and stacks can further enhance combustion efficiency and reduce emissions.[539]

Oil & Gas Decarbonization Charter (OGDC) signatories aim to achieve near-zero methane emissions in upstream operations and eliminate routine flaring in all operations by 2030. The initiative also plans to influence partners to adopt similar practices, where applicable.[540]

Technology pathway 2: Electrification

Electrification in upstream oil and gas operations is at a mature stage (TRL10), while in downstream operations (i.e. refining operations), it remains in the prototype stage (TRL 5). Various technologies enable electrification in upstream processes, enhancing efficiency and reducing emissions. Centralized grid connections enable access to existing electricity infrastructure, which is a preferred option in North America and Eurasia. Alternatively, decentralized renewable energy systems (such as wind and solar power with battery storage) facilitate on-site generation, particularly in regions like the Middle East and North Africa. Operators can choose between direct and alternating current (DC/AC) technologies and implement hybrid systems for reliability. For instance, companies operating in the North Sea have collaborated to develop shared clean electricity infrastructure.[541] Upgrading to more efficient equipment, like combined-cycle turbines, can further enhance efficiency.

Technology pathway 3: CCUS

The oil and gas industry has invested in over 90% of operational CCUS capacity and contributed more than 40% of total CCUS investment since 2010 in projects linked to oil and gas value chains. Currently, approximately 45 Mt of CO_2 is captured annually across 11 countries, with around 75% of this being used for enhanced oil recovery (EOR). However, EOR typically lacks the stringent monitoring needed to ensure permanent CO_2 storage. Around 30 Mt is captured from natural gas processing in the US, Brazil, Australia, the Middle East and China, while refineries and upgrading facilities in Canada and the US capture around 3 Mt per year.[542] CCS with permanent storage effectively captures CO_2 from refining processes, allowing for safe reuse and storage.[543]

Technology pathway 4: Clean hydrogen

Globally, around 42 million tons of hydrogen is used for refining oil, comprising almost half of the world's hydrogen demand and resulting in about 380 million tons of CO_2 emissions each year.[544] The processes of hydrotreating and hydrocracking consume over 90% of this hydrogen.[545] Refineries are well-equipped to adopt low-emission hydrogen technologies without needing new equipment. They can act as key sources of demand, helping to grow the supply of low-emission hydrogen and reducing risks for nearby operations that depend on coordinated investments.

2

OIL AND GAS

Infrastructure

Decarbonization of the oil and gas sector relies on three key factors: clean power, CCUS and clean hydrogen. Sufficient clean power generation capacity is needed for facility electrification, with a target of 178 GW by 2030.[546] As of 2022, oil and gas companies accounted for only about 1% of the total installed renewable energy capacity,[547] which translates to approximately 34 GW of clean energy used.[548]

Additionally, effective infrastructure for CCUS is essential at processing plants and refineries, requiring a total of 390 MTPA of CO$_2$ storage capacity by 2030,[549] down from 400 MTPA last year. Currently, approximately 33 MTPA[550] is already established for natural gas processing and LNG operations, an increase from 28 MTPA the previous year. The oil and gas industry possesses the necessary skills and expertise for CCUS, as it involves developing geological CO$_2$ storage resources, managing above-ground CO$_2$ handling facilities, monitoring gases underground and executing complex engineering projects. The CCUS Hub by the Oil and Gas Climate Initiative (OGCI) aims to help political decision-makers, industrial emitters, carbon transport and storage operators, and potential hub developers to set up their own CCUS hubs, learning from the experience of those already in advanced development.[551] It is important to note that the planning and permitting process for storing CO$_2$ is approximately 10 years, and could be a bottleneck in scaling up the use of CCUS.

In addition to CCUS, expanding clean hydrogen production is important for decarbonization efforts. The goal is to achieve a hydrogen production capacity of 10 MTPA by 2030,[552] which will support refining processes and contribute to overall emissions reduction.[553] Currently, clean hydrogen production has yet to gain momentum due to high costs, with a capacity of 0 MTPA.[554]

FIGURE 68 **Infrastructure for decarbonization capacity**

	Current capacity used	**Capacity required** (2050)
Clean power generation	34 GW	178 GW
Clean hydrogen production	0 MTPA	10 MTPA
CO$_2$ transport and storage	33 MTPA	390 MTPA

Source: Accenture calculations based on IEA.

3

OIL AND GAS

Demand

Achieving net-zero transitions requires addressing the growing demand for energy services while significantly lowering emissions. As markets evolve, low-emission alternatives such as biofuels, clean hydrogen-based fuels for transport and renewable energy sources for power generation are expected to become increasingly cost-competitive.

For example, the EV market has seen exponential growth, with nearly 20% of new cars sold globally in 2023 being electric. In the NZE Scenario, from 2040, all new trucks in advanced economies and China will be powered by electricity or hydrogen, with other emerging markets following suit by 2045. In aviation, low-emission fuels, including liquid biofuels and hydrogen-based liquids, currently account for less than 0.01% of total fuel use. However, by 2050 in the NZE Scenario, these fuels will make up approximately three-quarters of aviation fuel consumption. Similarly, for shipping, low-emission fuels (predominantly hydrogen and its derivatives) are expected to comprise around 85% of the global shipping fleet's fuel by 2050.[555]

Moreover, annual wind and solar capacity additions are projected to reach 1,150 GW in the NZE Scenario.[556] The integration of electric motors in industries that require low-temperature heat, along with the adoption of heat pumps in households, commercial buildings and small-scale industries, will further enable sustainable energy use.

To meet these ambitious targets, efforts are underway to decarbonize oil and gas operations, as these resources remain essential during the transition. For example, Chevron has made significant progress in reducing emissions in its Permian Basin operations, where oil and gas are produced with nearly one-third of the global industry average carbon intensity. Chevron's efforts also include converting traditional diesel-powered drilling rigs to electric or natural gas, and switching hydraulic fracturing equipment to dynamic gas blending, which uses a combination of diesel and natural gas. Furthermore, Chevron has installed electric-powered compressor stations and is supplementing grid power with solar fields, further driving down emissions.[557]

The B2B green premium for the oil and gas sector ranges between 7-10%, translating to a business-to-consumer green premium of 1-6%.[558] The market has shown limited price elasticity of demand in the long run, indicating that it can absorb these green premiums effectively.[559]

FIGURE 63

Top countries for oil production (2023),[560] gas production (2023),[561] and lowest CO_2 emissions from oil production (2022)[562]

Oil-producing countries (2023)		
1	US	20%
2	Saudi Arabia	12%
3	Russia	12%
4	Canada	6%
5	China	4%

Gas-producing countries (2023)		
1	US	26%
2	Russia	14%
3	Iran	6%
4	Canada	5%
5	Qatar	5%

Lowest CO_2 emissions from oil production (2022)		
1	Norway	36 kg CO_2e/boe
2	Saudi Arabia	66 kg CO_2e/boe
3	United Arab Emirates	74 kg CO_2e/boe
4	Kuwait	74 kg CO_2e/boe
5	Brazil	82 kg CO_2e/boe

3

OIL AND GAS

Capital

The oil and gas industry will need an estimated investment of $1.1 trillion by 2050.[563] The majority of this investment must be invested by the sector (around 60%), and the rest will need to come from the ecosystem to build the enabling infrastructure. Oil and gas decarbonization requires a scale-up of methane abatement, clean hydrogen, CCUS and clean power.

It is projected that out of the total additional investment required, around $780 billion is for electrification and efficiency, $110 billion is for CCUS, $102 billion is for methane reduction, $83 billion is for clean hydrogen and $70 billion is for flaring reduction.[564] Investing in electrification and efforts to reduce methane emissions and flaring can lead to new revenue opportunities by optimizing the use of natural gas and minimizing waste. These strategies could help companies quickly recover their initial investments. By 2030, these measures could provide over 200 bcm of additional natural gas. Even in a low gas price environment, these gas sales might generate around $30 billion in revenue each year.[565]

FIGURE 70 **Investments required by the sector and enabled by the ecosystem**

$1.1 trillion

required in investment by 2050

Investments by the sector
(around 59% of investments)

- 🟢 Invest in technologies like drones to quickly detect methane leaks
- 🟢 Invest in infrastructure that allows for gas capture and reinjection
- 🟣 Transition to electric-driven equipment
- 🟣 Switch to renewable feedstock sources
- 🟣 Provide low-carbon power/renewable grid
- 🟠 Invest in CCUS technology
- 🟠 Build CO_2 capture plants
- 🔵 Switch to hydrogen use in production process
- 🔵 Build hydrogen capacity for use in production

Enabled by the ecosystem
(around 41% of total investments)

- 🟢 Work with regulators to create supportive methane abatement policies
- 🟣 Provide a low-carbon power/renewable grid
- 🟠 Increase funding for R&D of advanced CCUS technologies
- 🟠 Establish clear regulatory frameworks that facilitate CCUS deployment
- 🔵 Establish policies that support clean hydrogen production and use

🟢 Methane abatement and flaring 🟣 Electrification 🟠 CCUS 🔵 Clean hydrogen

With the oil and gas industry's profit margin of 15%[566] (which is higher than all other sectors in scope), the business case for investing in decarbonization initiatives is strong. This profitability allows companies to allocate significant funds towards clean technologies and infrastructure development. Many oil and gas firms are already committing substantial portions of their budgets to sustainable energy projects, reflecting a strategic shift towards greener practices. However, the risk profile of investments in decarbonization varies significantly compared to traditional investments in oil and gas production, making it complicated to invest in decarbonization. Moreover, investments in national oil companies (NOCs) are driven by government budgets.

Policy

To achieve net zero in the oil and gas sector, key actions include accelerating methane emission reductions in line with the Global Methane Pledge; providing incentives for adopting zero-methane and zero-flaring technologies; and stimulating investments in electrification to help operators manage costs. Enhancing CCUS deployment through risk mitigation policies and performance-based payments for CO_2 avoidance is also necessary. Additionally, creating a market for low-emissions hydrogen will not only require production-based incentives and regulatory measures, such as cap-and-trade systems, but also incentives to stimulate demand for hydrogen. Establishing robust measurement and reporting frameworks is essential for ensuring clear eligibility criteria for support programmes and for effective governance of imports. While policies supporting methane abatement in the EU and US are quite advanced, efforts are required to scale up such policies in the rest of the world.

TABLE 19 **Oil and gas industry policy summary**

Policy type	Policy instruments	Key examples	Impact
Market-based	**Carbon price**	EU-ETS	Incentivizes oil refiners to reduce emissions.[567]
Mandate-based	**Targets**	Canada's target to reduce methane emissions from oil and gas	The new policy mandates a 75% reduction in methane emissions by 2030 compared to 2012 levels. This includes requirements for better leak detection, venting limits and equipment upgrades to capture fugitive methane emissions.[568]
		Nigeria's targets to eliminate routine flaring and fugitive methane emissions	Nigeria's emissions mitigation and reduction targets include the elimination of routine gas flaring by 2030 and a 60% reduction in fugitive methane emissions/leakages from oil and gas operations by 2031.[569]
	Direct taxes/fees	Methane fee under the IRA[570]	Establishes a maximum annual methane waste emission rate of 25,000 tonnes of CO_2e (vented, released or flared) for a facility and imposes penalty charges starting at $900 per tonne in 2024, increasing to $1,500 per tonne by 2026 for facilities emitting more.[571]
	National roadmaps	National Methane Action Plan – the EU, the US, Norway and Canada[572]	As part of the Global Methane Pledge, 150 countries have committed to work together to collectively reduce methane emissions by at least 30% below 2020 levels by 2030.[573]
	MRV guidelines	Colombia's national MRV standards	Technical standards and guidelines for fugitive and flaring emissions MRV for upstream oil and gas operations.[574]
	Standards and frameworks	GIIGNL framework for GHG neutral LNG MRV	Comprehensive framework for a consistent industry approach to declaring GHG neutral LNG cargoes.[575]
Incentive-Based	**International collaboration**	Oil and gas companies have joined the Oil and Gas Decarbonization Charter, a global industry Charter dedicated to high-scale impact, and to speed up climate action within the industry	Work towards industry best practices in emission reductions by:[576] – Investing in renewables, low-carbon fuels and negative emissions technologies – Enhancing transparency through better measurement, reporting, and verification of emissions and progress – Aligning with best practices to cut emission intensity and aiming to implement these by 2030 – Reducing energy poverty while ensuring secure, affordable energy for all economies
		US and United Arab Emirates' Partnership to Accelerate Transition to Clean Energy	A new bilateral Partnership for Accelerating Clean Energy (PACE) aims to fight climate change by deploying $100 billion and 100 GW of green energy by 2035.[577]
	Infrastructure capacity expansion plans	Norway government electricity capacity upgrade targets to support electrification of LNG assets	Targets grid expansion and renewables capacity by 2030 to support electrification of Norway's only LNG plant.[578]
	Direct technology funding	Methane Emissions Reduction Program	The initiative provides $1.36 billion in financial and technical assistance through various funding opportunities. It introduces a Waste Emissions Charge (WEC) for methane and mandates the EPA to update the Greenhouse Gas Reporting Program (GHGRP) subpart W regulations for the oil and gas sector.[579]

Conclusion

Over the past decade, hard-to-abate sectors have made progress towards reducing emissions, although not at the pace required to achieve net-zero emissions by 2050. In the last year, the sectors saw a decline in average emissions intensity. However, these sectors are expected to grow by 60% by 2050, meaning the reduction in emissions intensity must accelerate significantly. The readiness scores in this report indicate that none of the sectors in scope are currently on track to achieve net-zero emissions by 2050. It is important to note that the companies in these sectors cannot achieve this target alone. This will require the active collaboration of stakeholders throughout the value chains of supply and demand, as well as policy-makers.

The path forward demands sustained commitment from all sectors. This year's *Net Zero Industry Tracker* clearly shows that hard-to-abate industries must accelerate their efforts to transform operations and reduce emissions. The key priorities highlighted in this report can support stakeholders across the sectors in scope in deciding the next steps in their path towards the net-zero transition. The actions taken in the remaining years of this decade will be critical in ensuring that strong, long-term ambition is supported by immediate progress. The transition must be resilient to maintain momentum amid current market volatilities and potential future domestic or international disruptions.

Appendices

A1 Abbreviations and acronyms

AI	Artificial intelligence
AtJ	Alcohol-to-jet
ALK	Alkaline electrolysis
ARENA	Australian Renewable Energy Agency
ARPA-E	Advanced Research Projects Agency-Energy
ASTM	American Society for Testing and Materials
ATM	Air traffic management
BAU	Business-as-usual
BCC	Book and claim community
BECCS	Bioenergy with carbon capture and storage
B2B	Business-to-business
B2C	Business-to-consumer
BETs	Battery electric trucks
BF-BOF	Blast furnace-basic oxygen furnace
BIS	Bureau of Indian Standards
CapEx	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCfD	Carbon Contracts for Difference
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CIF	Climate Investment Funds
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DRI	Direct reduced iron
EAF	Electric arc furnace
EEXI	Energy Efficiency Design Index
EJ	Exajoules
EOR	Enhanced oil recovery
EU	European Union
EU-ETS	European Union Emissions Trading Scheme
EV	Electric vehicle
FID	Final investment decisions
FMC	First Movers Coalition
FT	Fischer-Tropsch
GCCA	Global Cement and Concrete Association
GCMD	Global Centre for Maritime Decarbonisation
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GIIGNL	International Group of Liquefied Natural Gas Importers
GJ	Gigajoule
GRI	Global Reporting Initiative
GSE	Ground support equipment
Gt	Gigatonnes
$GtCO_2$e	Gigatonnes of carbon dioxide equivalent
GW	Gigawatt
HEFA	Hydroprocessed esters and fatty acids
HETs	Hydrogen electric trucks
HFO	Heavy fuel oil
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cells
IAI	International Aluminium Institute

IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCA	International Council of Chemical Associations
ICCT	International Council on Clean Transportation
IDDI	Industrial Deep Decarbonisation Initiative
IEA	International Energy Agency
IED	Industrial Emissions Directive
IMF	International Monetary Fund
IMO	International Maritime Organization
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ISED	Innovation, Science and Economic Development Canada
ITA	Industrial Transition Accelerator
kgCO$_2$eq/boe	Kilograms of carbon dioxide equivalent per barrel of oil equivalent
LFO	Light fuel oil
LME	London Metal Exchange
LNG	Liquified natural gas
LSFO	Low-sulphur fuel oil
LTAG	Long-term aspirational goal
MB/D	Million barrels per day
MCFC	Molten carbonate fuel cells
MJ/RTK	Energy used per revenue tonne kilometre performed
MJ/ton-km	Energy use (MJ per transported tonne and km)
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MPP	Mission Possible Partnership
MRV	Measurement, reporting and verification
MT	Million tonnes
MTPA	Million tonnes per annum
MVR	Mechanical vapour recompression
NZE	Net-zero emissions
NZIA	Net Zero Industry Act
NZT	Net-zero technologies
OBPS	Output-Based Pricing System
OEMs	Original equipment manufacturers
OGDC	Oil and Gas Decarbonization Charter
PPA	Power purchase agreements
PtL	Power-to-liquids
R&D	Research and development
ROIC	Return on invested capital
RPK	Revenue passenger kilometres
SAF	Sustainable aviation fuels
SCM	Supplementary cementitious materials
S&P	Standard & Poor’s
SOFC	Solid oxide fuel cells
STEPS	Stated Policies Scenario
TCO	Total cost of ownership
T	Tonnes
tCO$_2$	Tonnes of carbon dioxide
tCO$_2$e	Equivalent tonnes of carbon dioxide
tCO$_2$e/t	Tonnes of carbon dioxide equivalent per tonne of output
TRL	Technology readiness level
TSCA	Toxic Substances Control Act
TW	Terawatt
UK	United Kingdom
US	United States
WACC	Weighted average cost of capital
WEC	Waste emissions charge
ZEF	Zero-emission fuels
ZEMBA	Zero Emission Maritime Buyers Alliance
ZET	Zero-emission trucks
ZEV	Zero-emission vehicles

A2 Readiness criteria

TABLE 20

Criteria for assessing the readiness dimensions

Dimension	Metric	Calculation methodology		Weight	Thresholds				
					Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Technology	**Technology readiness level (TRL)**	Weighted average of TRL calculated based on decarbonization levers		100%	TRL 1-3 Concept stage	TRL 4-6 Prototype stage	TRL 7-8 Demonstration stage	TRL 9 Early adoption stage	TRL 10-11 Mature stage
Infrastructure	**Infrastructure required for net zero by 2050**	Weighted average of the individual stage gate scores for each energy type based on 2050 requirement – current capacity	Clean power (GW)	Weights based on decarbonization levers for each sector	>300	100-300	30-100	0-30	<0
			Clean hydrogen (MTPA)		>75	50-75	30-50	10-30	<10
			CCUS (MTPA)		>750	500-750	250-500	100-250	<100
			Biofuels (MTPA)		>500	250-500	100-250	0-100	<0
Demand	**Price elasticity of demand**	Absolute value of price elasticity of demand (long-run)		25%	>1	0.75-1	0.5-0.75	0-0.5	<0
	B2B green premium	Additional cost to produce green product (%)		25%	>20%	15-20%	10-15%	5-10%	<5%
	B2C green premium	Increase in final price for end consumer (%)		25%	>6%	4-6%	2-4%	0-2%	<0%
	Current green supply	MPP: percentage of projects announced from 2030 target		25%	<10%	10-25%	25-50%	50-100%	>100%
Capital	**Required increase in capital**	Additional annual CapEx for decarbonization by 2050/ current annual CapEx		20%	>1	0.5-1	0.25-0.5	0.1-0.25	<0.1
	Capital efficiency	Total CapEx required by 2050/ total CO_2 emission reduction by 2050 ($\$/tCO_2$)		20%	>200	150-200	100-150	50-100	<50
	Ease of increasing capital	Sector-specific WACC (%)		20%	>10%	8-10%	6-8%	4-6%	<4%
	Current financed projects	MPP: percentage of projects financed from 2030 target		20%	<5%	5-10%	10-15%	15-20%	>20%
	Current return margins	Free cash flow after debt/revenue (%)		20%	<10%	10-15%	15-20%	20-25%	>25%
Policy	**Availability and maturity of policy**	Availability and maturity of policy across regions and globally		100%	Qualitative				

A3 Data sources

Methodology sources

Aluminium Stewardship Initiative (ASI)

BloombergNEF (BNEF)

Commodities Research Unit (CRU)

First Movers Coalition (FMC)

Global CCS Institute Global Cement and Concrete Association (GCCA)

Global Maritime Forum

International Air Transport Association (IATA)

International Aluminium Institute (IAI)

International Council on Clean Transportation (ICCT)

International Energy Agency (IEA)

International Maritime Organization (IMO)

International Renewable Energy Agency (IRENA)

Transition Pathway Initiative Centre, London School of Economics and Political Science (LSE-TPI Centre)

Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (MMM)

Mission Possible Partnership (MPP)

NYU Stern

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Standard & Poor's Global (S&P Global)

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