First Movers Coalition

WORLD ECONOMIC FORUM

In collaboration with Deloitte

High-Emitting Sectors: Challenges and Opportunities for Low-Carbon Suppliers

INSIGHT REPORT

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Images: Getty Images]

Contents

Foreword

By 2050, 50% of emissions reductions needed to achieve net-zero goals are expected to come from technologies not yet available at scale.[1]

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Building early market demand for breakthrough technologies is therefore critical to catalyse their commercial adoption and take steps towards global decarbonization. Given the scale and complexity of the challenge, strategic reforms and engagement from governments, regulators, investors, purchasing firms, researchers and the public are crucial to help accelerate the deployment of low-carbon solutions.

The World Economic Forum, alongside private firms and research institutions established the First Movers Coalition (FMC) to enable the acceleration of breakthrough technologies and send credible, large-scale demand signals to carbon-intensive sectors. FMC members pledge to purchase large volumes of goods that meet science-based emission reduction targets. As part of this FMC effort, the Forum created the First Suppliers Hub (FSH) with strategic support from Deloitte Consulting. The FSH is a global repository where suppliers provide information on their low-carbon projects to facilitate information-sharing and offtake agreements. This database connects users with a pool of suppliers as well as connecting suppliers to FMC members, policy-makers and financiers looking to grow the availability of low-carbon goods.

Suppliers are a key player in this ecosystem as they are responsible for piloting, developing and scaling-up the low-carbon technologies needed globally. They are instrumental in driving innovation and bringing these technologies to market, thereby influencing downstream emissions across the global value chain.

Informed by the lessons learned from the FMC and FSH, this report, developed in collaboration with Deloitte, provides an analysis from the perspective of the supplier on the value chain, decarbonization pathways, and challenges and opportunities for scaling-up their technologies. This report aligns with FMC's focus on carbon dioxide removal and six other sectors that represent ~25% of global greenhouse gas emissions: aviation, shipping, trucking, aluminium, cement/concrete and steel.

Executive summary

This report begins by analysing the supply chain, decarbonization pathways, challenges and opportunities for decarbonizing the heavy-emitting transport and material sectors from the supplier's perspective. It proceeds to describe the following three cross-sector obstacles for suppliers in accelerating the commercialization of their low-carbon technologies and proposes potential solutions for suppliers to navigate these barriers:

– **Lack of emissions measurement methods and standards**: Suppliers can engage with industry consortiums and international bodies to advocate for the establishment of sector-specific carbon accounting methodologies and standards, which can help secure buyers and financing.

– **Availability and cost of inputs**: Through strategic location decisions, collaborations to expand access to inputs, and engagement with government and finance stakeholders, suppliers can help overcome challenges to increase the supply of necessary materials and improve the cost-competitiveness of their solutions.

– **Buyers' risk aversion and unfamiliarity with decarbonized solutions**: Suppliers can leverage innovative contracting mechanisms to share or mitigate offtake agreement risk and educate potential buyers on valuing their solutions based on holistic economic and climate impacts.

This report also highlights unique opportunities across each of the FMC's seven sectors, organized around three heavy transportation sectors, three heavy industry sectors and carbon dioxide removal, as follows:

– **Aviation**: Opportunities to scale-up sustainable aviation fuel (SAF) include flexible terms in SAF offtake agreements such as "book and claim" schemes and expansion in emerging markets for feedstock supply while preserving sustainability.

– **Shipping**: Adoption of emission-reduction incentives such as carbon taxes proposed by industry players and regional entities can accelerate business development for suppliers of low-carbon shipping fuels.

– **Trucking**: Battery-electric vehicle fleets from multiple companies can use alternative charging models, such as shared charging infrastructure, to share costs and consolidate power use.

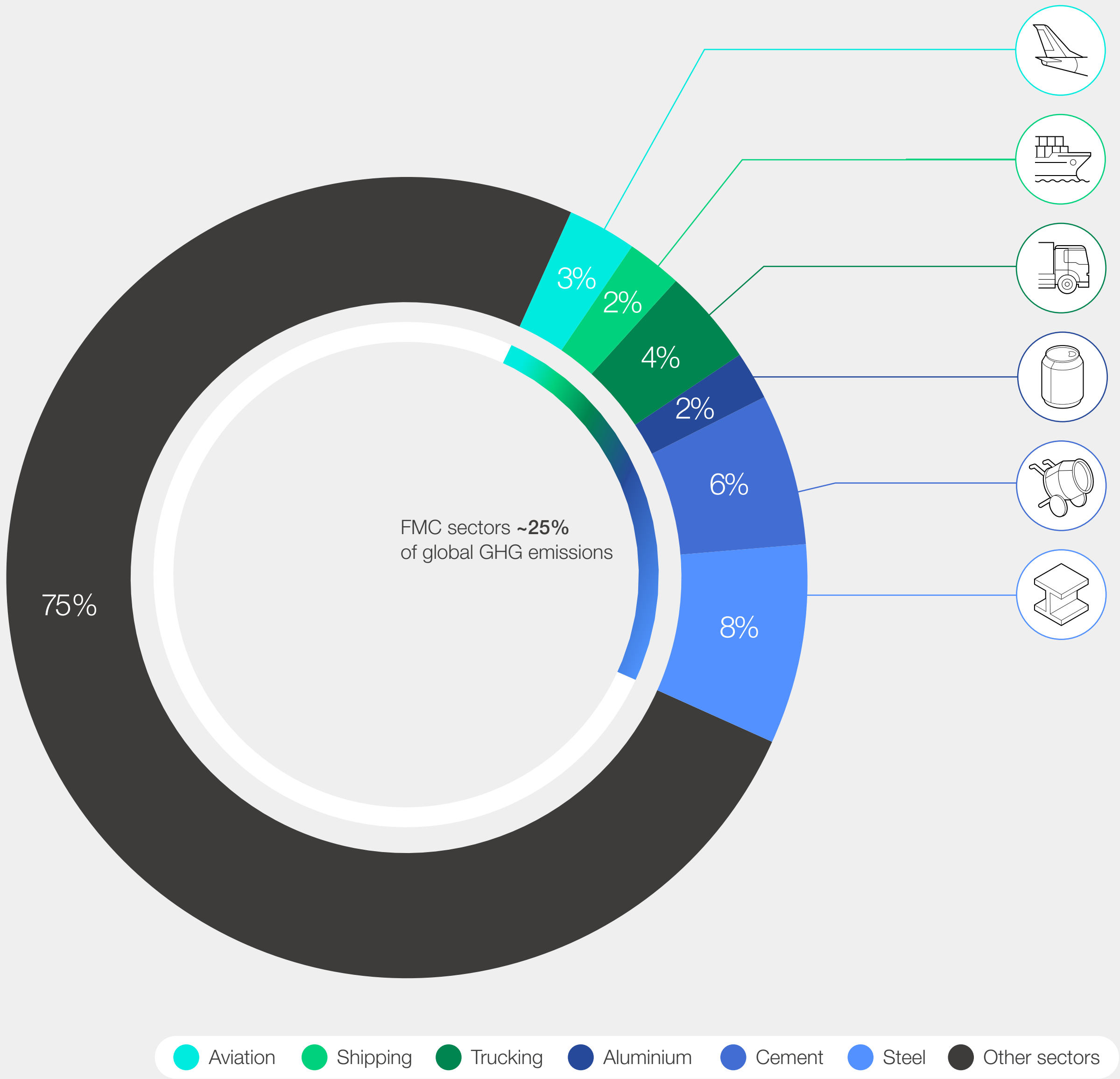
– **Aluminium**: The development, scaling-up and broad commercialization of emissions-free smelting technologies, renewable energy use in electrolysis and hydrogen, and carbon capture, utilization and storage (CCUS) present potential opportunities for decarbonization in the primary aluminium sector.

– **Cement/concrete**: Non-fossil alternatives such as calcium silicate cement and natural pozzolans[2] offer potential resilience to supply shortages and align with evolving regulations.

– **Steel**: Government interventions like the European Union's Carbon Border Adjustment Mechanism (CBAM) and the US Department of Energy's funding for industrial decarbonization projects can help balance cost disparities between suppliers and incentivize adoption.

– **Carbon dioxide removal (CDR)**: Exploring utilization markets, especially those involving long-term sequestration, can complement geologic storage solutions and further enhance carbon removal efforts.

FIGURE 1: **Global greenhouse gas (GHG) emissions, by sector**



Source: World Economic Forum.[3]

Based on the insights from this report, the World Economic Forum and Deloitte are dedicated to helping accelerate the adoption and demonstrating the feasibility of low-carbon technologies in heavy-emitting sectors. Relevant stakeholders, including governments and financial institutions, are encouraged to embrace innovative solutions for meaningful emission reductions and explore the resources available through the First Movers Coalition and First Suppliers Hub.

TABLE 1: **FMC sector emissions, pathways, opportunities and challenges**

Global share of GHG emissions, by sector	Deep decarbonization pathways in line with FMC commitments	Key opportunities	Key challenges
Aviation ~ 3%	– Sustainable aviation fuel (SAF) with life-cycle assessment (LCA) emissions abatement >85% (e.g. power-to-liquid, Fischer-Tropsch, alcohol-to-jet, and HEFA) depending on the production process. – Next generation near-zero emissions propulsion technologies, including battery-electric, hydrogen turbine and fuel cells.	– Growing public interest in reducing aviation emissions, driving demand for SAF. – Policy interventions and mandates increasing SAF demand and production. – Overcapacity in agricultural areas in emerging markets, offering potential for feedstock production for SAF. – Collaborative initiatives (e.g. Jet Zero Council) bringing together different stakeholders to de-risk private investments and innovate ways to reduce aviation emissions.	– High production costs and price premium, compared to conventional Jet A fuel. – Complex and capital-intensive supply chain, with significant investment required to scale-up production. – SAF competing with other forms of transportation for the same feedstock, particularly in emerging markets.
Shipping ~ 2%	– Methanol produced using low-carbon hydrogen and sustainable CO_2 (biogenic or recycled CO_2, e.g. from direct air capture etc.). – Ammonia produced with low-carbon hydrogen and nitrogen. – Low-carbon hydrogen as a combustion fuel. – Vessels capable of using zero-emission fuels.	– International Maritime Organization and regional bodies like EU setting ambitious GHG reduction targets. – “Book and claim” schemes allowing shipping companies to contribute to emission reductions without physically using low-emission fuels. – Global carbon taxes and mass-balance mechanisms to help industry and regional bodies drive investment in low-carbon fuels.	– Difficulties for suppliers in obtaining funding with appropriate risk appetite and investment size to develop and scale-up low-emission fuel projects. – High cost of zero-emission shipping fuels, compared to fossil fuels, making them less attractive for investment. – Gaps between suppliers and shipping companies on acceptable volume, offtake length and green premium levels.
Trucking ~ 4%	– BEV – Battery-electric vehicles – FCEV – Fuel-cell electric vehicles (hydrogen) – Zero tail-pipe emission fuels	– Establishment of clear incentives and regulations to encourage decarbonization technologies in medium- and heavy-duty trucking. – Innovative business models like trucking-as-a-service (TaaS) and collective charging farms can help offset the high upfront costs of transition. – Proposed tax credits and grants in countries promote investments in hydrogen production, storage and distribution, enhancing feasibility of FCEVs.	– Limited and region-specific hydrogen refuelling infrastructure. – High costs associated with transitioning to BEVs and FCEVs. – Difficulty for logistics companies managing large EV fleets to obtain necessary power allocation from electric utilities, due to fast-charging needs and high energy consumption.

Global share of GHG emissions, by sector	Deep decarbonization pathways in line with FMC commitments	Key opportunities	Key challenges
Aluminium			
~ 2%	Primary aluminium using breakthrough technologies, such as: – Electric or hydrogen boilers. – Concentrated solar thermal. – Mechanical vapour recompression. – Green hydrogen or electric calcination. – Inert anodes. – Carbon-chlorination. – CCUS (carbon capture, utilization and storage).	– Emissions-free technologies such as inert anodes and carbo-chlorination can eliminate smelting process emissions. – Transitioning to renewable energy for electrolysis processes can significantly reduce emissions. – By partnering with sectoral organizations to prepare procurement-ready documentation, suppliers can help buyers make informed decisions. – By collaborating with waste management sectors and governments, aluminium manufacturers can secure recycled aluminium and increase secondary production.	– High cost of scaling-up emerging refining technologies limits access to these technologies in some regions. – Mature nature of aluminium recycling leaves less room for improvement and adds competition in the material recovery landscape. – Industry faces challenges aligning on globally accepted standards and definitions for low-carbon aluminium.
Cement and Concrete			
~ 6%	– Replacing clinker with supplementary cementitious materials (SCMs). – Alternative chemistries and processes that replace limestone. – Point-source CCUS.	– With potential scarcity of SCMs, alternatives like non-fossil fly ashes and natural pozzolans could be used. – As landscape of clinker alternatives evolves, suppliers have opportunity to shape standards and regulations to accommodate alternative chemistries. – Suppliers can collaborate with regional value chain partners and regulatory bodies to develop localized approaches and standards.	– High costs of decarbonization and competition for investment with other sectors pose significant challenges. – Balancing historically local industry and the need for consistent, global standards and carbon accounting. – As the sector transitions, key inputs like SCMs may become scarce, particularly as coal combustion and iron-making blast furnaces are phased out.

Global share of GHG emissions, by sector	Deep decarbonization pathways in line with FMC commitments	Key opportunities	Key challenges
Steel			
~ 8%	– Direct-reduced iron electric arc furnace (DRI-EAF). – Scrap steel electric arc furnace (Scrap-EAF). – Novel reducing agents (e.g. low-carbon hydrogen or gasified biomass). – Other technologies, such as electrowinning to melt DRI to make it compatible with BOFs (DRI-melt-BOF), replacement of pulverized coal injection (PCI) with biomass- or hydrogen-based alternatives, etc.	– Policy mechanisms (e.g. EU's Carbon Border Adjustment Mechanism, CBAM) can help balance cost of transitioning to low-carbon steel production and prevent "carbon spillover". – Organizations signalling a strong demand for low-carbon steel can minimize risk of investments and drive innovation. – Use of clean hydrogen and biogas can help reduce emissions in steel production.	– Changes to steel production to lower carbon intensity will likely increase final cost. – The first firms to bring low-carbon steel to market are likely to struggle to sell their products, even while they de-risk low-carbon technologies for competitors. – Long life-cycle and high costs of major steelmaking assets may complicate transition plans. – Absence of global standards and definitions can make it difficult for suppliers to align production processes and for buyers to make informed decisions.
Carbon dioxide removal (CDR)			
N/A	– DACCS – Direct air capture with carbon storage. – BiCRS – Biomass carbon removal and storage. – BECCS – Bio-energy with carbon capture and storage. – BCR – Biochar carbon removal. – ERW – Enhanced rock weathering. – Mineralization.	– Measurement, reporting and verification (MRV) systems run by trusted third parties can assure suppliers about the credibility and durability of their carbon removal efforts. – Companies demonstrating demand for durable CDR solutions can accelerate the industry's growth and drive down costs. – Leveraging the collective purchasing power of companies can stimulate demand and accelerate the commercialization CDR technologies.	– Nascent technologies, lack of mature MRV standards and low support from policy-makers result in high costs that limit CDR uptake. – More robust climate policies to supplement demand-side efforts and achieve necessary scale. – Effectiveness of technologies can vary greatly based on geographic factors (e.g. availability of cropland, biomass, renewable power). – CDR often criticized for "legitimizing" continued emissions and avoidance of other abatement solutions. Transparent, responsible behaviour from CDR firms is necessary to counteract this perception.

1

Aviation

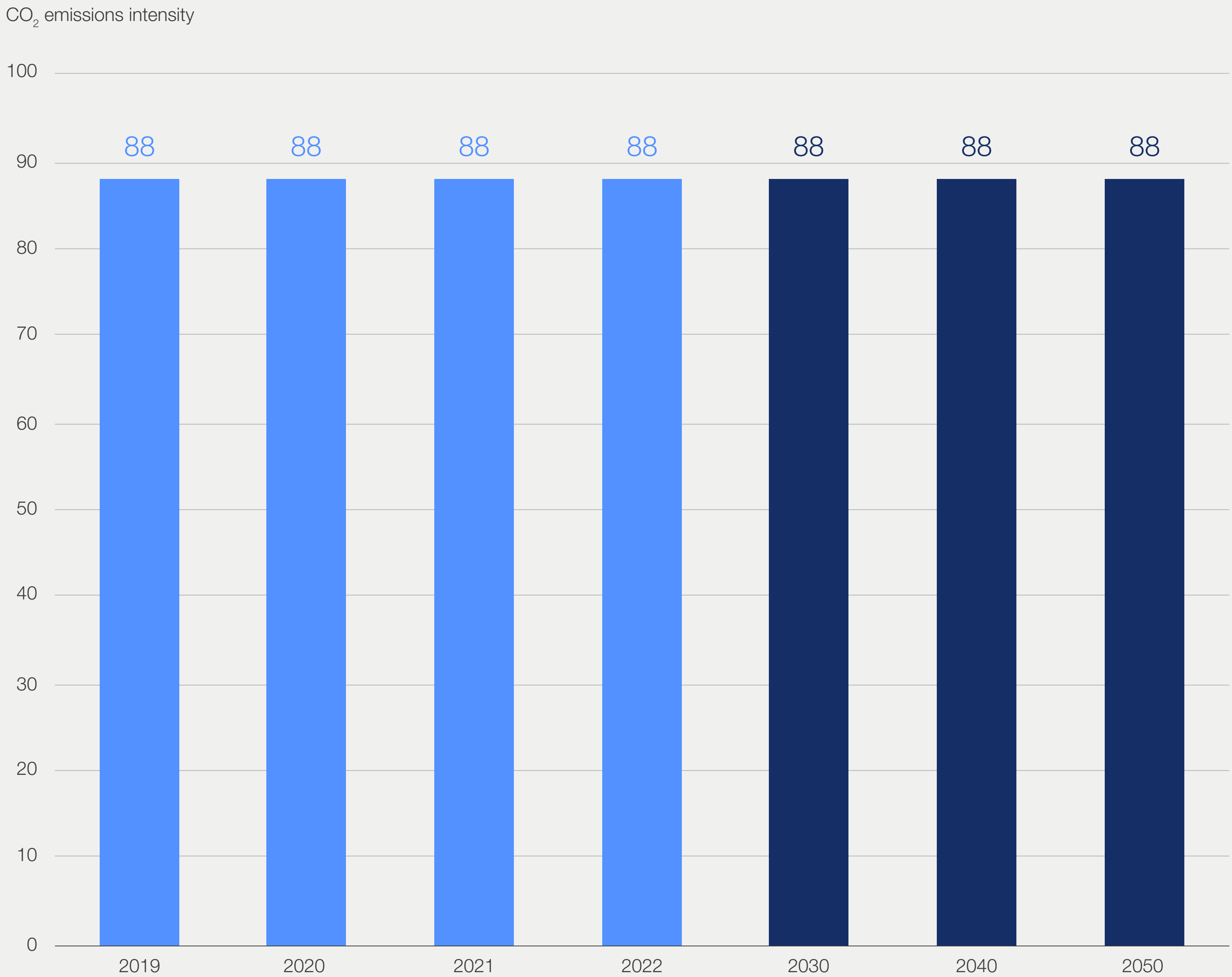
Aviation is well off-course from hitting the IEA's Net Zero Emissions by 2050 scenario. Long-term contracts are critical to accelerate the supply of SAF needed to decarbonize the industry.

1.1 Current emissions profile

The recovery of the aviation industry has accelerated post-pandemic in both its passenger and cargo sectors. By the end of 2022, the US marketplace alone offered over 1.52 trillion passenger miles to complement a global marketplace of more than 250 billion cargo tonne-kilometres (CTKs) of transported goods.[4,5] The aviation industry has a large carbon footprint due to its dependence on fuel consumption and a lack of viable alternatives to jet engines, especially for long-haul flights.

Although aviation accounts for only 3% of global greenhouse gas (GHG) emissions, its growth is outpacing other transport sectors.[6] Additionally, significant carbon reductions forecast in other transport sectors will likely lead to an increase in the aviation industry's relative contribution to global emissions. While the industry has pioneered several abatement and mitigation approaches, industry-wide adoption rates and supplier production capacities of alternative solutions indicate that aviation is well off-course for the 100 million tonnes (Mt) of CO_2 per year Net Zero Emissions by 2050 (NZE 2050) scenario of the International Energy Agency (IEA).[7] Without interventions, the emissions intensity of aviation fuel is expected to remain consistently high at 88 tonnes of carbon dioxide-equivalent (tCO_2e) per tonne of fuel, while other sectors see a decreasing business-as-usual (BAU) scenario due to efficiency gains (see Figure 2).

FIGURE 2: **Aviation emissions intensity trajectory, BAU scenario (tCO_2e/t of aviation fuel)**



Source: World Economic Forum.[8]

1.2 The FMC commitment

BOX 1: FMC Aviation commitment

Airlines and air transport companies:

By 2030, we will replace at least 5% of our conventional jet fuel demand with sustainable aviation fuels (SAF) that reduce life-cycle GHG emissions by 85% or more when compared with conventional jet fuel and/or zero-carbon emitting propulsion technologies.

Airfare and air freight purchasers:

By 2030, we will partner with air transport operators to replace at least 5% of conventional jet fuel demand for our air transport with sustainable aviation fuels (SAF) that reduce life-cycle GHG emissions by 85% or more when compared with conventional jet fuel and/or zero-carbon emitting propulsion technologies.

***FMC in-scope technologies include:**

- Sustainable aviation fuels (SAF) with life-cycle assessment (LCA) emissions abatement of >85%.
- Next generation near-zero emissions propulsion technologies, including battery-electric, hydrogen turbine and fuel cells.
- Other technologies with LCA GHG reduction >85%.
- These commitments do not include SAF with LCA <85%, fossil jet fuels and carbon offsets.

Full details of the commitment can be found here.

1.3 Decarbonization pathways in aviation

As emissions primarily arise from direct fuel consumption, a range of novel solutions have been developed across two key categories:

- **SAF which utilize alternative feedstock** hydrocarbon energy carriers that complement or replace conventional aviation fuels.
- **Alternative propulsion engines** including but not limited to: battery-electric aircrafts, hydrogen fuel-cell electric aircrafts, hybrid-electric aircrafts and emission-less hydrogen combustion propulsion.

Sustainable aviation fuels (SAF)

SAF is an umbrella term referring to both biofuels (based on non-petroleum feedstocks) and synthetic fuels derived from low-carbon hydrogen and sequestered CO_2 (also known as power-to-liquids, or PtL and e-SAF). While a range of technologies and feedstocks can be used to produce SAF, FMC only permits fuels resulting in a LCA GHG emissions reduction greater than or equal to 85%, also known as SAF85. Currently, SAF in production reduces carbon emissions by between 27% and 87%, of which a small percentage is greater than or equal to 85%.[9] In addition, there are limited production facilities at scale for SAF in general and especially for SAF85, with current plants relying mainly on feedstocks from pre-existing value chains rather than dedicated supply networks.

Nevertheless, SAF is the only commercially viable decarbonization pathway based on its high technology readiness level (TRL) and near-immediate potential horizon.[10] The commercial maturity and emissions reductions provided by SAF are dependent on the fuel source. Among the various SAF pathways, the hydro-processed esters and fatty acids (HEFA) approach has the highest technology readiness, is in the most advanced stages for commercial deployment and offers the cheapest SAF pathway.[11] Despite most SAF demand being met by HEFA, the production pathway of HEFA is constrained by its limited feedstock of fats, oils and greases and competition from other transportation sectors, at least in the short term, making HEFA unlikely to meet the FMC aviation commitment.

> SAF is the only commercially viable decarbonization pathway based on its high technology readiness level and near-immediate potential horizon.

In recent years, research and development investment has increased in other pathways, such as power-to-liquid. PtL pathways (via the Fischer-Tropsch method or methanol) also offer high technology readiness levels. However, this pathway currently experiences the highest production costs when compared to conventional jet fuel.[12]

In 2023, SAF production nearly tripled to 0.6 Mt from 0.24 Mt in 2022, representing 0.2% of global jet fuel use. A total of 43 airlines have committed to different SAF uptake levels, ranging from 5%-30% by 2030, with most of them committing to 10% SAF use by the end of the decade. Today, SAF production is primarily located within Europe and the west coast of the US; but with 130 projects announced by 85 producers in 30 countries, the SAF industry is expecting significant growth, with global production of SAF forecast to increase 30-fold by 2030.[13,14,15]

> **With 130 projects announced by 85 producers in 30 countries, the SAF industry could increase 30-fold by 2030.**

Complementary emissions abatement

It is important to note that SAF is only an abatement technology that reduces net life cycle emissions and will not eliminate the aviation industry's emissions impact entirely. To fully realize the IEA's NZE 2050 target, the industry will need to adopt a complementary portfolio of emissions abatement solutions ranging across fleet, operational and technological pathways, which are not in scope for FMC.

Several of these pathways have already reached commercial readiness and are being pursued by the industry, such as air-frame modernizations and weight reductions, air traffic management optimizations to increase route and airspace efficiencies and retirement of legacy fleet assets.

Alternative propulsion technologies

Alternative propulsion technologies, which are in scope for FMC, show promise for shorter-haul flights, but their scalability and feasibility for long-haul flights is uncertain. Battery, electric-motor and efficient integrated airframe/propulsion design technologies have not yet achieved sufficient range, charging and technology maturity to make long-haul, commercial electric air transport viable.[16,17]

1.4 Supplier challenges and opportunities in low-carbon aviation

Due to the current low penetration of SAF and especially high carbon abatement cost, the aviation and fuel supplier industries find themselves in a first-mover paradox. Commercially SAF therefore maintains a relative price premium of two to five times that of conventional aviation fuel (Jet A).[18,19]

The SAF industry is facing several challenges to scaling-up production, including high production costs, uncertain demand signals and a complex supply chain.

However, opportunities also exist to scale-up SAF, including growing public interest in reducing aviation emissions, flexible terms in SAF offtake agreements, and potential for partnerships and investment in emerging technologies and markets.

High production costs

The infrastructure required to produce SAF is highly capital-intensive. This challenge is occasionally addressed through brownfield-style approaches where existing facilities are enhanced to produce SAF for a fixed number of years while demand stabilizes. Overall however, an estimated $1.5 to $3.6 trillion is needed in investment by 2050. Thus, producers find themselves hesitating or financially incapable of scaling-up production through new facilities or conversions of existing plants.[20]

> **The infrastructure required to produce SAF is highly capital-intensive. An estimated $1.5 to $3.6 trillion is needed in investment by 2050.**

Public interest in reducing emissions

There has been growing public interest from regulators, governments and passengers for the aviation industry to reduce emissions.[21, 22] Therefore, in recent years, a number of airlines and other corporations with high emissions from corporate travel, including FMC members, have proactively signed offtake agreements for SAF.

While SAF's price premium is a barrier for adoption, SAF offtake agreements may have flexible terms or be contingent on future cost reductions. This structure provides an opportunity for airlines to balance their decarbonization commitments with their financial considerations. Additionally, policy interventions, consortiums and initiatives like FMC can bring together stakeholders interested in long-term purchasing agreements and help lower barriers to growing the market.

Uncertain demand signals

Despite this rising demand for SAF, the different tenors and non-binding nature of some offtake agreements, along with inconsistent policy regimes and sustainability standards across regions, can still result in uncertainty. Hence, the SAF industry is experiencing a gap between real and perceived demand signals, which does not resolve product premiums associated with the shift to sustainable inputs. As a result, suppliers continue to await solid and consistent demand signals that will yield long-term purchasing agreements.

The SAF industry is experiencing a gap between real and perceived demand signals, which does not resolve product premiums associated with the shift to sustainable inputs.

Value of industry collaboration

Furthermore, emergent SAF producers find themselves competing with established industry players with over a century of operational improvements and process harmonization.[23] For this reason, demand-side initiatives, such as the FMC, can play a critical role in generating offtake and creating multi-year agreements with fixed price premiums to reduce supplier investment uncertainties.

It is simply not possible to scale the industry without collaboration across the entire value chain. Organizations like the First Movers Coalition (FMC) can help educate their members and share important information about sustainability, carbon accounting guidance and production pathways and can help their members understand what to look for when considering a SAF or SAFc purchase. Only by working together can we achieve our collective goal of scaling the SAF industry and helping the aviation industry reach its net-zero goals.

Kathy Wight, Director of Net-Zero Skies, World Energy

Long-term contracts and supplier partnerships

So far, successful first movers have reduced the risks associated with pioneering new technologies through securing investments and forming partnerships. World Energy is aiming to produce SAF with an LCA GHG emissions reduction greater than 85% using emerging technologies such as steam methane reformers to produce clean hydrogen that lowers the carbon intensity of its SAF – but such technologies require significant investment.

Long-term fuel contracts of 7-10 years, such as that between World Energy and World Fuel Services to purchase as much as 10 million gallons of SAF, along with World Energy's "book and claim" SAF certificate (SAFc) inset agreements with Microsoft for 38 million gallons of SAFc, will help accelerate the significant cost reductions needed by providing stable revenue and funding sources.[24, 25, 26, 27]

Moreover, suppliers are beginning to form SAF-related partnerships to reduce risks, share resources and achieve economies of scale. Recently, there was a formal partnership between the Minneapolis-St Paul Regional Economic Development Partnership, Ecolab and Xcel Energy to establish the first large-scale SAF hub in the US.[28]

Long-term contracts are critical to scaling the supply of SAF. New refineries often take four to five years to construct and bring online, so banks and investors need confidence that buyers will be there once the SAF starts flowing. When banks see that a significant portion of a new plant's volume has been contracted for, they are far more willing to invest and do so at lower interest rates. All of this supports the virtuous cycle of confidence, with increased demand de-risking investment and accelerating and expanding SAF production.

Kathy Wight, Director of Net-Zero Skies, World Energy

Global SAF supply chain opportunities

While the SAF industry is expected to initially be concentrated in the US and European Union (EU), which may comprise 90% of SAF demand by 2030, there is growing recognition of the need for a global SAF supply chain to achieve the aviation industry's decarbonization goals.[29] Emerging markets with growing international and domestic travel, such as Asia, Brazil and Africa, are seen as key opportunities for SAF expansion. Despite new projects in these regions facing funding and infrastructure headwinds, these markets may be appealing to investors and suppliers because they have lower capital and operating costs, as well as fewer existing and established players.

In addition, these regions have the land and agricultural means to produce the required feedstocks. For example, Brazil has a robust biofuel industry currently producing 2 billion tonnes of waste and residue per year, which could in turn produce 9 billion litres of SAF.[30] Brazil also has overcapacity in certain agricultural areas, with the Brazilian oilseed-crushing industry averaging idle capacity of 50% in recent years due to the popularity of soybeans for biodiesel.[31] This overcapacity could be used for SAF if the proper infrastructure and incentives were put in place.

Brazil has a robust biofuel industry currently producing 2 billion tonnes of waste and residue per year, which could in turn produce 9 billion litres of SAF.

While these regions appear to be optimal investment targets, there are several challenges. First, SAF requires a sophisticated supply chain across feedstock production, intermediary/downstream logistics and blending and fuelling operations players. In the current state, suppliers have found gaps in availability for many of the required goods and services required throughout this supply chain.

In addition, these complexities mean it is difficult to trace and certify the carbon intensity of these value chains, which is critical to prove carbon reductions to buyers and to accelerate decarbonization. Another challenge is that in many of these regions, SAF is competing with other forms of transportation, since the same feedstock is required to produce biodiesel.

Policy incentives and public-private partnerships

Like many other sectors, the challenges that emerging markets are facing to produce SAF at scale can be solved or mitigated through appropriate, consistent and joined-up policy interventions across regions and by focusing on value-chain partnerships. For example, Indian authorities announced plans to mandate a 1% blending of SAF with regular fuel for all Indian carriers by 2025.[32] Doing so would increase SAF demand and potentially increase SAF production within the country.

In addition to advocating for policy interventions, suppliers should continue relying on partnerships and knowledge-sharing. For example, the Jet Zero Council, a public-private partnership convened by the UK government, industry and academia, aims to bring together ministers and C-suite executives to de-risk private investments to scale SAF production and discover innovative ways to reduce aviation emissions.[33]

2

Shipping

Suppliers face challenges securing sources of funding with the appropriate risk appetite and investment size to further develop and scale-up their low-emission fuel projects.

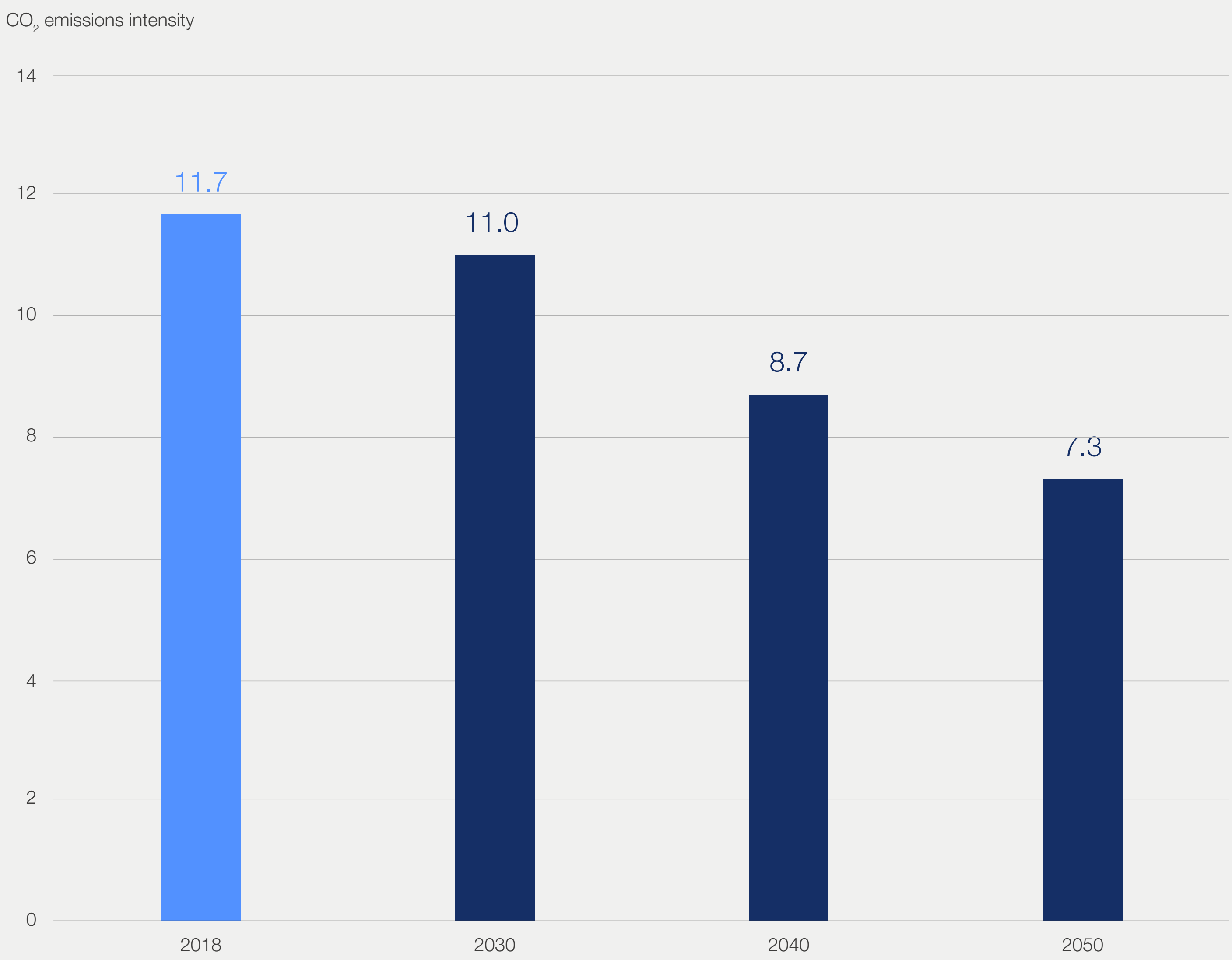
2.1 Current emissions profile

The shipping industry plays a critical role in the global economy, carrying 80% of international trade.[34] Currently, the shipping industry relies heavily on fossil-based bunker fuel, which results in the industry contributing to approximately 2% of global GHG emissions.[35] Shipping plays a significant role in global decarbonization, as not only will ships run on low-emission fuels, they will also carry zero-emission fuels around the world as an enabler for other countries to decarbonize.

In July 2023, member states of the UN's International Maritime Organization (IMO) adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships. The strategy includes "an enhanced common ambition to reach net-zero GHG emissions from international shipping by or around, i.e. close to 2050", as well as a commitment to adopt zero- and near zero-emission fuels by 2030 and a reduction in carbon intensity of international shipping by at least 40% by 2030.[36]

BAU emissions intensity is expected to decline due to fuel efficiency improvements, optimization of speeds, and the size and technological specifications of existing ship technologies; but this decline will not be sufficient to achieve net-zero targets (see Figure 3). Global goals have been set and the decarbonization pathways for shipping are becoming more defined, with low-emission fuels driving the transition. It is estimated that the industry will have to invest about $40 billion annually in zero-emission fuel bunkering and production to achieve the IMO's emissions reduction goals.[37]

FIGURE 3: **Shipping emissions intensity trajectory, BAU scenario (gCO_2e/tonne nautical mile)**



Source: World Economic Forum[38]

2.2 The FMC commitment

BOX 2: **FMC's Shipping commitment**

Carriers:

At least 5% (on an energy basis) of our deep-sea shipping will be powered by zero-emission fuels* by 2030.

Cargo owners:

At least 10% of the volume of our goods shipped via deep-sea shipping will be on ships using zero-emission fuels by 2030, reaching 100% by 2040.

***FMC definition:**

- Zero-emission fuels are those that reduce well-to-wake GHG emissions by 80% or more compared to fossil heavy fuel oil.[39]
- Current list of fuels includes: ammonia, methanol, hydrogen, battery.
- These commitments do not include biofuels, liquid natural gas (LNG), carbon offsets or efficiency improvements.

Full details of the commitment can be found here.

The FMC will assess and align its shipping commitment with the life-cycle analysis methodologies, standards and overall guidance of the IMO – once it is released, most likely in 2025.[40]

2.3 Decarbonization pathways in shipping

Reducing shipping emissions through energy efficiency and fuel conservation measures, such as wind-assisted propulsion or onboard carbon capture, are important steps to decarbonize the shipping industry. However, these technologies are not in-scope for the FMC shipping commitment. The most promising avenues towards reducing the sector's carbon footprint in line with FMC criteria are low-emission fuels, in particular hydrogen-derived fuels such as ammonia and methanol. However, these fuels cannot be considered low-emission unless the hydrogen feedstock used to produce them is itself generated in a low-carbon way, such as with renewable energy.

Ammonia

Ammonia is being explored as an option for shipping, given its extensive use in land-based applications including the petrochemical and fertilizer industries. Specifically, anhydrous ammonia, also known as pure NH_3, has been identified as a potential long-term zero- or near-zero emission fuel when produced using low-carbon hydrogen.[41] However, given that ammonia is toxic, it requires extensive safety precautions when handling at ports and bunkering into vessels, and will need to go through successful sea trials before implementation.

Nevertheless, positive progress is being made in this field: for example, an ammonia-capable vessel, the Fortescue Green Pioneer, successfully completed the world's first ammonia bunkering trial in the Port of Singapore in March 2024.[42] MAN Energy Solutions, a prominent ship-engine manufacturer, is currently working on a two-stroke ammonia engine, which it expects to be commercially available in 2025.[43]

Methanol

Methanol is a versatile product that can be used as a fuel for manufacturing plastics and other chemicals, as well as a hydrogen carrier. Known by the formula CH_3OH, often abbreviated to MeOH, methanol can be created by reacting hydrogen with captured CO_2, leading to near-zero net carbon emissions.

Methanol has gained commercial traction as an alternative shipping fuel, primarily led by the container-ship industry. Methanol-powered vessels are already commercialized, but their use has been confined to specific sectors and has not been adopted at scale. However, as of June 2024, there are over 200 orders for methanol-powered ships,[44] which now make up 62% of the new ship orderbook – 30% are LNG and just 8% are traditional fuel oil.[45]

Delivery of "Laura Maersk" in 2023, the world's first methanol-powered feeder ship owned by A.P Moller-Maersk, marked a historic milestone.[46] In January 2024, the world's first large methanol-enabled container vessel – the 350-metre, 16,592 TEU "Ane Mærsk" – was christened at a ceremony in the shipyard of HD Hyundai Heavy Industries in

Ulsan, South Korea, from where it embarked on its 21,500 km maiden voyage to Denmark. The vessel is fuelled by green bio-methanol from biomass waste, a technology that can reduce emissions from vessels by up to 95% compared to traditional bunker fuels.[47]

> **As of June 2024, there are over 200 orders for methanol-powered ships, which now make up 62% of the new ship orderbook – 30% are LNG and just 8% are traditional fuel oil.**

The primary difference between methanol and ammonia is that burning methanol still produces carbon dioxide. Combustion emissions may be captured onboard the ship using carbon capture and storage technology. In addition, the combustion emissions can be almost entirely offset by capturing carbon during the methanol production process.[48] For example, Liquid Wind plans to capture carbon by co-locating methanol production with a biomass combined heat and power plant, which sources waste from a nearby pulp mill.[49] While methanol is seen as easier to implement, access to the fuel is becoming scarcer due to competition with sustainable aviation fuel (SAF) developers over the required CO_2 coming from biogenic sources or Direct Air Capture (DAC).[50]

Low-carbon hydrogen

Low-carbon hydrogen, defined as hydrogen produced through electrolysis, biomass or conventional production coupled with CCUS, is a crucial feedstock for the production of hydrogen-derived fuels. Depending on the production method of the hydrogen, it may or may not meet the FMC guidelines of reducing emissions by 80% or more. It also remains at a nascent stage compared to the use of methanol or ammonia, due to its low energy density, renewable energy requirements, the need to store it at very low temperatures in liquid form, and other competing uses of low-carbon hydrogen.[51] However, like methanol and ammonia, it can be used for direct combustion.

2.4 Supplier challenges and opportunities in low-carbon shipping

Currently, the international shipping industry will likely face challenges to meet the IMO's strategy to reach net-zero GHG emissions by around 2050. While potential demand for low-carbon shipping fuels outstrips the supply of announced projects, it is difficult for producers to have confidence in investing in projects that have high barriers to entry.[52]

Securing investment funding of sufficient size and risk appetite

FMC's December 2023 report Fuelling the Future of Shipping: Key Barriers to Scaling Zero-Emission Fuel Supply gathered insights across the shipping value chain and revealed that suppliers face challenges securing sources of funding with the appropriate risk appetite and investment size to develop and scale-up their low-emission fuel projects. In addition, there are gaps between suppliers and shipping companies on acceptable volumes, offtake durations and levels of green premium.[53]

Complex ecosystem

The complex market dynamics of zero-emission fuel technologies require an ecosystem of suppliers, buyers and financiers to navigate. An additional complexity is that many of the emerging suppliers are small-scale and have alternative business models. The First Suppliers Hub will be a useful tool to surface these innovative projects and bring the group together to overcome challenges.

Unsustainably high green premiums

Green premiums for low-emission fuels remain unsustainably high: biofuels (out-of-scope for FMC) are 1.5-4 times the cost of regular bunker fuel, while synthetic hydrogen-based fuels (in-scope for FMC) are 2-6 times the cost.[54] In addition to the cost gap, it is difficult for shipping companies to compare and assess the green premium of emerging low-emission fuels. Various different policies and methodologies on emissions reduction make it confusing for buyers to determine the correct relative value of the fuel and whether it will be within the scope of global or regional mandates. To provide greater clarity on the definition of low-emission fuels, FMC adopted the guiding principle that in-scope fuels should have a well-to-wake GHG emissions reduction of 80% or more.

Green premiums for low-emission fuels remain unsustainably high: synthetic hydrogen-based fuels (in-scope for FMC) are 2-6 times the cost of regular bunker fuel.

Role of refuelling infrastructure and book and claim

Shipping is, by nature, global. Ensuring an efficient refuelling network – from fuel production to storage near refuelling ports – requires international cooperation, a similar level of industrial maturity across countries, and feedstocks that are both available and affordable.[55] Similar to aviation and trucking, chain of custody models (i.e., "mass balance" and "book and claim" schemes) will allow purchasers to allocate emission reductions even if their freight is not physically transported on that specific low-emission service.

Until such schemes are incorporated within regulatory frameworks, purchasers can only access low-emission fuels when they are physically available at bunkering ports. A book and claim approach would broaden the opportunities for shipping companies to partake in the green premium associated with low-emission fuels, which could help stimulate demand and expand the market. Book and claim is picking up momentum in the shipping industry, with an initial pilot underway conducted by the Rocky Mountain Institute (RMI) and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.[56]

Role of regulation

On the regulatory side, policies such as the European Union's Emissions Trading System (ETS) and FuelEU Maritime, which has set a GHG reduction goal of 6% by 2030 (reaching 80% by 2050), are still in the early stages of development but are important first steps towards enabling shipping decarbonization through regulation.[57]

The IMO has the authority to develop global standards in territorial and international waters, and plays a crucial role in regulating the global shipping industry, setting targets, and framing guidelines for safety, security and environmental performance.[58] In 2018, the IMO set a goal of reducing shipping emissions by 50% by 2050, compared to 2008 levels.[59] Then in 2023, the organization adopted the more ambitious goal to reach net-zero GHG emissions from international shipping by "close to 2050".[60] Nevertheless – however detailed the pathway to achieve this goal is and however fast the IMO can level the playing field for a collaborative effort between shipping companies – the industry will still need to rely on strong demand signals and innovation to reach the 2050 target.

In 2023, the International Maritime Organization adopted the goal to reach net-zero GHG emissions from international shipping by 'close to 2050'.

Taxes and incentives

Some emissions reduction incentives, such as carbon taxes, will likely be driven by industry players and regional entities to achieve decarbonization goals and spur business development for suppliers. In April 2021, the International Chamber of Shipping, which represents more than 90% of the world's merchant fleet, submitted a proposal to the IMO calling for a global carbon tax on shipping.[61] Since then, the IMO has agreed to implement some kind of emissions pricing by 2025, but negotiations are still ongoing.[62] Moreover, in January 2024, the World Shipping Council, a prominent trade association for liner shipping companies, proposed a green balance mechanism aimed at closing the price gap between low-carbon fuels and fossil fuels. In this approach, fees are applied to ships burning fossil fuels and credits are allocated to ships using low-carbon fuels, so the average cost of fuel used is equal.[63]

Europe's ETS is pioneering carbon taxes, requiring large ships to buy allowances for at least 50% of their emissions when starting or ending at an EU port. The measure, which took effect in January 2024, requires shipping companies to monitor their emissions and acquire and surrender EU allowances (EUAs) for each tonne of greenhouse gas emissions they report. The cost is then passed on to each shipment.[64] There are other similar regional efforts to accelerate the decarbonization of the shipping industry, but the importance of global policy remains key.

Carbon taxes alone may not fully close the gap between grey and green hydrogen until the industry reaches maturity. Like early subsidies for renewable energy technologies, additional market interventions such as minimum blending requirements may be required. Hydrogen projects need long-term offtake and price certainty to become bankable. It is imperative to define not only the mechanisms of carbon taxes and other market interventions today, but also their escalation over time to establish long-term viable forward-pricing certainty.

Patrick Stein-Kaempfe, Project Director, HYPHEN Hydrogen Energy

3 Trucking

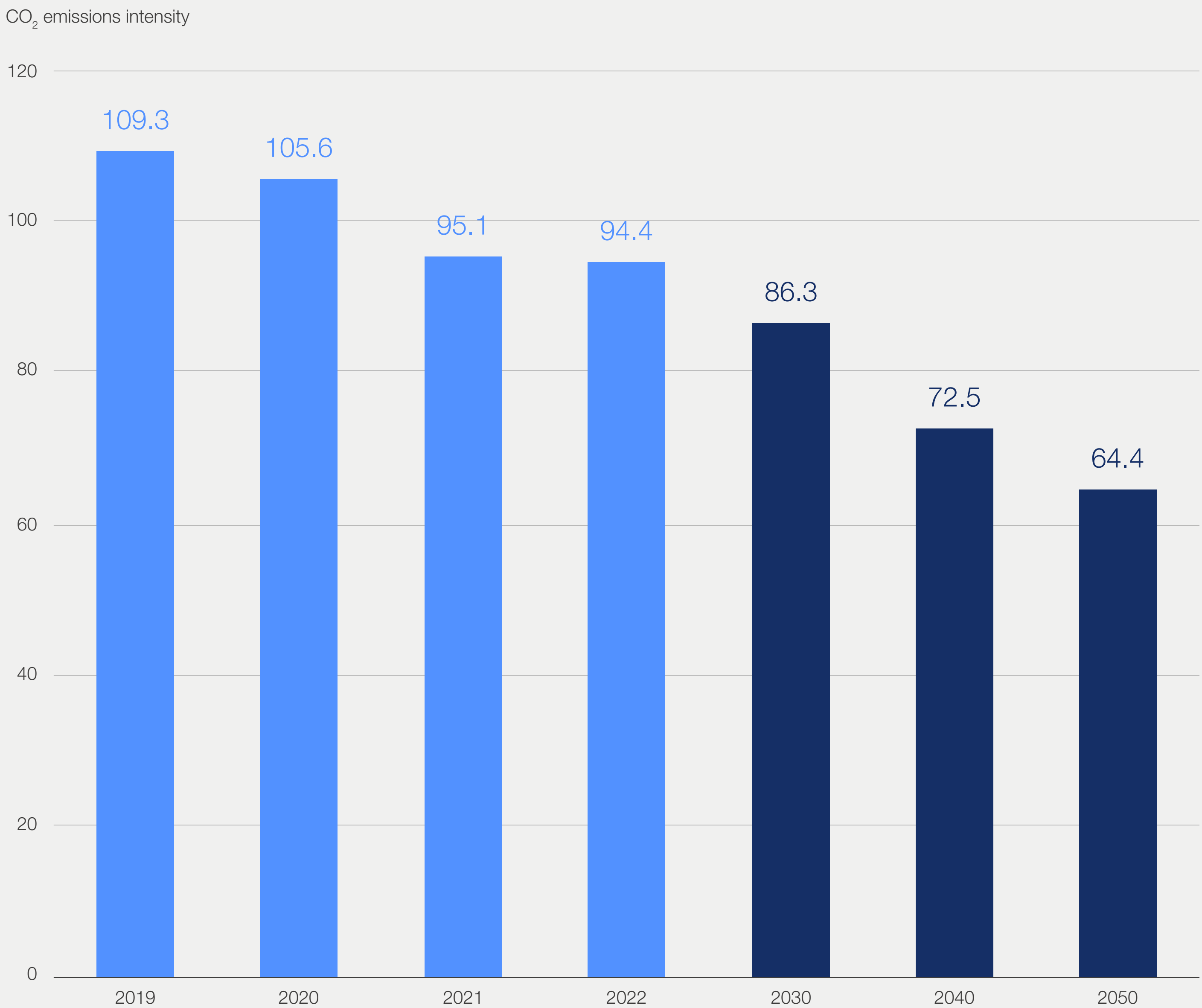
As demand for zero-emission trucks grows, the current diesel-powered heavy- and medium-duty trucking sector is having to rethink the technologies needed for the transition.

3.1 Current emissions profile

Currently, the heavy- and medium-duty trucking sectors rely heavily on diesel fuel. In regions such as Europe, India, China and the US, diesel powers 95% of heavy-duty trucks. These regions alone contribute to half of all global emissions from heavy-duty trucking.[65] Since 2000, heavy-duty vehicles have seen tailpipe CO_2 emissions rise by an average of 2.2% per year, while emissions from medium-duty vehicles increased 1.3% per year.[66,67]

Today, medium-and heavy-duty trucks are responsible for approximately 1.8 billion tonnes of CO_2 emissions per year and 4% of global GHG emissions.[68] Global demand for trucking is expected to double from 12 trillion tonne-kilometres (tkm) in 2023 to 26 trillion tkm by 2050.[69] Along with carbon emissions, diesel combustion emits airborne pollutants like carbon monoxide, sulphur, nitrogen oxides and fine particulate matter that damage human health. Emissions intensity is expected to decrease over time due to efficiency measures, operational improvements and an increase of biofuels in the mix (see Figure 4). However, as demand for zero-emission trucks grows, the current diesel-powered heavy- and medium-duty trucking sector is having to rethink the technologies needed for the transition.

FIGURE 4: **Trucking emissions intensity trajectory, BAU scenario (gCO_2e/tonne-kilometre)**



Source: World Economic Forum.[70]

3.2 The FMC commitment

BOX 3: **FMC's Trucking commitment**

Trucking owners and operators:

At least 30% of our heavy-duty and 100% of our medium-duty new truck purchases are zero-emission trucks* by 2030.

Retailers and manufacturers:

We require our trucking service providers to meet the commitment that at least 30% of heavy-duty and 100% of medium-duty new truck purchases will be zero-emission trucks* by 2030.

***In-scope technologies include:**

- Battery-electric vehicles (BEVs).
- Fuel-cell electric vehicles (hydrogen – FCEVs).
- Any zero tail-pipe emission technologies.
- Commitments do not include liquid or compressed natural gas, drop-in fuels and carbon offsets.

Full details of the commitment can be found here.

3.3 Decarbonization pathways in trucking

Battery-electric vehicles (BEVs) and hydrogen fuel-cell electric vehicles (FCEVs) offer the most promising technology pathways for zero tailpipe emissions road freight for medium- and heavy-duty vehicles, with large market entries planned for FCEVs after 2025. Depending on usage and region, BEVs and FCEVs are expected to reach a comparable total cost of ownership (TCO) between 2025 and 2034.[71]

> Battery-electric vehicles (BEVs) and hydrogen fuel-cell electric vehicles (FCEVs) offer the most promising technology pathways for zero tailpipe emissions road freight for medium- and heavy-duty vehicles.

Battery-electric vehicles

BEVs are likely to be adopted for long-haul journeys with predictable routes and on-the-go charging. However, they are expected to take off more rapidly in urban and regional segments, due to operational feasibility considerations such as shorter trips and greater charging availability.

Many prominent truck manufacturers are in the process of either bringing to market or intending to launch a BEV model, including BYD Trucks (a division of BYD Co. Ltd), Mercedes-Benz Trucks and Freightliner (both divisions of Daimler AG), Scania (a TRATON brand and subsidiary of Volkswagen AG), and Volvo Trucks and Renault Trucks (both under the Volvo Group umbrella).

Volvo Trucks, an FMC member, is targeting 50% of global sales of new trucks to be electric by 2030 and 100% to be net-zero emission by 2040.[72] Similarly, Scania signed the first global memorandum of understanding for zero-emission heavy trucks and buses, committing to 30% zero-emission sales by 2030 and over 90% zero-emission sales worldwide by 2040.[73] In addition, the market is seeing an emergence of BEV start-ups, such as Volta Trucks, XOS Trucks and GreenPower Motor Company, demonstrating significant activity in the space.

Fuel-cell electric vehicles and zero-emission inventory

FCEVs are expected to have higher adoption rates for long-haul routes compared to urban and regional segments, owing to hydrogen's high energy density and low refuelling times. The development of these vehicles is driven by emerging companies, but legacy companies are becoming more involved in this space too.[74] Hyundai and FAW Jiefang are among the top suppliers of FCEVs, while established companies like Toyota/Paccar and Volvo are expected to roll out models by 2024. Meanwhile, start-ups including Hyzon Motors, FTXT (a division of Great Wall Motor), Tevva and Nikola are making notable strides in the field.

> In 2022, around 66,000 electric (incl. BEVs, FCEVs, hybrid-electric vehicles) medium- and heavy-duty trucks were sold globally, making up 1.2% of global truck sales.

The Zero-Emission Technology Inventory (ZETI) summarizes the current market status and trends on low-carbon trucking. As of 2023, there were over 300 models of FCEVs and BEVs available, including 99 heavy-duty BEVs and 17 heavy-duty FCEVs.[75] In 2022, around 66,000 electric (encompassing BEVs, FCEVs and hybrid-electric vehicles) medium- and heavy-duty trucks were sold globally, making up 1.2% of global truck sales.[76] This is especially true for last-mile delivery due to shorter ranges and ease of recharge. Logistics companies are increasingly adopting low-emission vehicles, not only to reduce their scope 1 emissions, which can represent most of their emissions, but also to win market share with customers who demand strict emission targets from their logistics service suppliers. Scope 1 emissions for logistics vectors are scope 3 emissions for their clients and this supply-chain effect enables pioneers to win market share.[77]

3.4 Supplier challenges and opportunities in low-carbon trucking

The trucking industry faces various challenges in its pursuit of more sustainable transportation, including the reliability of refuelling and recharging networks, high costs with implementing new technology and complex global regulatory frameworks.[78] However, these challenges also create opportunities for BEVs and FCEVs in areas such as investments in hydrogen infrastructure, decarbonization incentives and the exploration of innovative technologies.

Charging challenges

Unlike personal electric vehicles that can be charged overnight, logistics companies often need their vehicles to be ready quickly due to high usage and tight schedules. Many logistics companies managing large EV fleets struggle to obtain the necessary power allocation from electric utilities, due to their fast-charging needs and high energy consumption. For example, in the US, local grids struggle with congestion and new project queues, resulting in a lengthy process that can take up to two years to secure the necessary power from electric utilities.[79]

> Many logistics companies managing large EV fleets struggle to obtain the necessary power allocation from electric utilities, due to their fast-charging needs and high energy consumption.

High upfront costs

In the US and Europe, the initial investment needed for transitioning to BEVs and FCEVs is 25-30% higher than continuing with diesel. In India and China, the cost of transition is even more significant due to the lower cost of internal combustion engine (ICE) trucks. Despite these upfront costs, the transition is justified by long-term operational savings, especially if financing for the transition can be secured.

Solutions include:

- Innovative business models like "trucking-as-a-service" (TaaS) and "battery-as-a-service" (BaaS) that lower upfront costs.
- Shared charging infrastructure where BEV fleets from multiple companies can share the costs and consolidate power use in an industrial area.
- Bolstering the second-hand market and battery recycling industry.
- Incentive programmes such as toll discounts and subsidies.[80]

> **We see a necessity for broad and cost-efficient charging networks with access to renewable energy to enable BEV truck deployment at scale. Maersk anticipates grid readiness and powerful grid connections to be a potential bottleneck, and in the majority of cases, investments into grid upgrades are outside private companies control and require government regulation, EU directives etc. Coordinated global action among operators, manufacturers and regulators on grid development is critical to pursue a future geared towards net zero.**
>
> Nikolaj Michael Pihl Kristiensen, Head of Energy Transition Execution and Partnerships, A.P. Moller-Maersk

Important role for policy incentives

Furthermore, global regulatory frameworks for zero-emission vehicles are varied and often uncertain, posing challenges for truck manufacturers and logistics companies. Countries have different standards and regulations regarding BEVs and FCEVs, including factors such as emissions, safety and energy efficiency. This lack of uniformity can complicate the development and distribution process for original equipment manufacturers (OEMs) operating in multiple markets.[81]

In addition, incentive programmes, such as subsidies and tax breaks, can vary between countries and even within regions of the same country. Despite these inconsistencies, many countries are establishing clear incentives and regulations to encourage decarbonization technologies in medium- and heavy-duty trucking. In California, the Zero-Emission Vehicle programme mandates that 100% of medium- and heavy-duty truck sales must be zero-emission vehicles by 2045.[82] In Austria, all new sales of medium- and heavy-duty vehicles are required to be zero-emission.[83] Meanwhile, the EU's Alternative Fuels Infrastructure Regulation directive aims to promote the widespread adoption of electric trucks by mandating the development of recharging and refuelling infrastructure across Member States.[84]

> **In Austria, all new sales of medium- and heavy-duty vehicles are required to be zero-emission.**

Limitations in battery and hydrogen technologies

Truck OEMs are striving to gain economies of scale on costly vehicle components such as batteries and fuel cells. Some truck OEMs are exploring synergy opportunities with their other business lines, such as off-road vehicles for construction or mining. While the business case for electrified off-road vehicles is appealing (especially for FCEVs), TRLs do not match up to those achieved for passenger vehicles or freight trucks – at least not until the industry sees a solid breakthrough in battery technologies or an acceleration of hydrogen economies. This limits OEMs' ability to create efficiencies and further drive down costs.[85]

Lower operational costs and better health outcomes

Suppliers can also utilize the improved operational features and reduced operations and maintenance costs of zero-emission trucks as a selling point. BEVs and FCEVs are quieter than diesel-fuelled trucks and are more comfortable to operate because they do not release tailpipe emissions. This improves the user experience, reducing health problems among truck drivers, while improving quality of life for the communities in which these trucks operate, by reducing the emissions of idling vehicles in urban areas. Several other advantages (e.g. being able to load trucks indoors without the need for ventilation equipment) can also help simplify distribution centres' layouts and ultimately reduce total cost of ownership for buyers.

Policy incentives for hydrogen production and FCEVs

Several countries are beginning to recognize the use of hydrogen as a sustainable fuel in the trucking sector. For example, in the US, the Inflation Reduction Act and the Bipartisan Infrastructure Law propose ambitious tax credits and grants to invest in hydrogen production, storage and distribution.[86] In addition, Japan is promoting the use of fuel-cell vehicles and aims to have 40,000 FCEVs on the road by 2030, including trucks.[87] Although hydrogen refuelling infrastructure is currently limited to California and Europe, investments could drive its growth, potentially enhancing the feasibility of FCEVs in trucking.

> **Japan is promoting the use of fuel-cell vehicles and aims to have 40,000 FCEVs on the road by 2030, including trucks.**

In the meantime, OEMs and fleet operators can benefit from joining “clean hydrogen hubs” to secure low-cost clean hydrogen and tax credits, as well as increasing synergies with other applications of fuel cells, such as material handling equipment. For example, in 2023 the US Department of Energy announced $7 billion to launch seven regional clean hydrogen hubs (H_2Hubs) across the nation and accelerate the commercial-scale deployment of low-cost, clean hydrogen.[88]

Alternative technologies

Finally, some early signs of non-conventional innovations are surfacing in the trucking industry. Hydrogen direct combustion has shown recent progress, with encouraging results demonstrated by Toyota and Cummins. Meanwhile, there is progress on compact carbon capture technologies that can eliminate all CO_2 emissions from regular diesel engines.

However, it is important to note that hydrogen direct combustion vehicles, while offering a transitionary opportunity, are not in scope for the FMC. Despite their potential, these vehicles emit nitrogen oxides and particulate matter and cannot therefore be considered zero-emission vehicles.

Meanwhile, alternative battery-electric charging options are being tested globally, with induction-charging roads, catenaries and battery swaps being the most promising. Demand signals for zero-emission trucking are also fostering the emergence of book and claim schemes for trucking: a system already mature in aviation that allows more sustainable fuels to be sold in the market.[89]

4 Aluminium

Production of sufficient quantities of low-carbon aluminium will require broader access to novel, breakthrough technologies, public policy intervention, and reliable product-level data.

4.1 Current emissions profile

The lightweight, ductile and corrosion-resistant properties of aluminium make it a critical material for a wide variety of global industries, primarily transportation and construction. Driven by an increase in population, urbanization and green transformation, global aluminium demand is expected to increase by almost 40%, from 86.2 Mt in 2020 to 119.5 Mt in 2030.[90] From a carbon perspective, aluminium is responsible for 2% of human made GHG emissions and, critically, most of these emissions are indirect and come from the electricity consumed for smelting.[91 92]

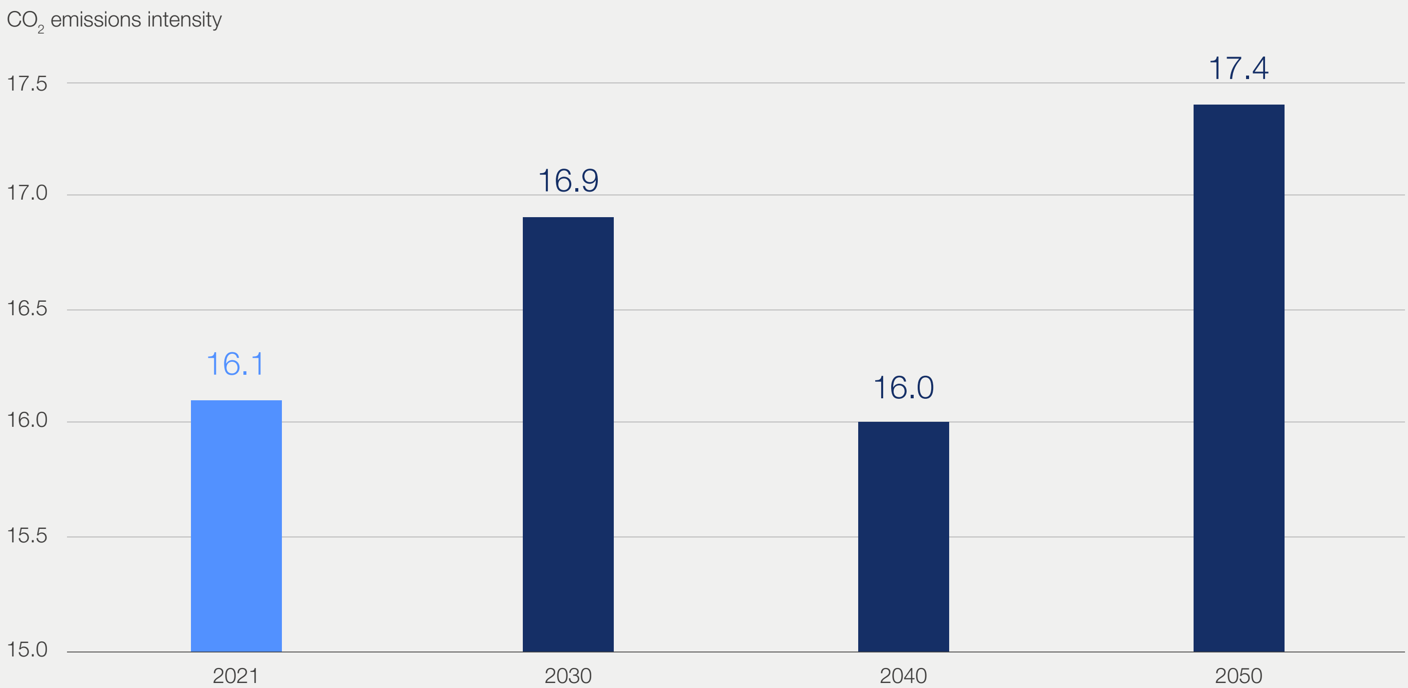
Primary aluminium production begins in a bauxite mine, where the ore is collected and sent to refining. The separation of alumina from bauxite generates about 15% of emissions, almost entirely indirect and attributable to thermal energy applied in the refining process. The resulting alumina is a molecule composed of pure aluminium and oxygen.[93] More than 70% of emissions are generated in smelting: the process of stripping the oxygen away from the pure aluminium. This is done through electrolysis, where high temperatures and a high electric current (55% of total emissions) are applied to alumina through carbon anodes and cathodes, generating carbon dioxide and perfluorocarbon in the process (15% of total emissions). The resulting liquid aluminium is then cast at high temperature into ingots and shipped to customers or processed further.[94]

More than 70% of emissions from primary aluminium production are generated in smelting: the process of stripping the oxygen away from the pure aluminium.

Without interventions, the emissions intensity of aluminium is expected to increase to 17.4 tCO_2e/t of aluminium for primary production alone, due to carbon-intensive production processes and ageing technology and infrastructure (see Figure 5).

Secondary production requires using recycled aluminium and re-casting it, avoiding the mining, refining and electrolysis processes and therefore using only 5% of the energy used to produce primary metal, thereby avoiding the majority of emissions.[95] Given the inherently lower emissions in recycled aluminium, the First Movers Coalition's commitment is for the use of primary aluminium and associated novel technologies, with an optional secondary commitment for recycled aluminium.

FIGURE 5: **Primary aluminium: emissions intensity trajectory, BAU scenario (tCO_2e/t of aluminium)**



Source: World Economic Forum.[96]

4.2 The FMC commitment

BOX 4: **FMC Aluminium commitment**

At least 10% (by volume) of all our primary aluminium procured per year will be low-carbon (as per FMC definition*) by 2030.

***FMC definition of low-carbon:**

Emitting <3 tonnes of CO_2e per tonne of aluminium produced, including all emissions from cradle to gate.

Optional commitment on secondary [recycled] aluminium:

In addition to our primary aluminium commitment, we commit to ensuring that at least 50% of all aluminium we procure per year is sourced from secondary aluminium by 2030.

***In-scope technologies include:**

– Electric or hydrogen boilers.

– Concentrated solar thermal.

– Mechanical vapour recompression.

– Hydrogen or electric calcination.

– Carbo-chlorination.

– Inert anodes.

– CCUS (carbon capture, utilization and storage).

Full details of the commitment can be found here.

4.3 Decarbonization pathways in aluminium

According to the aluminium sector transition strategy of the Mission Possible Partnership,[97] the main avenues for decarbonization of primary aluminium production are through electricity decarbonization, direct emissions reductions and improved recycling and resource efficiencies.

More than 70% of primary aluminium emissions are from electricity or heat. In particular, smelter emissions are highly dependent on the carbon intensity of the electricity employed and therefore on the producing country.[98] Because of their need to operate constantly and at high-power levels, the generation options of preference for smelters are coal-fired (50% of power consumed globally in 2022), gas-fired (10%), or hydroelectric (34%) plants. Variable renewable energy represents only 4% of power consumed for smelting globally, which is often self-generated rather than sourced from a local grid.[99]

Decarbonization options for primary aluminium can be summarized as follows:

Low-carbon power

– Accessing renewable energy through grid partnerships.

– Decarbonizing self-generated power through options such as onsite wind turbines, solar panels, hydro power, and/or nuclear small modular reactors.

Refining

– Scaling-up CCUS at plants that use coal and gas power generation for refining. However, it should be noted this pathway is at an early stage of technology development and commercialization for aluminium, compared to other industrial sectors. Only two of the 12 most mature carbon capture technology categories have reached a commercial stage of development for any application.[100]

– The use of energy recovery processes to recycle heat and improve overall efficiency, such as mechanical vapour recompression.

– Other innovative energy technologies under development – including boilers powered by zero-carbon hydrogen or electricity, calciners powered by zero-carbon hydrogen or electricity, or concentrated solar thermal (CST) to produce high temperature heat for power generation.

Smelting

– Significant upscaling of emissions-free inert anode smelting technologies – as most process emissions currently originate rom the carbon anodes used in the electrolysis process. By contrast, inert anodes, generally made of materials such as ceramic or cermet (a composite material composed of ceramic and metal materials),[101] can absorb and release the oxygen without it binding with carbon.

– Application of carbo-chlorination where alumina is converted to aluminium chloride intermediate compounds through chemical reaction with carbon and chlorine sources through a closed-loop process where both the carbon and chlorine are sourced from the aluminium production process.

– Scaling-up CCUS at plants that use coal and gas power generation for smelting.

4.4 Supplier challenges and opportunities in low-carbon aluminium

Decarbonization in the aluminium sector faces challenges related to access to technology innovations, volatile pricing and globally accepted low-carbon standards for secondary aluminium. Opportunities lie in facilitating widespread access to GHG emission-reducing technologies, collaborations for secondary production and reliable product-level data for informed decisions.

A large share of decarbonization in the aluminium sector will come from the general increased use of renewables and increased recycling. This report focuses on primary aluminium emission reductions, including the importance of scaling-up emission-free smelting technologies, renewable energy use in electrolysis and the hydrogen and CCUS economies.

> **A large share of decarbonization in the aluminium sector will come from the general increased use of renewables and increased recycling.**

Emission-free smelting technologies

To eliminate smelting process emissions, inert anodes and carbo-chlorination are currently being developed by a limited pool of companies that collectively face the challenge of how these technologies will become viable and by when. As expected, scaling-up emerging technologies faces large financial barriers within the margin-hungry refining environment.

The closest innovator expected to hit the market (Elysis, a joint venture between Alcoa and Rio Tinto) has already produced batches of low-carbon aluminium in commercial-sized pilot plants utilizing inert anodes and is marketing its solutions.

Meanwhile, Norsk Hydro, which is investing in HalZero (carbon-chlorination technology), plans initial production for 2025, according to company communications, but has yet to publicly announce its commercialization plan. Meanwhile, Aluminium Dunkerque, Trimet and Rio Tinto are joining forces with the Fives Group to advance the use of CCUS in the aluminium sector with a pilot plant at an early stage in France.[102]

> **As the first two aluminium entrants in the FMC First Suppliers Hub, we agree that the race to zero is a complex one requiring breakthrough technological innovations, financing, value chain collaborations, clean energy access, creative thinking and people ready to face new challenges. The biggest obstacles for accelerated decarbonization within the primary aluminium sector remain the upscaling of new technologies, sustained access to renewables and partners who understand the value of deeply decarbonized aluminium.**
>
> Eivind Kallevik, CEO, Norsk Hydro and Luciano Francisco Alves, CEO, CBA

Premiums possible in evolving markets

These announced investments in additional quantities still represent only a small fraction of overall primary aluminium supply. In the near-term, temporary supply/demand imbalances may lead to volatile pricing and the ability for suppliers to charge premiums as negotiated bilaterally between the buyer and supplier. Due to long lead times for new facilities, there is a potential for first-moving suppliers to benefit from premiums for several years. However, this is counteracted by the risk of investing ahead of market demand, which could cause sub-optimal economic outcomes for both incumbents and new entrant producers.

Access to affordable technology – especially in emerging markets

Ideally, manufacturers in developed countries would bear the cost of developing novel technologies, with environmentally conscious buyers in those regions willing to pay a premium for those technologies to cover at least part of their product portfolio. The manufacturers could then license those novel technologies to aluminium producers globally.

Currently, the risk is that some developing-country companies might have to wait decades for the technology to enter the public domain, unless strong incentives or subsidies encourage the few companies working on novel technologies to move quickly and license the technology to other actors. The main risk for the global decarbonization of the aluminium industry comes from the lack of supply and the need for widespread access to technologies that could reduce GHG emissions.[103]

Offtake deals with waste management sector and governments

In the domain of secondary aluminium supply, aluminium manufacturers face two distinct challenges. One is the extremely competitive material recovery landscape. Aluminium recycling is fairly mature across end-markets and leaves less room for improvement, except for some extra pockets of optimization available in consumer durables and packaging within developed countries. Industries such as construction and aviation have longer aluminium use periods and as a result, it is estimated that approximately 75% of the aluminium ever produced is still in use today.[104] Securing offtake deals for recycled aluminium – by collaborating with the waste management sector and governments – can substantially increase the mix of secondary production and help shave emissions, costs and energy consumption.

Global standards and definitions

The second challenge, given the material's broad span of discontinuous markets and value chain steps, is that the aluminium industry finds immense difficulty in aligning on a set of globally accepted standards and definitions for low-carbon aluminium.[105] Comparable and reliable data at the product level is critical for enabling aluminium buyers to make well-informed business decisions and decreasing the risk of greenwashing.

One example of a potential solution to this problem is shown with RMI's Aluminium GHG Emissions Reporting Guidance. Recently launched at COP 28, it is meant to be a first step towards helping producers disclose the emissions of their aluminium products in a transparent, comparable and high-quality way.[106] Suppliers have a unique opportunity to partner with sectorial organizations to prepare procurement-ready documentation, educate buyers on the advantages and emission reduction of their products and enable diversification of end-use industries.

> **Comparable and reliable data at the product level is critical for enabling aluminium buyers to make well-informed business decisions and decreasing the risk of greenwashing.**

5 Cement and Concrete

The cement and concrete sector will face challenges stemming from the high cost of decarbonization and competition with other industries; and will require nimble regulatory bodies.

5.1 Current emissions profile

Concrete is the second most-widely used material after water, but critically, one of the largest contributors to climate change, responsible for about 6% of global GHG emissions.[107,108] Meanwhile, global annual production of concrete is forecast to grow from 14 billion m^3 (cubic metres) today to 20 billion m^3 by mid-century, as human societies urbanize and demand for infrastructure grows. This trajectory would see CO_2 emissions from the sector soar to 3.8 billion tonnes per year, based on current practice.

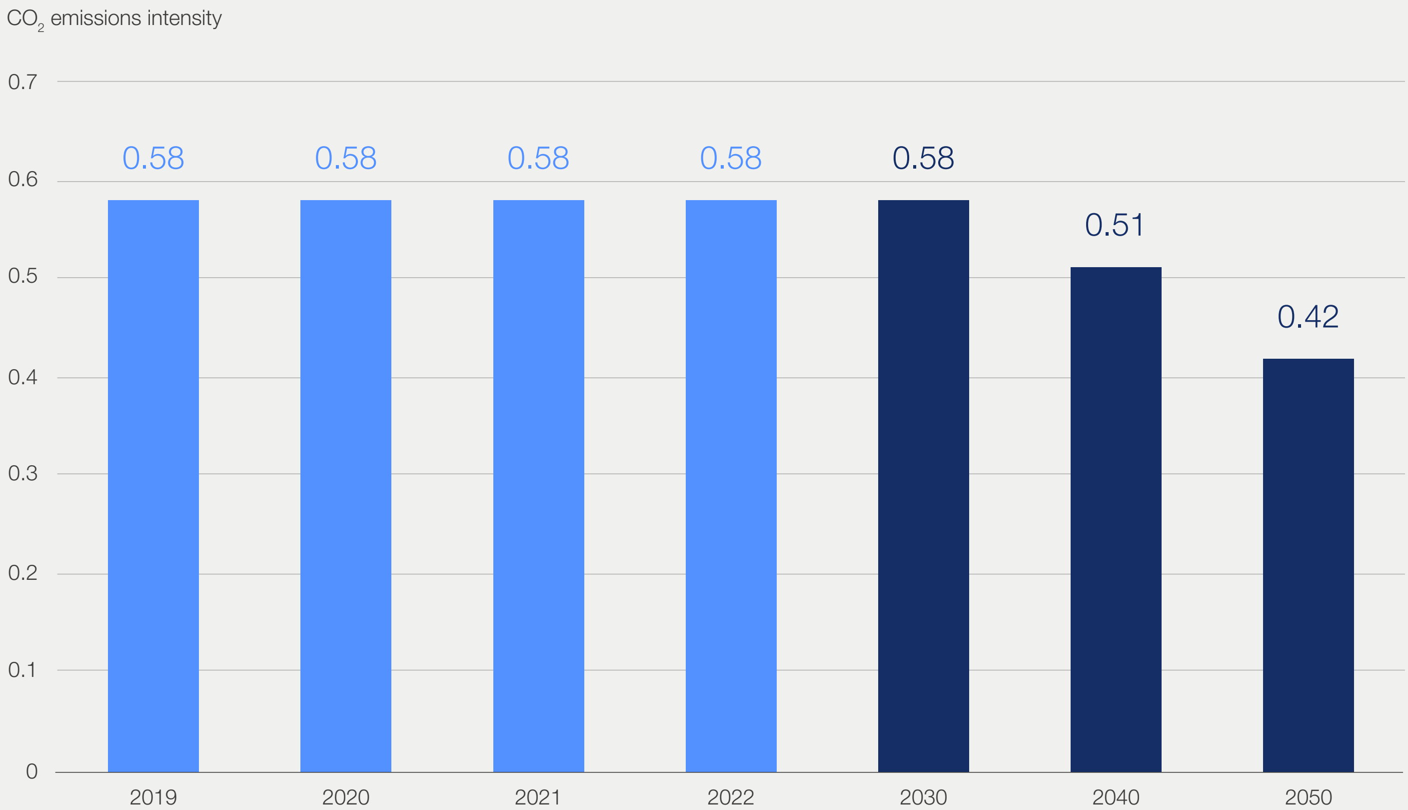
Unlike other sectors, where the largest share of emissions is energy-related, in cement and concrete production, more than half are process emissions, therefore requiring either novel solutions to a millennia-old industry, or strong reliance on carbon capture.

The cement manufacturing process starts with the extraction of raw materials – mainly limestone, which gets transformed into clinker in a rotary kiln heated up to 1,450°C. Clinker, which represents almost 95% of cement's composition, is responsible for 88% of its overall emissions, related both to the energy input for heating (35%) and the CO_2 chemically separated from the crushed limestone (53%). Clinker is then ground and supplemented by other materials to form cement, which can be mixed with sand, water and other aggregates to make construction-ready concrete.[109]

There are many variants of cement depending on the chemical composition, but ordinary Portland cement is the most widely used and is the industry standard against which most carbon-reduction alternatives are measured. Emissions intensity is expected to decrease over time due to increased use of biomass and non-renewable waste in the fuel mix, but a significant gap still remains to achieving a near-zero emissions intensity (see Figure 6).

> **Clinker is responsible for 88% of cement's overall emissions, related both to the energy input for heating (35%) and the CO_2 chemically separated from the crushed limestone (53%).**

FIGURE 6: **Cement emissions intensity trajectory, BAU scenario (tCO_2e/t of cement)**



Source: World Economic Forum.[110]

5.2 The FMC commitment

BOX 5: **FMC's Cement and Concrete commitment**

Construction and engineering:

We commit to purchasing at least 10% (by volume) of our cement/concrete per year as near-zero cement/concrete* inclusive of any SCMs by 2030 and excluding fossil-based SCMs by 2035.

Real estate, developers and advisory:

We commit to ensuring/specifying that at least 10% (by volume) of the cement/ concrete procured for our projects per year is near-zero carbon cement/concrete* inclusive of any SCMs by 2030 and excluding fossil-based SCMs by 2035.

***Cement and Concrete: Detailed commitment**

Subject of demand signal
First Movers will make a commitment[1] for either cement or concrete

1. **Cement** with embodied carbon below 184kg CO_2e/tonne.[2, 3]
2. **Concrete** that meets the embodied carbon limits below.[4, 5]

Specified compressive strength (f'c in psi)[6]	Embodied carbon (kg CO_2e/m³)
0 – 2500 psi	70
2501 – 3000 psi	78
3001 – 4000 psi	96
4001 – 5000 psi	117
5001 – 6000 psi	124
6001 – 8000 psi	144

Technological pathways
Solutions may include (but are not limited to):

- **CCUS**
- **Non-fossil-based SCMs**[7]
- **Fuel switching**
- Renewable electricity
- Energy efficiency improvements
- Decarbonated raw materials
- Alternative cement chemistries
- CO_2 mineralization during curing

Out-of-scope

- [By 2035] Fossil-based SCMs (i.e. GGBS and fly ash)
- Carbon offsets

Bolded abatement technologies seen as most critical to meeting FMC targets according to FMC research.

1. Depending on locality-specific regulatory / technology requirements **2.** Using 2021 baselines for US-based manufacturers with >80% clinker ratio chosen to avoid penalizing suppliers in countries with inherently low clinker ratios **3.** Modules A1, A2, A3 in life-cycle analysis (cradle-to-gate) as per EPD standards for Portland cement; Scope 1 and 2 emissions **4.** Modules A1, A2, A3 in life-cycle analysis (cradle-to-gate) as per EPD standards for ready mix concrete; Scope 1 and 2 emissions **5.** Standard applies to both RMC and precast concrete given that both are specified by compressive strength and do not present significantly different emissions profiles **6.** Specified compressive strength of concrete using standard cylinders of six inches diameter and twelve inches height after 28 days of curing **7.** Any supplementary cementitious materials from non-fossil-based processes (i.e. not GGBS and fly ash).

Sources: 2021 US-based NRMCA Member Industry-average EPD for Ready Mixed Concrete with 0-19% SCM, 2021 US-based Portland Cement Association Industry-average EPD for Portland cement (91.4% clinker by weight), 2018 IEA Cement Low-Carbon Transition Technology Roadmap.

Full details of the commitment can be found here.

5.3 Decarbonization pathways in cement and concrete

There are four main decarbonization pathways for the cement and concrete industry. Most of them – also the main focus of this report – are related to the middle part of the value chain: cement production. These pathways address process emissions, energy emissions and the share of inevitable residual emissions.

Reduction of clinker with supplementary cementitious materials

Replacing clinker with supplementary cementitious materials (SCMs) that are less carbon intensive directly tackles process-related emissions, but no existing commercialized solutions exist that can completely replace clinker at scale. SCMs such as fly ash (a by-product of coal combustion), ground granulated blast furnace slag (GGBS, a by-product of ironmaking) and limestone are all able to cut between 5% and 70% of emissions, depending on the SCM used.

Limestone serves multiple purposes in the cement production process. It is used traditionally to make clinker, which produces significant emissions. However, companies like Ecocem (part of the First Suppliers Hub) are using limestone as a SCM to *replace* clinker. For example, in European CEM II M cements, mixtures of limestone and other SCMs may replace up to 46% of the clinker in cement.[111]

> **In European CEM II M cements, mixtures of limestone and other SCMs may replace up to 46% of the clinker in cement.**

As the world moves away from coal power and blast furnaces, there will be less fly ash and GGBS available so they are not seen as scalable solutions. As a result, fossil-based SCMs are considered by FMC as an out-of-scope technology after 2035. However, the global shift away from fossil fuels creates an opportunity for novel SCMs that are not derived from carbon-heavy combustion. Due to this, non-fossil based SCMs, such as calcined clays (also known as industrial pozzolans) and limestone, are in scope for FMC.

Replacing limestone with alternative non-carbonate materials

Given that the heating of limestone to produce clinker accounts for 50% of emissions in cement production, alternative chemistries and processes that replace limestone from the clinker-production process provide a significant GHG emissions reduction pathway.[112]

Some examples of this technology in action among members of the First Suppliers Hub include the following:

- Brimstone is producing ordinary Portland cement using calcium silicate instead of limestone; this has the potential to abate process emissions since calcium silicate does not release carbon when processed. In addition, the resulting magnesium waste residue from their process can absorb carbon.[113]
- Sublime Systems is using calcium silicate minerals or industrial wastes to produce cement using an electrochemical process rather than heat.

Fuel switching and electrification

Fuel switching and electrification are critical to lowering energy-related emissions until novel isothermic chemistries have emerged. Partially heating up the kiln with a decarbonized electricity source and replacing fossil fuels with low-carbon fuel alternatives for the remaining part can help phase out coal. For example:

- CoolBrook, SaltX and Rondo Energy have all developed electric or thermal-based alternatives to fossil-based kilns and calciners – a stage that preheats limestone before entering the kiln.[114]
- Another approach to achieve the very high temperatures required is concentrated solar, which has been tested by start-ups like Synhelion[115] – in collaboration with Cemex – and Heliogen.[116]
- Low-carbon fuel alternatives are common to other industries as well and go from near-term drop-in solutions, including biomass and plastic waste, to longer term alternatives such as green hydrogen.

Carbon capture

Point-source carbon capture is an enabling technology on the path to net zero, especially for cement and concrete production. Projections by the Global Cement and Concrete Association show that CCUS could provide a 36% carbon dioxide emission reduction by 2050, the largest lever to reduce the cement industry's emissions and an approach being piloted by FMC (trucking commitment) members Cemex and Heidelberg.[117,118,119]

Advancing technologies, falling costs and the emergence of CCUS units suitable to fit kilns – such as the ones that Carbon Clean and Svante are commercializing – are helping these solutions hit the market. Experimentations specific to the cement industry have also identified ways to re-inject captured carbon into cement and concrete to improve its properties – an approach pioneered by CarbonCure.

Efficiency savings

Much like for steel and aluminium, efficiency and input reduction are expected to be a large share of emissions saving. Using less clinker per unit of cement and less cement per unit of concrete can reduce emissions by 25% by 2050.[120] Efficiency is even more important when considering the inevitable increase in concrete costs for construction firms, which might then opt for building designs that require less of it in the first place. Combining efficiency savings with novel technologies is critical for suppliers looking to achieve near-zero emission cement and concrete in line with FMC's commitments.

> **Using less clinker per unit of cement and less cement per unit of concrete can reduce emissions by 25% by 2050. Combining efficiency savings with novel technologies is critical for suppliers looking to achieve near-zero emission cement and concrete in line with FMC's commitments.**

5.4 Supplier challenges and opportunities in low-carbon cement and concrete

High costs of decarbonization, along with competition for investment with other sectors, pose challenges for the concrete industry. The transition may also lead to a scarcity of SCMs, but alternatives like non-fossil fly ashes, slag from hydrogen-based products and natural pozzolans can be used. Suppliers need to adapt to the evolving landscape of clinker alternatives, influence standards and regulations to accommodate alternative chemistries, and prepare for major overhauls of manufacturing facilities, such as retrofitting with hydrogen heating or CCUS.

Meanwhile, the localized nature of the cement industry, coupled with the need for global standards, requires suppliers and regulatory bodies to strike a balance between emphasizing the importance of localized approaches, consistent standards and strengthened carbon accounting and life-cycle assessment (LCA) methodologies.

> **High costs of decarbonization, along with competition for investment with other sectors, pose challenges for the concrete industry.**

Competition with other sectors

As with all hard-to-abate sectors, the high costs of scaling-up enabling pathways such as CCUS and clean hydrogen are a large hurdle for decarbonization. In addition, the cement and concrete industry could face competition for investment with more "publicly visible" transportation sectors such as automotive, shipping and aviation. However, the magnitude of emissions and the low maturity of solutions to eliminate process emissions would suggest that cement will likely be prioritized over other industries.

The US Department of Energy's Office of Clean Energy Demonstrations recently announced up to $6 billion in funding across eight industrial sectors with the largest portion going to six projects in cement and concrete for up to $1.6 billion.[121] In addition, many CCUS projects are focusing on cement applications first. For example, in Europe, approximately 15% of all CCUS projects are focused on cement applications, the second largest category after projects focused on carbon storage.[122]

> **Securing capital for a first-of-a-kind industrial plant is extraordinarily challenging, particularly in the cement industry, where there is no tradition of project finance. In this context, receiving DOE [US Department of Energy] funding is especially transformational, accelerating Brimstone's path to market, opening up access to other resources, and sending a compelling validation of Brimstone's outsize promise, technically and economically.**
>
> Simon Brandler, VP of Policy & Public Affairs, Brimstone

Securing low-carbon SCMs

Another critical input that might become scarce as the sector transitions are SCMs to reduce or replace clinker. The two main sources of SCMs are coal combustion (generating fly ash) and iron-making blast furnaces (generating slag). As the world's power generation and steel industry work towards phasing out both processes, suppliers might find themselves short of an ingredient for which currently demand already exceeds supply.[123]

Luckily, non-fossil fly ashes, such as silica (a by-product of calcium silicate), slag resulting from hydrogen-based products, and other non-fossil-based materials (e.g. calcined clay, natural pozzolans) can replace them. It is important that cement suppliers look ahead and secure offtake from alternative low-carbon SCMs that are expected to be resilient to the phase-down in fossil fuels.[124]

Shaping new standards to accommodate alternative chemistries

The list of possible alternatives to clinker is in continuous evolution and TRLs vary widely, but some of the challenges are shared.[125] Materials are not always available at competitive prices, and standards and regulations need to evolve to accommodate alternative chemistries. This requires changing the focus from prescriptive standards (e.g. focusing on specific chemical composition) to performance-based specifications such as solidity and endurance.[126]

To compound this, offtakes are normally completed on a short-term basis, making it difficult for suppliers to achieve the advanced market commitments needed to grow.[127] Suppliers have an opportunity to shape standards and regulations to be more accommodating of alternative chemistries and can take part in newly emerging advance market commitment financing mechanisms.

One more investment cycle before 2050

When considering major overhauls of manufacturing facilities, such as retrofitting with hydrogen heating or CCUS, suppliers face a dilemma that is shared with the steel industry. Facilities are built with long lifespans and are expected to operate for multiple decades. This means that, once commissioned, they are just one investment cycle away from 2050. Most of the capital expenditures and likely additional operating expenses in concrete production are expected to come from the addition of CCUS units to current kilns. Estimates of the cost vary widely, falling between $200 million and $500 million per plant, depending on the technology adopted and the year of investment.[128] Additionally, as the TRL of CCUS improves, carbon capture units are expected to get cheaper over time, potentially creating a dangerous incentive to postpone investments.

Cement manufacturers need to be prepared to adapt their footprint and plants to incorporate the new technologies that help decarbonize cement production right from the next investment cycle. Ensuring plants are ready for CCUS units, hydrogen-based combustion and alternative SCMs – as soon as the enabling technologies hit the market – is crucial to avoid additional investments off-cycle.

Localized supply chains pose challenges

Lastly, striking the balance between an historically local industry and the need for global standards has proved to be extremely challenging for suppliers and regulatory bodies. Cement and concrete are usually produced close to where they are used – on average less than 50km for concrete and 250km for cement.[129] This means nearly every country is a producer of its own concrete and supply chains are built locally, potentially limiting the use of SCMs that are not available in the market. Additionally, newer cement and concrete technology providers can have a challenging time ensuring their solutions gain approval for use by regulatory bodies.

Consistent definitions and standards

This calls for regulatory bodies and regional value chain partners to adopt localized approaches. To reach global climate goals, it is imperative that GHG accounting frameworks share similar language for measuring and reporting, so as to enhance transparency and inform better decision-making. Defining what carbon-free cement actually means can be challenging, since the carbon intensity of SCMs highly depends on their LCA, including the logistics of various ingredients and technologies. In addition, CCUS is a critical emissions abatement lever. Yet major reporting and standards bodies do not provide a process for cement suppliers to claim emission reductions.[130]

Suppliers can help push towards consistent standards and industry collaboration both at local and global levels, focusing on strengthening carbon accounting and LCA methodologies, promoting performance-based specifications, and preparing to comply with a future market that has different low-carbon procurement and offtake policies.

6 Steel

Early producers of low-carbon steel will benefit from public policy interventions, but may face challenges relating to the life-cycle of steelmaking assets and supply chain disruptions.

6.1 Current emissions profile

There are three well-developed production routes for steelmaking, defined by its two major steps: the processing of raw iron ore (stripping oxygen out of it) and smelting iron into virgin steel. The most common production routes are: blast furnace-basic oxygen furnace (BF-BOF – 72% of global steel production), scrap steel electric arc furnace (Scrap-EAF – 21% of global steel production) and direct-reduced iron electric arc furnace (DRI-EAF – 7% of global steel production).[131]

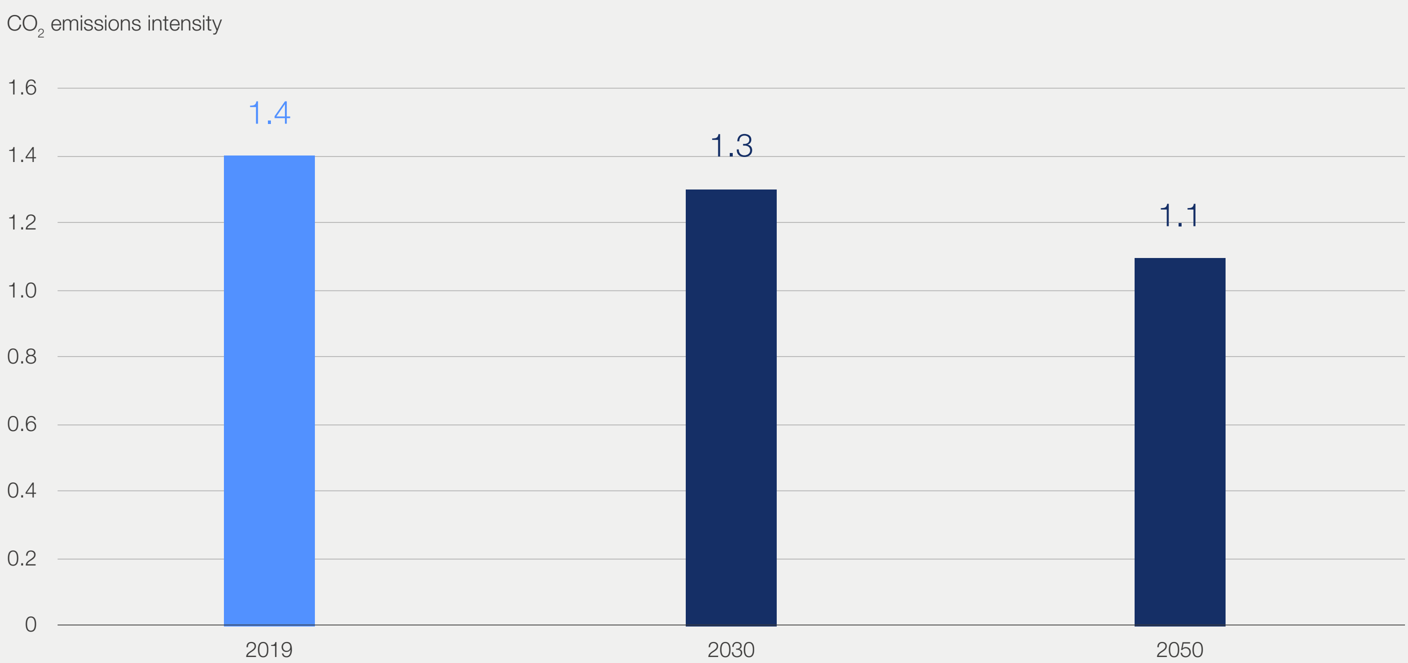
These technologies vary in their emissions intensities. Direct emissions come from the burning of fossil fuels to achieve ultra-high temperatures (energy emissions) and from the chemical reactions necessary to produce steel (process emissions). There are also indirect emissions, which come from the purchased energy used to power electric arc furnaces and other mill equipment. Making steel by starting with raw iron ore is called primary steelmaking and is more carbon intensive than secondary steelmaking, which uses recycled or scrap steel as a feedstock. Both are predicted to have reduced emissions intensity over time, given improvements in the energy intensity of production and increased secondary steel production.

The BF-BOF process produces on average 2.2 tCO_2 per tonne of finished steel, DRI-EAF produces 1.4 tCO_2 and Scrap-EAF produces 0.3 tCO_2 (with the potential to be zero emissions where powered by renewables).[132] Today, BF routes typically use coking coal for heat, while EAFs use natural gas as a reducing agent, which is the main reason for their different emission levels. As a whole, the steel industry produces roughly 8% of global GHG emissions, including 2.6 billion tonnes (Gt) of direct CO_2 emissions and a further 1.1 Gt CO_2 of indirect emissions, including off-gassing and energy usage.[133,134]

The share of scrap in the feedstock for EAF along with other factors, such as grid mix and age of technology, can have significant impacts on emissions. Steel scrap may also have limited availability depending on the geography. For example, during the Brazil in-country workshop hosted by the First Movers Coalition in October 2023, scrap availability was highlighted as a key challenge due to the lack of municipal steel recycling infrastructure – in 2020, Brazil's steel scrap recycling rate was around 36%, compared to a global average of 66%.[135]

The BF-BOF process produces on average 2.2 tCO_2 per tonne of finished steel, DRI-EAF produces 1.4 tCO_2 and Scrap-EAF produces 0.3 tCO_2 (with the potential to be zero emissions where powered by renewables).

FIGURE 7: **Primary steel: emissions intensity trajectory, BAU scenario (tCO_2e/t of steel)**



Source: International Energy Agency (IEA), stated policies scenario (STEPS).[136]

6.2 The FMC commitment

BOX 6: **FMC's Steel commitment**

At least 10% (by volume) of all our steel purchased per year will be near-zero emissions (as per FMC definition*) by 2030.

***FMC definition:**

- Crude steel from breakthrough technology production facilities
- As per IEA guidance, the steel should emit <0.4t (0% scrap inputs) to <0.05t (100% scrap inputs) of CO_2e per tonne of crude steel produced, from cradle-to-gate

In-scope technologies include:

- Using zero-carbon hydrogen for direct reduction.
- Electrowinning.[137]
- Electrolysis-based production processes.
- CCUS (carbon capture, utilization and storage).

Full details of the commitment can be found here.

6.3 Decarbonization pathways in steel

Realistic decarbonization scenarios for the steel industry depend on a confluence of several factors; this report focuses on carbon emissions reduction and other technologies.

Increased use of scrap

Demand reduction for primary steelmaking includes recirculation of material, increasing per-mass productivity of steel usage and driving material efficiency measures in steel plants. Increased use of scrap steel reduces the need for iron-ore processing, an emissions-heavy step. Steel has a very high recycling rate, with current scrap usage roughly 35% of primary demand and estimated to increase to 1,180 Mt/year by 2050, roughly 45% of business-as-usual primary steel demand. Scrap usage is an important decarbonization tool, as it can be used to feed EAF plants directly, without the need for pre-processing iron ore.[138] Accordingly, the FMC definition of near-zero emission steel considers the importance of scrap by providing a range of <0.4 (0% scrap inputs) to <0.05 t (100% scrap inputs) of CO_2e per tonne of crude steel produced.

DRI-EAF with green hydrogen

Reducing direct carbon emissions can be achieved by moving from BOFs to EAFs. EAFs are a mature technology that already makes up some 70% of US steelmaking (28% worldwide). However, to produce near-zero emission steel, DRI-EAF must be combined with hydrogen produced from renewable energy, which is currently available in very limited quantities.

SSAB was recently selected for the US Department of Energy Industrial Demonstrations Program to build the first commercial-scale facility in the world using its HYBRIT® technology, a fossil-free direct-reduced iron (DRI) approach using 100% hydrogen, in Perry County, Mississippi.[139] Other firms working on this technology include but are not limited to H_2 Green Steel, Hydnum Steel, Gerdau, Blastr Green Steel, Emirates Steel Industries, GravitHy, Liberty Steel, Salzgitter and JSW Steel.

Novel technologies

Other technologies, such as the use of equipment to melt DRI to make it compatible with BOFs (DRI-melt-BOF), replacement of pulverized coal injection (PCI) with biomass- or hydrogen-based alternatives, electrowinning and other emerging solutions may provide significant additional emissions savings.[140] For example, Gerdau (part of the First Suppliers Hub) is piloting the use of charcoal as a bio-reducer, replacing the use of mineral coal in their Divinópolis Mill with charcoal from Gerdau's 250,000 hectares of planted forests. Meanwhile, Electra is developing a process for producing iron at the temperature of a cup of coffee, by using unconventional feedstocks and electrochemical processes known as electrowinning.

Carbon capture, utilization and storage (CCUS)

CCUS is being commercialized or is under consideration for BF-BOF techniques by some firms, such as Shougang, Tata Steel, Delong Steel

Group and JFE Steel Corporation.[141] Blast furnace relining, which occurs roughly every 15-20 years, requires plants to be idle for long stretches and provides good opportunities to retrofit or upgrade equipment, for instance to improve efficiency or install CCUS systems.[142] CCUS is essential to preserve the useful life of existing heavy infrastructure, as well as to mitigate the remainder of emissions that are not easily abated by shifting technologies.

Blast furnace relining, which occurs roughly every 15-20 years, provides good opportunities to install CCUS systems.

Unabated emissions

It is important to note that there will likely be an unavoidable remainder of emissions from steel production. These emissions will arise from less-than-perfect capture rates for CCUS, process emissions and other irreducible elements. Given the centrality of steel to modern economies, it is unlikely production can be reduced enough to completely avoid this remainder and instead carbon dioxide removals or "negative emissions" will be necessary to fully decarbonize the sector.

6.4 Supplier challenges and opportunities in low-carbon steel

The transition to low-carbon steel production presents a significant challenge for suppliers due to the potential increase in cost and lack of a strong demand signal for a green premium on reduced-emission steel. However, this also presents opportunities for early adopters and organizations willing to invest in low-carbon steel, especially given policy interventions in Europe, for example, that seek to tax carbon.

Additionally, even though the life-cycle of steelmaking assets may complicate transition plans, rapid innovation and early demonstration of commercial viability for low-carbon steel technologies can help in decarbonizing the industry. Firms committing to this path can leverage developments in other sectors, such as the use of clean hydrogen and biogas, as well as effective and economical CCUS.

First mover disadvantage

Suppliers looking to pivot to low-carbon steel production face a challenging task, given the sector is facing systemic disruption to a globalized commodity market. Changes to steel production designed to lower the carbon intensity of the final product, such as novel ore-reduction methods, are likely to increase the final cost. In the absence of a strong demand signal indicating an appetite for a green premium on reduced-emission steel, suppliers face a disadvantage when being a first mover in the globalized commodity market. This is because the firm that first brings low-carbon steel to market is likely to struggle to move its product, even while it de-risks low carbon technologies for competitors.

Green premium and role of governments

Premiums for low-carbon steel are estimated at ~40% more than traditional production today, but could fall by 2050 so that green steel costs 5% less than fossil-based routes.[143] Industries where material costs are not a major driver of total cost are likely to become early adopters: for example, a 25% premium on steel would raise the price of a car by only 1%, compared to the significant price increase of using net-zero emission steel for wind turbines.[144] Organizations such as FMC members, willing to shoulder this burden and signal robust demand for low-carbon steel, can help minimize the risk of investments and make progress in the industry. In addition, government grants, such as the recent $1.5 billion of funding from the US Department of Energy for six iron and steel projects can help solve this first-mover dilemma.[145]

Premiums for low-carbon steel are estimated at ~40% more than traditional production today, but could fall by 2050 so that green steel costs 5% less than fossil-based routes.

Policy interventions

Policy interventions are also key to resolving this bind. The EU's Carbon Border Adjustment Mechanism (CBAM), for instance, applies tariffs to goods entering the EU's single market based on the carbon footprint of imported goods.[146] This helps to balance out the cost premiums that EU producers (subject to the bloc's carbon tax) must internalize, relative to producers in other countries (that are not subject to carbon taxes). The CBAM is therefore intended to help prevent "carbon spillover", where carbon taxes simply result in moving emissions outside taxing jurisdictions without substantially reducing them.

Putting aside complications in bringing CBAM into practice, such interventions can still only reduce emissions on the portion of demand they govern. Domestic demand in emerging markets (such as India and China), is forecast to be significant in coming years and remains outside the EU's jurisdiction.[147] Policy developments in these emerging markets, such as expansion or upgrading of carbon markets, would have significant effects on emissions intensity.

Long lifespan of incumbent assets

As noted above, the life-cycle of major steelmaking assets may complicate transition plans and create tight investment windows between furnace campaigns. Refractories, the vessels in which steel is smelted, are relined roughly every 15-20 years, with major plant overhauls taking place on longer time scales. These renovations are expensive and the economic structure of the steel industry can make it cost-prohibitive to make major changes at any time outside of these windows.

Operators are thus faced with a difficult predicament: if an economically viable low-carbon solution suitable to their region is not available when mills are ready for overhaul, firms must pick between costly gambles on novel technology and locking in legacy systems for another cycle.[148] This makes rapid innovation and early demonstration of commercial viability for low-carbon steel technologies a crucial step in decarbonizing the broader industry. Half the current stock of steel plants is due for relining or refurbishment before 2030, according to the Mission Possible Partnership.[149]

> **Half the current stock of steel plants is due for relining or refurbishment before 2030.**
>
> Mission Possible Partnership

Multi-use technologies to lower emissions

Firms that commit to lowering the emissions impact of steel will face technological and supply chain hurdles. Fortunately, many of these technological developments are required for a variety of sectors, increasing the incentive for research and development (R&D). For instance, clean hydrogen and biogas – used as alternative low-carbon reducing agents – are inputs in a variety of other low-carbon pathways and hence enjoy broad-based support. Steel decarbonization will also depend on effective and economical CCUS, another multi-use technology, which will benefit from government support and applications in a multitude of industries. Low-carbon steel producers benefit from the technological and economic maturity of EAF, as well as a variety of developing technologies that can solve problems of ore quality, make use of existing assets and diversify technological risk.

7 Carbon dioxide removal (CDR)

For CDR to achieve its required climate impact, the sector needs increased policy support, lower costs, broadly accepted MRV standards and a diverse set of buyers.

7.1 Current emissions profile

By 2050, global emissions must reach net zero, which means removing up to 10 Gt of CO_2 from the atmosphere every year. Throughout the second half of the century, global emissions have to stay net-negative (where more CO_2 is removed than emitted, see Figure 8). Current carbon dioxide removal (CDR) totals 2 Gt CO_2/yr, of which 99.9% comes from natural climate solutions (e.g. afforestation, reforestation). New CDR solutions are needed urgently – technologies that can deliver additional, permanent and quantifiable impact at the speed and scale required to make a difference.

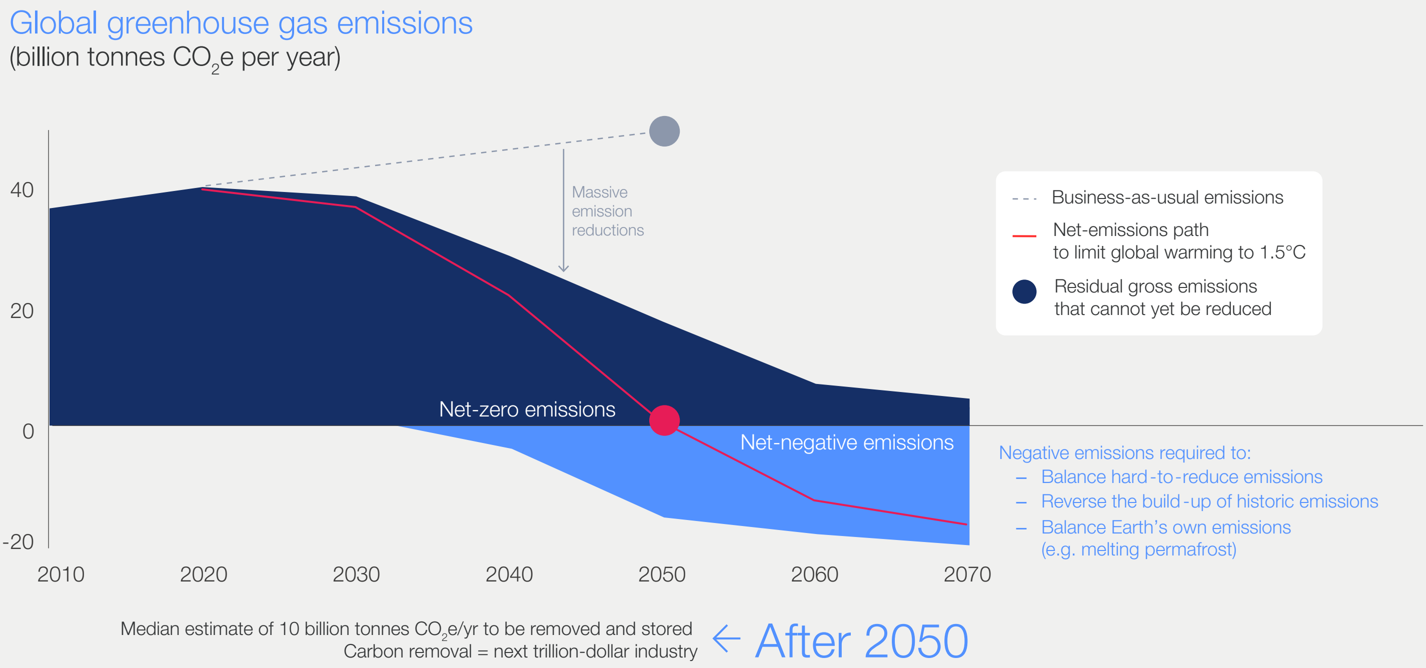
This chapter focuses on engineered CDR solutions, including direct air capture with carbon storage (DACCS), biomass carbon removal and storage (BiCRS), bio-energy with carbon capture and storage (BECCS) and biochar carbon removal (BCR), as well as hybrid natural solutions, including enhanced rock weathering (ERW) and mineralization. A more detailed analysis of CDR can be found in the World Economic Forum's January 2024 white paper, Carbon Dioxide Removal: Best-Practice Guidelines.[150]

For many engineered CDR methods, the estimated cost varies widely and is currently high. For example, DACCS prices can be as high as $600-1000 per of tonne of CO_2.[151] The scalability of DACCS is currently limited by its high cost, which is primarily driven by the large amount of clean energy used for air filtration. The cost of such CDR options will remain high until the technology matures and sees a step-change in deployment rates, access to low-cost capital, supportive infrastructure and energy prices, and actions that accelerate collaborative learning. Nevertheless, despite its current cost, DACCS is seen as a promising solution for more permanent carbon storage.

Despite its current cost, direct air capture is seen as a promising solution for more permanent carbon storage.

Biochar carbon removal is generally more affordable than other engineered CDR solutions. The UN's Intergovernmental Panel on Climate Change (IPCC) estimates the cost of biochar at between $10 and $345 per tonne of CO_2 removed, with a mitigation potential of between 0.3 Gt and 6.6 Gt CO_2/year by 2050, cited in the Forum's January white paper.[152] Given its relative affordability, biochar represented about 93% of all engineered removals in 2023.[153] It therefore has the potential to be scaled-up both rapidly and immediately. However, biochar faces issues with carbon storage permanence when compared to other engineered carbon removal methods, such as DACCS.

FIGURE 8: **Beyond net zero – negative emissions required through carbon removals**



7.2 The FMC commitment

BOX 7: **FMC Carbon dioxide removal commitment**

In addition to our maximal direct emissions reduction efforts, we commit to contract for at least 50,000 tonnes of durable and scalable (see definitions*) net carbon dioxide removal to be achieved by the end of 2030.

As an alternative to contracting for 50,000 tonnes, companies joining FMC can contract for at least $25 million of durable and scalable (see definitions*) net carbon dioxide removal to be achieved by the end of 2030.

***FMC definitions:**

Carbon removal solutions that satisfy the following are in-scope:

- Durable solutions that can demonstrably store captured carbon for a minimum of 1,000 years.
- Scalable solutions that have the potential to reach Mt scale (millions of tonnes) by 2030 and Gt scale (billions of tonnes) by 2050.

Full details of the commitment can be found here.

7.3 Decarbonization pathways in carbon dioxide removal

This chapter only examines CDR technologies with the potential to meet FMC's durability and scalability requirements. Reaching the required level of CDR is likely to require a portfolio approach combining the following (and possibly other) technologies:

- Engineered solutions such as DACCS, BiCRS and BECCS.
- Biochar, also considered an engineered solution, is only in-scope for FMC if proven to provide 1,000+ years of permanent CO_2 storage. Most biochar is expected to fall short of this requirement, though specific solutions may reach the threshold.[154]
- Hybrid natural processes such as enhanced rock weathering and mineralization.
- Note: Ocean-based CDR is not in-scope for FMC.

Direct air capture with carbon storage (DACCS)

DACCS technology uses banks of fans to pass ambient air through physical or chemical filters that selectively trap CO_2 molecules. The captured CO_2 can then be compressed or stored in deep geological formations for thousands of years. The benefits of DACCS as a CDR option include high storage permanence (when stored geologically) and a limited land and water footprint. Alternatively, instead of being stored and therefore producing negative emissions, the captured CO_2 can be combined with hydrogen to produce carbon-neutral synthetic fuels.[155]

Biomass carbon removal and storage (BiCRS)

BiCRS technologies rely on vegetation to pull CO_2 from the atmosphere via photosynthesis, binding it within plant tissues. Crop and forestry residues, organic waste and purpose-grown crops such as corn can all be used as biomass. However, the burden placed by these feedstocks on land use is an important consideration. BiCRS principally relies on converting the biomass into a product that can be used and CO_2 that can be sequestered. Novel approaches involve sequestering the carbon in long-lived products, such as concrete, or directly injecting bio-liquids into geological formations, such as former oil wells (sometimes known as direct bioliquid injection and disposal, DBID).

Bio-energy with carbon capture and storage (BECCS)

BECCS is a variant of BiCRS technology where biomass is used to generate power, either directly or after being converted into biofuel or biogas. Point-source CCS equipment is then applied to the power plant to capture the emissions and the captured CO_2 is subsequently stored.

Biochar

Biochar carbon removal relies on a type of charcoal created when biomass from crop residues, grass, trees or other plants is combusted at high temperatures without oxygen. This process, known as pyrolysis, enables the carbon in the biomass to resist decay. When mixed with existing soil, most biochar options are expected to have a durability of less than 500 years. However, some recent studies suggest that biochar could last 1,000+ years, depending on the feedstock and temperature of pyrolysis used. Biochar also improves soil fertility.

Enhanced rock weathering (ERW)

ERW technology harnesses natural geological processes wherein CO_2 in the atmosphere binds with certain minerals. By mining, crushing and distributing these minerals across broad areas, the relevant reactions can be materially sped up, providing long-term, stable carbon sequestration.

It is important to note that CDR is a required complement to, not a substitute for, the other emissions abatement pathways already discussed in this report.

It is important to note that CDR is a required complement to, not a substitute for, the other emissions abatement pathways already discussed in this report. CDR faces criticism by those who worry it may be seen as conferring a "right-to-emit". Companies must reduce the absolute emissions of their value chains by at least 90% and remaining emissions must be removed or "neutralized" through permanent CDR. According to the Science Based Targets initiative's (SBTi) corporate net-zero standard, "a company is only considered to have reached net-zero when it has achieved its long-term science-based target and neutralized any residual emissions."

All CDR technologies exhibit benefits as well as drawbacks and achieving the necessary removals will require a portfolio approach, with a mix of technologies that balances considerations such as availability of geological sequestration storage, water and land use, access to renewable power and existing infrastructure.

CDR suppliers today are mainly either emerging developers, such as Climeworks (DAC), Pacific Biochar, Charm Industrial (BiCRS); or divisions of legacy industry players, such as Project 1.5, a part of Occidental Petroleum and Drax, an electrical services company.

7.4 Supplier challenges and opportunities in carbon dioxide removal

So far, the high cost of CDR is due to the technology's nascent nature, lack of mature measurement, reporting and verification (MRV) standards, and low support from policy makers, which is limiting CDR uptake. The evolution of the CDR market towards wider corporate adoption requires constructive ecosystem collaboration, more developed infrastructure, and harmonized standards and guidelines. All these elements need to be supported with strong policies.

The high cost of CDR is due to the technology's nascent nature, lack of mature measurement, reporting and verification standards, and low support from policy makers, which is limiting CDR uptake.

Measurement, reporting and verification (MRV) standards

To support integrity and transparency in CDR credits, suppliers need to demonstrate that their removals are credible and durable through robust MRV systems, run by trusted third parties. This will be essential to ensure both effective carbon removal and public trust in removal markets and firms. Removal efforts are commonly criticized as covers for the continued emission of carbon and avoidance of other abatement solutions. CDR firms should be aware of this perception and respond transparently. Accreditation, coupled with clear and transparent accounting of removals to avoid double counting, will be essential to secure actual net reductions and maintain CDR as a required complement for other abatement methods and not a substitute. Responsible suppliers should be seen as a step ahead of policy-makers in holding themselves to high standards of fair accounting and being unequivocal in public statements and marketing materials around the need for concurrent abatement of emissions.

> Responsible suppliers should be unequivocal in public statements and marketing materials around the need for concurrent abatement of emissions.

Demand signal needed to lower cost

Novel engineered solutions are significantly more expensive than nature-based solutions (which are not in-scope for FMC), but are likely to offer greater total potential and may offer more reliable carbon removal. However, even with robust and standardized MRV schemes that can confirm durable, verifiable removals, the CDR market will face a fundamental challenge of demand. The current scale of removals by novel technologies is in the order of 2 Mt CO_2/yr. The main constraint to scaling up durable CDR is the high cost, which is where private-sector leaders have an important role to play. The sooner companies can demonstrate demand for durable CDR solutions, the quicker the industry will scale-up and the faster prices will fall. Now is a time for leadership. Committing to durable CDR through a long-term offtake agreement (tailored to the company's size and budget) guarantees suppliers an income stream to leverage lines of credit to invest in their chosen technology.

> **Like any other nascent and disruptive industry, direct air capture follows the principles of Wright's Law: it gets cheaper at a consistent rate, as the cumulative production of that technology increases and learning rates improve. Solar energy is the prime example here. Climeworks is on a cost-reduction journey through intensive R&D and constant learnings from our field data, which you can already clearly see with Mammoth. Compared to Orca, CO_2 recovery improved by 15 percentage points, we achieved a twofold reduction in operation and maintenance cost and had around 20 percent lower specific CAPEX spending.**
>
> Christoph Gebald, Co-CEO and Co-founder, Climeworks

Role of First Movers Coalition

FMC leverages the collective purchasing power of companies to send a clear demand signal to scale-up emerging decarbonization technologies that are critical to the net-zero transition. By stimulating sufficient demand, FMC aims to help accelerate the commercialization of these technologies and ultimately drive down their cost.

In addition, the FMC has created the First Suppliers Hub, which for CDR is focused on surfacing the different suppliers and their projects that are producing durable and scalable carbon removals as per the FMC commitment. While other providers may enable CDR transactions, the FSH provides an objective platform for suppliers working on novel technologies to feature their projects directly to FMC members and beyond.

Suppliers, for their part, should start or continue planning for the ambitious ramp-up in their services that the world will require.

Unintended adverse consequences

Scaling-up CDR technologies will require careful attention to unintended adverse consequences. Several pathways rely on dedicated cropland or ready availability of biomass to achieve cost-effective removals. For example, 30 million to 43 million hectares is required to raise sufficient BECCS feedstocks to provide 1 Gt per year of negative CO_2 emissions. This could put pressure on essential food production. Other technologies, such as DAC, require large amounts of renewable power, which may create additionality concerns if the technology ends up in competition with other users of renewable energy.

Challenges around long-term storage locations

Another challenge is the distribution of geological formations conducive to long-term storage of captured carbon or bio-liquids. Salt domes and exhausted oil formations are often most suitable, but these are unevenly distributed globally. Suppliers can build on detailed studies, such as the Roads to Removal Report,[156] to mould CDR projects to the form most closely contoured to the comparative advantages of specific places. Opportunities to utilize the captured CO_2, particularly those that involve long-term sequestration through mineralization or concrete, may provide complementary to geological storage.

8 Cross-sector challenges and opportunities

Challenges facing suppliers include a lack of emissions measurement standards, the availability and cost of inputs, and buyers who are both risk-averse and need educating in the benefits and impacts of decarbonized solutions.

Each of the sectors described earlier faces unique risks and challenges to decarbonization. They also share some common ones: many relevant decarbonization solutions are still very novel and uncertainty lingers around how to scale-up those solutions.

Overcoming some of these challenges will require actions by government, academia, industry, finance and other stakeholders. One stark and significant example is the need for financial innovations to unlock the trillions of dollars necessary for large-scale climate infrastructure projects.[157] Heavy-emitting sectors will lean heavily on infrastructure projects, such as carbon capture retrofits or low-carbon hydrogen or fuel production facilities.

Commercial lenders often view large investments in these projects as too risky due to unproven returns on investment. Lenders should develop further expertise with these technologies and tailor risk frameworks to their unique characteristics. In addition, government incentives, as well as support from multilateral agencies and development banks,[158] will likely play a critical role in funding early-stage infrastructure projects until suppliers prove their commercial viability.

However, there are also cases where solution providers can make significant progress in helping break down adoption barriers. This chapter details three of these challenges and how suppliers can help solve them:

- Lack of emissions measurement methods and standards.
- Availability and cost of inputs.
- Buyers' risk aversion and unfamiliarity with decarbonized solutions.

TABLE 2: Cross-sector key challenges and opportunities

	Emissions measurement standards	Inputs availability	Buyers' risk aversion and unfamiliarity[1]
	How mature are the standards and frameworks to calculate emissions from producing the product (e.g. LCA, PCF, EPD)[2]?	**Are the required inputs currently available in sufficient amounts?**	**How familiar are buyers with decarbonization options, risks and value of purchasing decarbonizing goods?**
Aviation	High	Low	Medium
	ICAO's CORSIA[3] is an established emission reduction scheme, expected to be responsive enough to adapt to new decarbonization pathways.[4]	Strong reliance on and significant competition for hydrogen and biomass as feedstocks (with potential to expand feedstock sources in the future).	Buyers have some understanding of SAF's production pathways, fuel feedstocks, risks and life-cycle emissions.
Shipping	Medium	Low	High
	IMO has authority over global vessel fleet and is moving towards creation of standardized guidelines for GHG emissions.	High reliance on and competition for hydrogen made from renewable energy, both in pure form and as ammonia or methanol.	Shipping companies familiar with decarbonized options; most major companies have plans towards their deployment.
Trucking	High	Medium	Medium
	Standards well-developed and mature; but challenges in consensus on life-cycle emissions and accurately tracking indirect scope 3 emissions.	Zero-emission vehicles available; but bottlenecks for infrastructure required for operational logistics (e.g. clean energy for BEVs, hydrogen for FCEVs).	Buyers of medium/heavy-duty trucks and logistics services aware of decarbonization options; but uncertainty over benefits of BEVs vs. FCEVs and timing of these markets.
Aluminium	Medium	Low	Medium
	Accounting standards for primary aluminium are more mature, but are nascent for secondary aluminium.	High competition over the significant amount of low-carbon reliable electricity needed for decarbonizing smelting, in addition to hydrogen and novel technologies (e.g. inert anodes).	Buyer's industry impacts their interest and education in aluminium decarbonization (e.g. consumer products are most advanced).
Cement/Concrete	Low	Low	Low
	Complex LCA accounting for different production pathways, with CCUS not fully incorporated into carbon accounting methodology.	High reliance on carbon capture technology, low-carbon power and heat, and alternative raw materials.	Significant education needed on decarbonization options and on role of performance-based vs. prescriptive standards.
Steel	Medium	Medium	Medium
	Steel-specific non-profits are working to create consistent standards but there are many different production pathways with complex LCA accounting.	Competition over low-carbon power and hydrogen, but increasing availability of scrap provides an opportunity.	High variety of end-users, requiring stronger education on supply-chain related emissions (scope 3).
CDR	Low	Medium	Medium
	Project-based standards available, but no single global standard for CDR, due to complexity of different types of projects and buyers.	DAC technologies will need to compete for renewable energy as market grows, while BECCS technologies will need to compete for feedstocks.	Buyers of CDR are present in most industries but need education on high-quality removals and offset; significant efforts already underway.

1 Low/medium/high grading of buyer familiarity is primarily informed by discussions with First Movers Coalition members and does not claim to represent the viewpoints of all buyers in the market.
2 Life-cycle assessment (LCA), product carbon footprint (PCF), environmental product declaration (EPD).
3 International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation.
4 Regional differences in carbon accounting maturity may exist, based on factors such as varying environmental policies, technology readiness etc.

TABLE 3: **Criteria for cross-sector analysis**

	Emissions measurement standards	Inputs availability	Buyers' risk aversion and unfamiliarity
High	An organization in the industry has standards or ambitions published that are widely accepted.	Little to no competition over input materials.	Buyers have comprehensive understanding of decarbonization options and may have published decarbonization plans.
Medium	At least one organization in the industry is working towards creating standards or ambitions.	Some competition around one input required.	Buyers have some understanding of decarbonization options and associated risks and value.
Low	No organization has made progress on publishing standards or ambitions.	Significant competition for multiple inputs required.	Buyers have limited understanding of decarbonization options and associated risks and value.

8.1 Lack of emissions measurement methods and standards

Standards are needed for suppliers to follow when calculating the GHG emissions of the products they are producing. Depending on the sector, these assessments may go by different names such as a life-cycle assessment (LCA), product carbon footprint (PCF) or environmental product declaration (EPD).

Without broadly accepted standards and methodologies, buyers and investors cannot adequately determine how solutions might impact their own carbon footprints. Financial services providers might also struggle to determine if a supplier qualifies for sustainable financing mechanisms like green bonds if they use different methodologies, potentially hurting suppliers' ability to access low-cost financing.

For example, many common standards do not provide visibility into upstream emissions at the product level for materials like steel and aluminium.[159] In the burgeoning carbon removal sector, measurement, reporting and verification (MRV) standards are still being developed for different removal and sequestration methods. The lack of such standards poses a major challenge for the entire sector and has undermined trust in the fledgling voluntary markets for carbon removal credits.[160]

Emerging global standards

Fortunately, standards tailored to these sectors are starting to emerge. Some examples include the following:

- Responsible Steel™ International Standards provides an ESG assessment framework for steel production sites and was updated in late 2022 to include GHG emissions.[161]
- The International Aluminium Institute has developed a methodology for quantifying life-cycle emissions for aluminium products.[162]
- CORSIA, the carbon offsetting and reduction scheme for international aviation, is the one standard for a heavy-emitting sector that has achieved broad adoption. Designed for measuring and offsetting emissions from international flights, CORSIA provides flexibility with multiple approved carbon accounting methodologies and enjoys government support across much of the world.[163] However, even in aviation, regional differences in GHG measurement may exist based on factors such as varying environmental policies or technology readiness.

Role of suppliers

It will take time for other standards to gain similar acceptance, but suppliers can help accelerate progress. As drivers of innovation in decarbonization, suppliers have unique insight into how such standards might promote or hinder further innovation and market adoption. They should proactively engage with industry consortiums and international bodies and boldly voice their support for preferred standards and how to improve upon them.

> **Suppliers should proactively engage with industry consortiums and international bodies and boldly voice their support for preferred standards and how to improve upon them.**

8.2 Availability and cost of inputs

Another major challenge suppliers face in some cases is limited availability of inputs to their solutions. This poses a significant challenge to their ability to scale-up and may cause buyers to question their near- and long-term viability.

Many solutions across heavy-emitting sectors, for instance, rely on renewable energy to help power operations and maximize their emissions impact. Technologies dependent on renewables include direct air capture, electrified cement kilns or steel blast furnaces, electrolysers for green hydrogen, and power-to-liquid for SAF. However, despite great progress, growth in renewables and other low-carbon energy sources is still slower than required for net-zero, hampered by permitting and supply chain bottlenecks.[164] Further expansion is needed to kickstart growth for suppliers of these solutions.

Input constraints

Beyond energy, other technologies may face constraints around material inputs. For example:

- Burning plastic waste, instead of fossil fuels, to fire cement kilns is becoming increasingly common.[165] However, it requires mature local plastic waste management networks to ensure supply.
- Alternative cement chemistries that replace ordinary Portland cement with less carbon-intensive binding agents might have availability constraints. Alkali-activated binders, for instance, are not available in sufficient quantities in certain regions, while magnesium oxide-based binders rely on production processes that remain unproven at scale.[166]
- The aviation and shipping industries are exploring the use of biomass and hydrogen for low-carbon fuels. However, the availability of biomass could become limited due to land use constraints, while there is likely to be competition for hydrogen between industry sectors.

Competition drives up costs

Certain inputs may face cost challenges due to high demand, threatening suppliers' cost competitiveness. Some examples include the following:

- Alternative cement chemistries, such as Belite-Ye'elimite-Ferrite (BYF) cement, include aluminium as a critical ingredient – however, competition for aluminium from other sectors, such as chemicals and consumer goods, could drive up costs.

- In trucking and aviation, concerns over lithium supply could drive up long-term costs for battery makers.[167]

- Low-carbon hydrogen will be an important input for many low-carbon fuels and manufacturing processes in steel, aluminium, trucking, shipping and aviation. All of these sectors competing with each other could drive up costs until supply scales-up to meet demand.

- New supply chains for biofuels are being established around the world, with critical crops and land also showing cross-sectoral competition where crop-based fuels are allowed by regulation.

The ability to access required inputs at scale and cost is already influencing where suppliers site production facilities. Direct air capture companies, for example, are targeting locations with abundant renewable energy potential to meet their energy demands.[168]

Suppliers should pursue partnerships

However, suppliers should take the opportunity to collaborate with others to expand access to inputs and overcome bottlenecks. For instance, suppliers could partner with innovators working to increase the supply of much needed materials. New direct lithium extraction (DLE) techniques, for example, can boost lithium recovery from production sites by 40% or more.[169] Battery makers can contract with lithium producers exploring DLE to tap into greater supply.

Suppliers could partner with others up and down their value chains to share costs of inputs, for example by forming an industrial hub with shared onsite renewables and green hydrogen production.

Suppliers can also engage with government and finance stakeholders to help shape policies and green finance solutions to open up access to critical inputs. These organizations often have their own net-zero targets for their jurisdictions and investment portfolios. Suppliers can help them achieve progress on these goals while improving the cost-competitiveness of their solutions by voicing their needs for crucial inputs and working together to overcome supply challenges.

8.3 Buyers' risk aversion and unfamiliarity with decarbonized solutions

Risk aversion

As well as upstream risks, suppliers also face significant challenges downstream. Many struggle to find willing buyers for solutions that have yet to be proven at scale. This is evident in the market for low-carbon hydrogen, where only a small proportion of the capacity planned for 2030 has offtake agreements in place.[170] Potential buyers are wary of risks related to uncertainties over future demand, regulation, technology, development of supporting infrastructure and collaboration between stakeholders.[171]

Lack of tools to value decarbonization

In addition to risk aversion, many buyers are often unsure how to value decarbonization solutions. Most have net-zero targets and some may be willing to pay a green premium. But few have the tools, expertise and procurement frameworks to determine *how much* of a green premium they would pay for a specific solution, whether that premium is cost-driven or demand-driven and the impact of price on consumers, for example when it comes to airlines. Most companies do not have an internal carbon price,[172] making it challenging to quantify the value of any carbon emissions reductions. This leaves procurement teams ill-equipped to engage in meaningful conversations with suppliers, let alone enter long-term commercial agreements.

> **Few buyers have the tools, expertise and procurement frameworks to determine how much of a green premium they would pay for a specific solution.**

Buyers hesitating to commit to long-term offtake

Without long-term offtake agreements from willing buyers, suppliers may struggle to prove the commercial viability of their products. This can make investors and financiers less willing to back them. H_2 Green Steel stands out as an exception, as the company was able to secure billions from more than 20 major lenders and commercial banks for its flagship factory in Sweden.[173] Securing five- to seven-year offtake agreements for more than half of its initial annual production volume helped it earn the vote of confidence from financiers.[174]

To score similar successes, suppliers should utilize innovative contracting mechanisms to share or mitigate risk as part of offtake agreements. This should help allay buyers' hesitation over uncertainties around future market development. In the case of low-carbon hydrogen, for example, "take or pay" agreements could help share risks while guaranteeing future payment schedules and cash flows. These agreements involve buyers paying upfront for a pre-determined amount of hydrogen, while allowing them to choose not to accept delivery if they do not need it, so they need not worry about paying for storage of excess hydrogen. The contracts for difference (CfD) mechanism is another way to help buyers guard against price hikes resulting from supply or demand shocks. Buyers could also explore "hydrogen-as-a-service" models to engage suppliers long-term to provide hydrogen transport and storage as well as supply.

Help buyers value long-term benefits and impacts of decarbonized technologies

Before getting to the contract stage, suppliers should go above and beyond to educate potential buyers in how to value their solutions. The discussion should not be limited to upfront costs and emissions reductions. Instead, it requires a holistic assessment of economic and climate impact over time.

That means more than just placing a dollar value on carbon emissions. Suppliers should help procurement teams understand the economics of their solutions, which may differ substantially compared to conventional alternatives. Low-carbon materials and fuels may have higher upfront costs, but, in some cases, could offer long-term cost benefits thanks to greater efficiency or performance. For example, geopolymer-based concrete has been shown to offer greater compressive strength in some cases, reducing long-term building maintenance costs.[175] Some bio-cement alternatives feature lower thermal conductivity than ordinary Portland cement, which can lower emissions and energy costs related to heating and cooling buildings.[176] In transportation, some estimates suggest that battery-electric trucks already offer lower total cost of ownership for urban and regional trucking fleets than diesel trucks.[177]

Suppliers should be ready to walk buyers through the impacts of such performance and efficiency benefits and showcase results from real-world deployments wherever possible. And they should be prepared to help buyers understand how to value these benefits and climate impacts using emerging frameworks in their respective sectors and tools like carbon pricing schemes in relevant jurisdictions.

9 Conclusion

Innovative suppliers, both incumbents and new entrants, play a critical role in decarbonizing heavy-emitting transportation and industry sectors.

This report's exploration of opportunities and challenges for suppliers in heavy-emitting sectors underscores the importance of embracing innovative strategies and fostering robust collaborations across industries to address the pressing challenges of decarbonization.

Embracing sustainability and innovation

To achieve the world's decarbonization goals, breakthrough technologies must be researched, developed and commercialized by suppliers at a rapid pace. Relying on technologies available today will not be sufficient and all stakeholders along the value chain need to embrace sustainability and innovation. The role of technologies, such as electrochemistry applications for cement and steel, illustrates the potential for innovative solutions to environmental challenges, showcasing how traditional and new industries can converge towards sustainability goals.

Strengthening collaborative networks

One of the critical takeaways from the report's findings is the necessity of strengthening collaborative networks among suppliers, businesses and regulatory bodies. By enhancing communication and cooperation, stakeholders can better navigate the complexities of the global supply chain, mitigate risks and capitalize on opportunities for growth and sustainability. The insights derived from this document should serve as a catalyst for continued dialogue and partnership between all involved parties.

Future directions

Looking forward, it is crucial for businesses and suppliers not only to adapt to changing regulations and market conditions but also to shape the future through proactive engagement and leadership in sustainable practices. The decisions made today will impact decades of decarbonization. Therefore, a forward-thinking approach, coupled with a commitment to sustainability, will be essential for enduring success and environmental stewardship.

Call to action

In light of these findings, the First Movers Coalition calls upon all stakeholders to reflect on the insights shared in this document and to engage in a concerted effort to advance sustainability. Whether through adopting new technologies, enhancing supplier relationships, or participating in global forums, the path forward should be one of collaboration and innovation.

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Endnotes

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FMC allows book and claim when available for cargo owners as long as it occurs on the same carrier. FMC also encourages the continued development of a book and claim framework for the transition period.

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- The volume of high-quality biochar (as per conditions specified by FMC) in any portfolio that counts towards meeting the FMC commitment will be limited to the larger of: a) 20% of the CDR volume commitment by tonnes of CO_2, or b) $5 million worth.
- Biochar production must use pyrolysis temperatures of >550ºC and result in an H:C molar ratio of <0.4. This is to ensure that biochar achieves the high sustainability goal required by FMC, while recognizing that the science is still imperfect.
- Biochar must be certified by a credible third party to ensure that it meets the principles of MRV, sustainable biomass, additionality and high-quality biochar production standards.
- The CDR commitment conditions are currently being revised and will be updated by the end of 2024.

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