First Movers Coalition

WORLD ECONOMIC FORUM

In collaboration with Deloitte

Turning Challenge into Opportunity: Supplier Voices from Heavy-Emitting Sectors

INSIGHT REPORT

DECEMBER 2025

Images: Getty Images, Unsplash

Contents

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Foreword

Dilip Krishna
US Consulting Managing Director, Deloitte

Noam Boussidan
Programme Head, First Movers Coalition, World Economic Forum

Catalysing the widespread adoption of low-carbon technologies and products today demands more than early market enthusiasm – it requires identifying and addressing barriers that hinder scale, streamlining collaboration across sectoral frontlines and thoughtfully addressing the operating realities that suppliers confront. Since its inception, the World Economic Forum's First Movers Coalition (FMC), through its First Suppliers Hub (FSH), has worked to advance the market by illuminating supply-side perspectives and fostering direct engagement between innovative suppliers and critical decision-makers within heavy-emitting industries. As market architecture evolves, one clear lesson stands out: the journey from demonstration to commercial maturity is shaped as much by structural headwinds as it is by ambition or capital.

This report, created in partnership with Deloitte Consulting, builds on last year's *High-Emitting Sectors: Challenges and Opportunities for Low-Carbon Suppliers*. It moves beyond foundational analysis to examine supplier perspectives more deeply, at a time when urgency and complexity are becoming more acute. Drawing on fresh interviews and operational insights from project developers, technology pioneers and early producers across the aluminium, aviation, carbon dioxide removal, cement and concrete, shipping, steel and trucking sectors, we delve into the specific friction points slowing supplier momentum. In doing so, we underscore that while sectoral dynamics may vary, entrenched challenges prove to be obstacles across the value chain and require unified interventions.

Suppliers serve not merely as implementers in this ecosystem, but as trailblazers whose capacity to innovate, attract investment and reliably deliver is pivotal to achieving net-zero ambitions. By centring on their perspectives and experiences, this report aims to help policy-makers, procurement leaders, financiers and R&D partners find the most appropriate levers – be they more consistent regulatory signals, robust offtake frameworks or targeted support mechanisms – to foster thriving early and scaled-up markets.

By bringing to light candid, practical viewpoints from the FMC and FSH communities, this report extends our prior work, offering supplier-led insights to accelerate progress in some of the hardest-to-abate industrial sectors. We trust that these findings will help clarify where coordinated, pragmatic action can tip the scales, ensuring that breakthrough solutions move decisively from innovation to global implementation to advance decarbonization goals.

Executive summary

This report connects on-the-ground experience with pragmatic solutions, offering insights valuable to producers, but equally relevant to offtakers, investors and policy-makers.

The accounts of efforts to decarbonize heavy industry are often told from the demand side – through buyers, regulators and financiers. Yet the pace and practicality of this transition ultimately hinge on those building and supplying the low-carbon solutions themselves. This report seeks to elevate the voice of the low-carbon supplier in high-emitting sectors – the producers, project developers and innovators working within the hardest-to-abate sectors that underpin the world's mobility and materials systems.

Drawing on extensive, structured interviews across the industries that comprise the First Movers Coalition (FMC) and First Suppliers Hub (FSH) – aviation, aluminium, carbon dioxide removal (CDR), cement and concrete, shipping, steel and trucking – this report captures candid supplier perspectives that identify where progress is tangible, where challenges persist and how many suppliers view the path forward. Each sector analysis delves into the most consistently raised and pressing issues identified through these conversations, grounding the analysis in suppliers' experiences rather than abstract targets.

The report's perspective is deliberately specific: that of the supplier navigating early commercial deployment and scaling-up difficulties following final investment decision (FID), amid uncertain policy, financing and infrastructure environments. It is also inherently relational – suppliers operate within ecosystems of buyers, regulators, financiers and technology partners whose direct objectives may diverge but which require collaboration to achieve. By viewing systemic challenges through this lens, the report uncovers where these interdependencies can accelerate or inhibit scale and how coordination could help close the gap between ambition and adoption.

To enhance the clarity of the analysis, this report groups the seven hard-to-abate sectors into two broad families:

- Mobility sectors (aviation, shipping, trucking)
- Materials sectors (aluminium, cement and concrete, steel, CDR)

In this report, CDR is categorized within the materials sectors. However, unlike other core materials sectors, CDR does not manufacture physical goods for end-consumption. This distinction is important to ensure accurate sector analysis and meaningful comparisons within the report.

Each sector analysis focuses on a particular, nuanced systemic challenge, highlighted by suppliers:

- **Aluminium** – Powering low carbon aluminium: achieving parity with traditional supply.
- **Aviation** – Scaling-up SAF: infrastructure integration, bottlenecks and future readiness.
- **Carbon dioxide removal** – Creating a market structure to commercialize proven technologies.
- **Cement and concrete** – Reimagining procurement practices to reward low-carbon innovation.
- **Shipping** – The critical need for robust offtake in low-carbon fuel supply.
- **Steel** – Commercializing pioneering technologies in an evolving policy landscape.
- **Trucking** – Electrification realities: scaling-up, barriers and the road to decarbonization.

The report also highlights structural challenges that cut across the broad sectors of Mobility and Materials, respectively. In the Mobility sectors, these include specific infrastructure premises that govern growth and financing mechanisms struggling to keep pace with technological maturity. In the Materials sectors, these include weak and volatile market signals, lack of unified standards and accounting, and project financing. Persistent inconsistencies and variations in policies continue to challenge both sector groupings. The cross-sector synthesis explores how these shared themes converge and where collaborative approaches could unlock scale. While sector-specific in scope, this report demonstrates that low-carbon suppliers across industries face common challenges: the need for durable demand signals, investable infrastructure, access to capital and consistent public policy. Their experiences, captured here in their own terms, help form a practical blueprint for the next phase of industrial decarbonization: one led not only by commitments, but by suppliers making those commitments real.

1 Mobility sectors

1.1 Aviation – scaling-up SAF: infrastructure integration, bottlenecks and future readiness

Aviation contributes 2.5% of global CO_2e emissions.[1]

<0.1% proportion of SAF in global jet fuel supply today.

Introduction

Many commercial aviation stakeholders face an urgent dual market directive: meet a projected doubling of passenger demand by 2050 while delivering on net-zero commitments. Sustainable aviation fuel (SAF) is widely viewed as one of the largest decarbonization levers currently available to aviation. SAF is able to significantly cut lifecycle emissions compared with conventional Jet-A kerosene. Yet today, SAF represents less than 0.1% of global jet fuel supply.[2] Several SAF production facilities have reached final investment decision (FID) and are now progressing towards construction or are already producing sustainable fuels.

However, a number of low-carbon fuel projects across different regions were paused or cancelled in 2025.[3,4] These start/stop developments underscore the complexities of scaling-up emerging technologies while maintaining commercial viability. Bridging that gap from kilotonne-scale pilots to multi-megatonne production hinges not only on breakthrough conversion technologies but, critically, on the infrastructure ecosystem that moves feedstock to refineries, blends SAF with conventional fuel, certifies quality, stores it safely and delivers it to aircraft wings. Yet producers and buyers face challenges across the value chain – both in the logistics of integrating SAF from gate to wing and in understanding how renewable fuel production can be optimally integrated within existing fuel systems.

While the Forum's February 2025 report, *Financing Sustainable Aviation Fuels: Case Studies and Implications for Investment*, offers a comprehensive analysis of the production challenges faced by suppliers, this chapter examines the distinct obstacles present at the next stages of the value chain – specifically, the complexities involved in scaling-up SAF delivery to aircraft centres, including both upstream and downstream operations.[5]

Upstream, feedstock security and availability can affect the techno-economic feasibility of SAF production. Downstream, an increasing number of SAF project developers are facing a range of challenges when accessing both off-airport blending and distribution networks and on-airport storage, quality control and delivery systems. This results in one clear imperative: the need to unlock access to infrastructure.

> **Scaling high-integrity SAF production depends on overcoming barriers related to SAF blending, storage and transport infrastructure and doing so in a way that complies with safety and product quality specifications. Restricted access to these critical links in the supply chain limits competition and increases costs for delivered SAF.**
>
> Dan Johnson, Managing Director, World Energy

The complex realities faced by prospective SAF producers have often been overlooked, as market conversations tend to focus on SAF availability, price and policy rather than pragmatic barriers preventing the deployment of SAF's full potential. Following critical conversations with leading SAF fuel producers, this section aims to amplify their voices and perspectives and highlight their pivotal role in scaling-up supply. The next section explores the infrastructure and market conditions necessary for their success, with an overview of the upstream SAF supply chain and a more detailed analysis of the downstream supply chain.

Insights from off-airport SAF value chain – upstream

➔ **Insight:** Infrastructure, feedstock production and collection

Before SAF reaches an airport, a complex web of supply chain activities determines its availability, cost and quality. The journey begins upstream, at feedstock aggregation and conversion.

What we heard

SAF can be produced from multiple production pathways (Appendix: TRL Tables). Hence SAF plants rely on the collection of a wide range of sustainable feedstocks, including crops, agricultural residues, tallow, used cooking oils and municipal solid waste. On top of sustainability challenges associated with certain feedstocks (not covered by this report), some, but not all, industry stakeholders expect future supply chain constraints due to geographical location and dispersion, alongside seasonal variability and trade dynamics.

In addition, when collected, each feedstock presents its own challenges. For instance, biomass is often bulky, heterogeneous and more difficult to process and store, while municipal solid waste is subject to regulatory requirements that are often set at a municipal level.

Why it matters

Several reports are confident in the availability of a wide range of feedstocks that can be unlocked to produce SAF, such as a recent paper from the International Air Transport Association (IATA). However, real world feedstock availability challenges as well as processing can significantly affect both the commercial and technical feasibility of SAF production.[6]

To secure investment, producers made clear that SAF facilities need reliable, long-term feedstock supply – since investors are concerned about the prospect of short-term market disruptions and alternative use of bio-resources resulting in competition across sectors, short-term price hikes and uncertain long-term supply. Even when feedstocks are secured, their heterogeneity can poison catalysts, reduce process efficiency and ultimately lead to project failure.

Smart solutions

The continuation and expansion of scientific studies and inventories on existing and potential feedstock availability across regions can deepen the sector's understanding of product potential and feasibility of conversion into SAF. Alongside continuous R&D, this can help identify new pools of feedstocks that can be used for future SAF production, subject to fuel quality and regulatory approval, as well as assisting with sustainability certification.

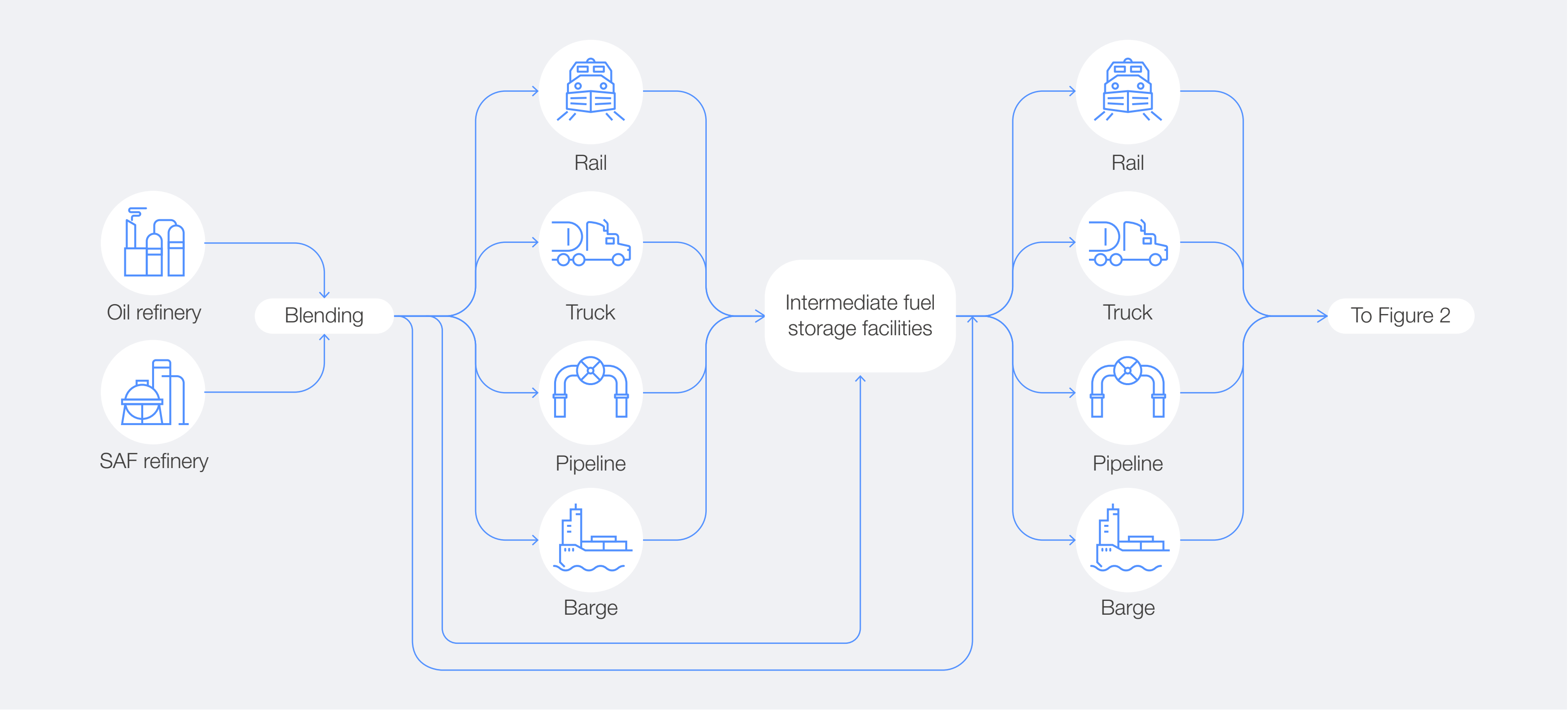
Some of these feedstock resources will increasingly be sought after by other sectors too – whether to produce biofuels for shipping and road transport or for other hard-to-decarbonize sectors – highlighting the need for a cross-industry discussion on sectoral feedstock allocation and prioritization that could lead to the formation of policy principles governing the use of finite resources.

To manage feedstock variability, processing and conversion, greater knowledge-sharing of lessons learned from existing projects is needed (including failed projects), while alternative feedstock procurement processes need exploring, such as tolling models, that could increase focus on players well-suited to managing feedstock supply risks while reducing price impacts.

Insights from off-airport SAF value chain – downstream

Once SAF is produced, it needs to be blended with conventional jet fuel and delivered to airports, often over long distances, for uplift in aircraft. The length and complexity of the value chain can expose producers and suppliers to fragmented logistics, limited pipeline access and evolving regulatory standards – ultimately with an impact on SAF quality, delivery and price. These off-airport challenges can introduce significant friction and uncertainty. Addressing these barriers is essential for ensuring that sustainable fuel can reliably and efficiently make its way to the airport gate, where additional infrastructure hurdles often await. The focus of this section is on downstream infrastructure taking SAF from its production site to its usage point.

FIGURE 1 **Off-airport SAF supply chain mapping**



➔ **Insight:** Blending points and quality control

What we heard

Blending SAF with conventional jet fuel, required by technical fuel specifications, can occur at multiple points, usually before entering the airport environment. Blending needs to meet specific quality assurance requirements and recommendations, such as those set out by the Energy Institute's EI 1533 standard.[7] These include directions on the inclusion of additives, issuance of refinery certificates of quality, sampling, settling time and product release, among other areas, which all require dedicated infrastructure, capabilities and skills.

Often it is necessary to have additional blending terminals outside of refineries to provide greater flexibility to fuel systems and improve logistics and resilience. However, blending at these sites also needs to comply with the same quality and safety regulations prescribed by fuel specifications and quality guidelines.

Why it matters

SAF producers/suppliers and jet fuel producers/suppliers may not be the same entity, hence multiple parties could be involved in this necessary blending step. Blending points and storage facilities face challenges accommodating the infrastructure needs of SAF producers, given the high cost of SAF storage in incumbent infrastructure. In addition, SAF quality assurance is complex, as a single off-spec batch can ground flights. It is preferable if blending takes place as close as possible to the neat SAF production point or at refineries; but not all SAF producers can accommodate that, or may not be in a position to own their own jet fuel production and blending infrastructure, along with associated capabilities.

Smart solutions

Collaboration among key ecosystem members, including policy-makers, fuel producers and airlines, is needed to discuss financial support and incentives (e.g. infrastructure grants) that make dedicated SAF storage and blending investments more viable for blending and storage providers.

➔ **Insight:** Financial and physical infrastructure access

What we heard

Access to pipelines and the selection of SAF/jet fuel suppliers by airports are critical considerations, in particular to guarantee security of supply. While this varies regionally, infrastructure access at present is often concentrated among major players that may own or lease pipelines and associated fuel delivery infrastructure. This can limit physical access to airport supply for newcomers or even for larger suppliers when looking at new regions. In turn, this potentially leads to increased SAF prices, even if physical access is possible but financial restrictions, such as fees, are in place. Some markets in particular, such as the UK or France, have highly complex-to-access logistics systems.

Why it matters

Local infrastructure access rules determine whether blended SAF can be transported through pipelines and to airports. Restricted physical access to infrastructure can reduce competition and discourage innovation, potentially prompting new SAF project developers to sell to incumbent suppliers instead of directly to airlines.

Access to infrastructure may be possible but it could still add costs to jet fuel delivery that need to be factored into offtake contracts with airlines. Even if this were feasible, producers or suppliers will need to reassure airlines of their security of supply – something that, alongside price, can influence airlines' buying decisions.

All these factors can restrict new producers' ability to secure offtake agreements and limit business model flexibility or efficiencies. As a result, market diversity and the pace of SAF scale-up are both constrained, slowing progress towards price parity and decarbonization targets and requiring the involvement of multiple players along the downstream supply chain, adding to both complexity and costs.

Smart solutions

To address limited SAF access to existing infrastructure, countries and regions alike can explore more open logistics models, as long as product quality and security of supply are guaranteed. Spain, for example, has established a neutral fuel infrastructure operator that ensures non-discriminatory access to pipelines, storage and hydrant systems for fuel suppliers, including SAF producers. By integrating shared blending facilities, centralized quality control and digital traceability, the system reduces technical and logistical barriers that can curtail SAF blending and delivery to airports.

Some airports already have open access to fuel infrastructure, promoting competition and lower prices. For example, John F. Kennedy International Airport, which serves New York City, owns its fuel farm and provides open access to any supplier and supplier type.[8] Meanwhile, Bangkok International Airport works with a collaborating entity that allows open access to the fuel farm, enabling supplier competition.[9] These airports enable new producers to rely on existing infrastructure to deliver their SAF without additional costs. Even so, their SAF still needs to be blended to specification to access this infrastructure in the first place and this may require other parties to be involved or other challenges to be addressed, as explained below.

➔ **Insight:** Blending ratios

What we heard

While higher blend ratios are technically feasible, with fuel specifications allowing for selected SAF pathways up to 50% blends, market demand for higher blends is affected by both technical factors and commercial parameters. Blends therefore need to be maintained within the range of fuel specifications. Technical factors such as flash point, lubricity and thermal stability impact blend feasibility and, more widely, the technical specifications of the blend do not necessarily change linearly with the ratio of SAF and jet fuel, requiring a clear understanding of the parameters of the jet fuel the SAF is being blended into.

At the same time, cost and procurement processes may not be typically designed for blends above ~30%. While some scope 3 buyers may be interested in higher blends that could result in lower carbon abatement costs, on a volumetric base, greater SAF blends can cost more.

Why it matters

Under-utilization of blend potential leaves decarbonization tonnes "on the table", slowing progress towards net-zero commitments. By not enabling technically feasible higher SAF blends – through aligned standards, faster certification and fit-for-purpose procurement – airlines and buyers miss low-cost abatement opportunities and delay growth pathways that could unlock deeper emissions reductions. Addressing these constraints can translate technical feasibility into operational reality, catalysing the market confidence, investment and innovation needed to move beyond current blending limitations.

Smart solutions

To unlock the full decarbonization potential of higher SAF blend ratios, a coordinated policy approach is essential. The prospect of regulatory harmonization of blending quality standards may allow the relaxation of certain specification parameters to provide greater flexibility in blending, as long as operational safety and product quality are maintained.

Additionally, it is necessary to promote new production pathways or reassess those already approved to increase current blending ratios where allowed. Government policy should support R&D into advanced SAF pathways and innovative conversion technologies, building on the work of existing SAF clearing houses and industry expertise. For example, in 2025 the UK approved fuel specifications that increase blending rates from 5% to 30% for co-processing SAF technology (processing renewable or waste-derived feedstocks together with conventional petroleum streams), which can now be blended with jet fuel.[10]

As the process to secure fuel certification is both mandatory and laborious (it can take years), cross-industry collaboration and rapid approvals are needed to accelerate the development, testing and use of novel SAF production pathways that can achieve greater blend rates. In addition, market-driven mechanisms such as book-and-claim can facilitate market liquidity and flexibility in meeting decarbonization targets, while reducing the cost burden on buyers.[11] If book-and-claim were to allow the vast majority of SAF to be used in specific locations, this would indirectly stimulate the collaboration, technological innovation and infrastructure investment needed to move beyond current blending limitations.

Insight: Storage requirements

What we heard

Effective blending requires multiple storage tanks for mixing and quality testing, but producers only deliver small batches of SAF periodically.

Why it matters

Segregated SAF storage is logistically complex and costly but necessary. Currently, the size of fuel tanks exceeds the storage needed by SAF deliveries, forcing SAF producers to increase the unit cost to cover unneeded storage. In turn, SAF storage and delivery become inconsistent and expensive.

Smart solutions

The development of modular, scalable storage units with a tailored approach towards accommodating smaller SAF batches and varying pathways (e.g. HEFA vs. PtL) would enable flexible infrastructure upgrades without full-scale tank conversions. Similar to the potential action noted above to address challenges in blending ratios, coordinated policy approaches are needed between regulatory bodies and ecosystem members to incentivize and catalyse modular storage R&D and uptake until technical and economic viability are achieved.

Insight: Traceability and fuel delivery points

What we heard

Digitalization could streamline chain-of-custody auditing and enable robust book-and-claim systems. This can bring benefits to both physical traceability of SAF, where physically possible and required by different standards and traceability of the credentials associated with the original neat SAF when fuel is blended and moved along the supply chain, especially when book-and-claim systems are introduced.

Despite its increasing maturity, especially compared to other sectors, the existing landscape of SAF registries and tracking mechanisms can suffer from fragmented information across multiple parties and limited interoperability between different platforms. While the framework defined by the Greenhouse Gas Protocol allows for co-claiming emissions savings from multiple parties, diverging business models and approaches to double counting and certificate allocation can also create uncertainty, which may undermine trust in SAF claims, increase administrative burdens and reduce private sector involvement, ultimately slowing down SAF adoption and investment.[12,13]

In addition, physical supply of SAF may be mandated in specific airports, resulting (in some cases) in higher logistics, financial and efficiency challenges than if this SAF were delivered to a different location.

Why it matters

Digitalization and book-and-claim systems can facilitate effective SAF logistics and overcome the physical and environmental complexities of SAF distribution. They can facilitate the commercialization of SAF by spreading the price premium of the fuel across a higher number of players, while supporting logistics efficiency in fuel blending and delivery.

Smart solutions

It is important to continue testing and standardizing digital solutions that can increase transparency of SAF supply chains, thereby ensuring traceability and interoperability of existing schemes. More integrated guidelines are needed to standardize measurement, reporting and verification (MRV) methodologies for book-and-claim throughout the SAF supply chain, from feedstock to final use, to strengthen the accurate transfer of the environmental attributes of SAF along the supply chain.

Stakeholders can engage with the Science Based Targets initiative (SBTi), Greenhouse Gas Protocol and other bodies to support the recognition of high-integrity book-and-claim systems as a legitimate tool that corporates can deploy to reduce their emissions. They can also engage with governments to understand:

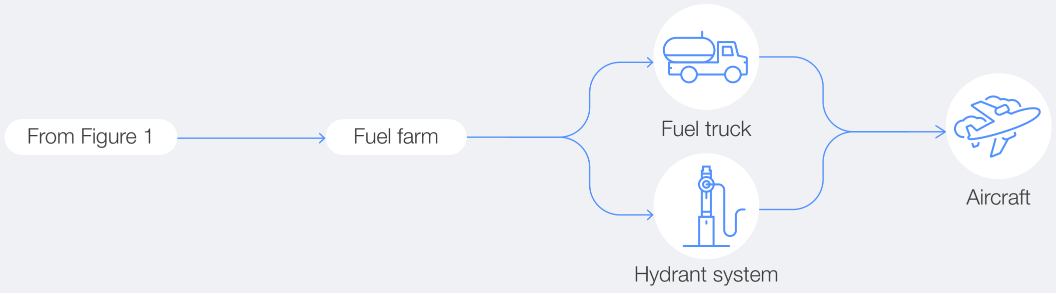
- Potential benefits of book-and-claim in reaching SAF targets.
- Implications of airport-specific supply requirements on logistics.
- Potential benefits of book-and-claim.
- Lessons learned from more flexible mandates. For example, Brazil and the United Kingdom introduced SAF mandates based on the progressive reduction of the carbon emission intensity of the fuel rather than on specific volumetric targets and supply points.

Insights from on-airport SAF value chain

Once SAF enters the airport environment, a distinct set of operational and logistical complexities comes into play. Airports and airlines have legacy systems built for conventional Jet-A and thus need to change these to handle SAF's unique properties, blending protocols and certification needs directly on-site. For this reason, blending typically or often by law, takes place off-airport.

However, there are signs the market is making pragmatic developments, such as the opening of a dedicated SAF blending terminal in Toowoomba Wellcamp Airport, Queensland, Australia. Nevertheless on-airport challenges persist, ranging from the lack of segregated fuel farm storage tanks to robust traceability and real-time quality controls. These are pivotal in ensuring that SAF not only arrives at the wing but does so safely, efficiently, in the right volumes and at the right time, in compliance with stringent industry standards. Overcoming these hurdles is critical for enabling seamless integration of SAF into daily flight operations and unlocking its full decarbonization potential.

FIGURE 2 **On-airport SAF supply chain mapping**



59%
of the largest airports globally surveyed by IATA have some form of restricted access to fuel infrastructure.

➔ **Insight:** Infrastructure ownership

What we heard

Fuel infrastructure at airports is generally managed by consortia, third parties or oil companies. Regional models differ across the regions. While in Europe and Asia-Pacific, energy and oil producers typically own the infrastructure, in the US the airlines have more decision-making power. Mapping these ownership models is crucial to understanding how they influence airport-level decisions on SAF supply. Additional clarity on regional ownership is needed, given its effect on airports' decisions on fuel supply handling. IATA's survey of 123 of the largest airports globally, covering 48% of global fuel uplift, revealed that 59% have some form of restricted access to fuel infrastructure, due to ownership by a single fuel supplier or a limited group of fuel suppliers.[14]

Why it matters

Infrastructure ownership shapes how quickly and efficiently SAF can be integrated into daily airport operations, as well as who controls fuel logistics and quality assurance. When infrastructure is managed by a limited group, airports and airlines may have less flexibility to accommodate new SAF suppliers or innovative blending solutions. This can undermine airlines' ability to execute direct offtake agreements, complicate operational planning and slow the overall transition to SAF at the airport gate.

Smart solutions

Airports and regulators may assess whether current ownership structures present possible friction to SAF market entry and direct access for SAF suppliers to existing fuel infrastructure. Where restrictive ownership is identified, lessons can be learnt from airports that have successfully opened infrastructure to greater competition. For example, Amsterdam Airport Schiphol (Netherlands), Los Angeles International Airport (US), John F. Kennedy Airport (US) and Suvarnabhumi Airport (Thailand) have adopted collaborative frameworks or revised access policies to enable new SAF suppliers to participate directly.[15] Mapping regional ownership models and sharing best practice, both for airports as well as wider supply chains, will help inform targeted interventions that foster a more open, competitive and innovation-friendly SAF infrastructure environment.

➔ **Insight:** Segregated delivery of SAF to potentially mitigate non-CO_2 impacts of aviation

What we heard

Delivering SAF to specific flights with higher contrail formation potential could conceivably help reduce non-CO_2 emissions, but current infrastructure at airports may not be suitable for such operational changes. This may require segregated SAF delivery or even onsite blending. In turn, this would entail duplication of infrastructure as well as an additional feasibility and operational impact assessment – with the necessary skills and risk management required alongside. Airports interested in this specific solution may need to explore alternatives such as adjusting gate assignments for flights that are likely to produce contrails.

Why it matters

Failure to do this risks missing opportunities to unlock potential sustainability benefits through contrail reduction.

Smart solutions

Directing SAF supplies to mitigate the non-CO_2 impacts of aviation requires identifying and prioritizing locations for strategic deployment. To achieve this requires collaboration to understand which regions, airports or routes could benefit from dedicated SAF infrastructure or on-airport blending capabilities, compliant with fuel quality requirements, which could deliver the greatest environmental impacts.

Notwithstanding the uncertainties associated with contrail science, focusing trials and resources on these high-value opportunities can support scientific understanding while developing airport blending and storage best practice and ensuring that investments are targeted and effective, rather than requiring widespread, costly changes across all airports.

Pilot-dedicated and innovative fuelling logistics solutions, such as mobile SAF fuelling trucks or modular dispensing units that can deliver SAF directly to specific aircraft or gates, would minimize the need for extensive new infrastructure. Skills and risk management need developing to ensure quality risks can be managed if blending does not take place at refineries.

Optimized gate and flight assignments would streamline logistics and maximize climate impact, but this requires collaboration between airlines and airports to assign contrail-sensitive flights to gates where dedicated SAF delivery is operationally feasible.

Insights on emerging SAF business models and supply chain options

Building on the infrastructure challenges discussed in the off-airport and on-airport sections above, SAF producers are exploring a range of business models to bring SAF to market. The structure and dynamics of these models are shaped by the realities of supply chain access, operational risks and emerging market demands.

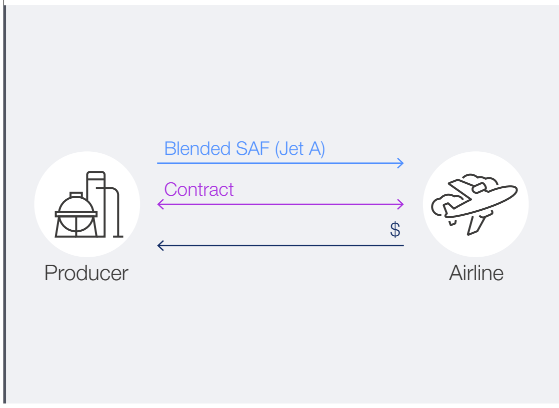
As the industry matures, producers must navigate established supply chain arrangements and innovative approaches. Each dimension offers distinct opportunities but also presents shortcomings, particularly from the producers' point of view. The following overview highlights six business model solutions across the two dimensions, along with some of the challenges associated with each model. Note: there are many potential supply chain combinations and regional variations – this overview does not aim to be comprehensive.[16]

Insight: More-established business models

MODEL A: Producer-managed blending and delivery

Solution: The producer blends neat SAF into jet fuel and delivers directly to the airline. The airline typically takes control at the airport fuel terminal or point of sale.

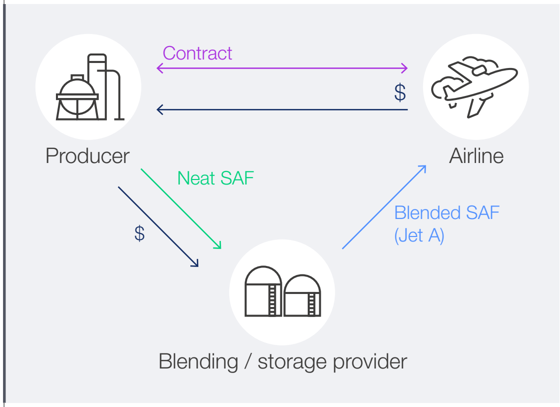
Challenge: New SAF producers may struggle to access blending and supply chain infrastructure, facing high entry barriers and logistical complexity.



MODEL B: Producer relies on third party or airline for storage/blending

Solution: The producer sells SAF to the airline but depends on a third party (or the airline itself) for storage and blending, with infrastructure access costs factored into the offtake agreement.

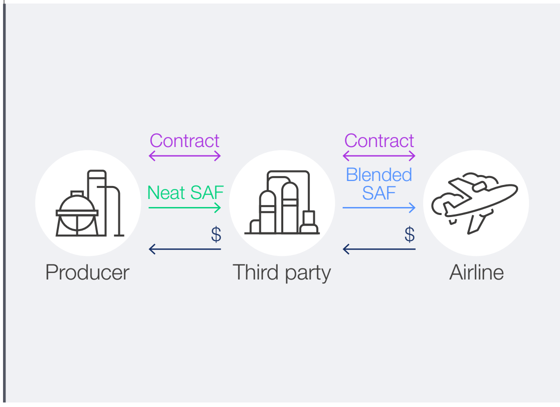
Challenge: Producers may face renegotiation of contracts and additional supply chain charges, reducing margins and complicating commercial relationships.



MODEL C: Producer sells to traders or third parties

Solution: The producer sells neat SAF or semi-finished products to a trader or third party (e.g. an incumbent integrated fuel supplier), who assumes control at a storage terminal, blending facility or port and markets/delivers to the airline.

Challenge: Producers risk sharing commercially sensitive information with competitors and may lose visibility or control over the end-user relationship.

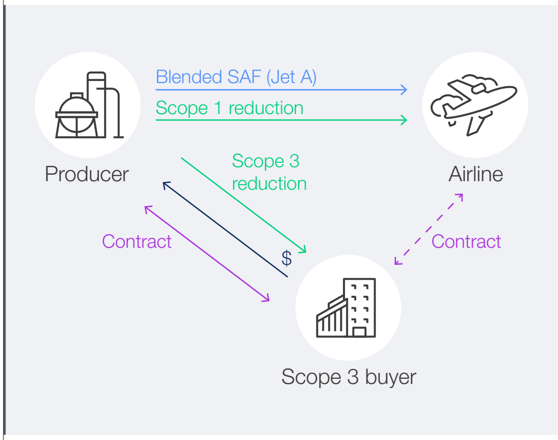


➔ **Insight:** Emerging or potential business models

MODEL D: Book-and-claim

Solution: The producer sells SAF to an airline while selling scope 3 certificates to third party buyers via the book-and-claim platform, spreading the cost of SAF over a larger pool of parties and contributing to market development.

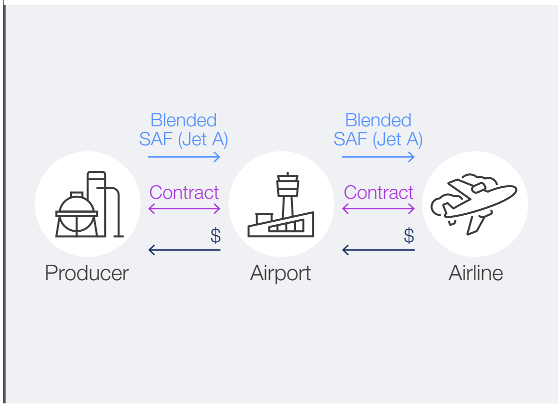
Challenge: The market for scope 3 buyers is currently limited and interoperability of registries is needed for scale and credibility. SAF would still need to be blended and delivered to a certain site, potentially via one of the previously identified business models, strengthening the need for traceability as the fuel and its environmental credentials are traded along the supply chain.



MODEL E: Direct sale to airports for blending and distribution

Solution: The producer sells SAF (to be blended off-airport) directly to an airport who then makes it available to airlines, if the airport manages refuelling operations.

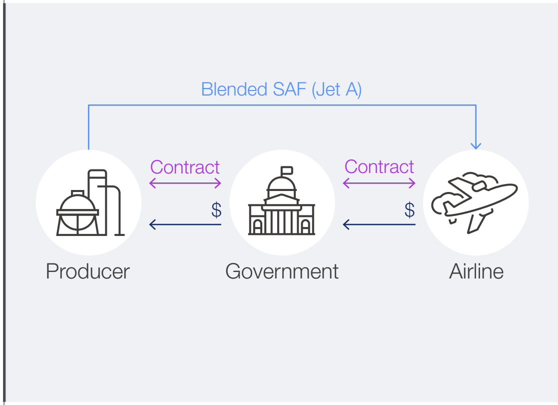
Challenge: Offtake risk shifts to airports, raising questions about contractual complexity, logistics and the relevance of this model in regions where airports do not control refuelling.



MODEL F: Sell to governments or intermediaries with long-term contracts

Solution: The producer sells SAF, under long-term contracts, to a government entity or intermediary which then resells to airlines.

Challenge: Producers may face competitive allocation processes (such as auctions) and operationalization challenges, including regulatory compliance and contract management.



Across all the business models outlined above, many SAF producers, particularly new market entrants, face challenges around infrastructure access and commercial complexity. While emerging business models such as book-and-claim and government procurement can help expand SAF supply, scaling-up these approaches will still require coordinated infrastructure development, expansion and traceability as SAF molecules move along the supply chain.

Conclusion

SAF infrastructure across the value chain is not merely a logistical challenge, it is a linchpin for realizing aviation's decarbonization ambitions. This analysis, grounded in the perspectives of SAF suppliers, reveals that unlocking the full potential of SAF can hinge on addressing critical bottlenecks in feedstock availability, collection and processing upstream, as well as blending, distribution, storage and on-airport operations downstream.

With the focus of this report primarily on downstream challenges, the potential actions across both off-airport and on-airport blending and infrastructure considerations outlined above offer some pragmatic steps that can support accelerating SAF adoption. These ideas share a common thread: they require careful experimentation, standardization and innovation across the aviation ecosystem that would greatly benefit from cross-sectoral collaboration and knowledge-sharing between all parties – producers, suppliers, traders, airports and governments.

1.2 Shipping – the critical need for robust offtake in low-carbon fuel supply

Shipping contributes

2%

of global CO$_2$e emissions.[17]

Introduction

With approximately 80-90% of global cargo transported by sea, and 99% of vessels currently operating on high-emission fuels, the maritime industry represents a critical frontier for decarbonization efforts.[18] Amid technical debates around fuel choice, vessel retrofits, emissions standards and certification, among others, the most prominent question suppliers voiced was: who will buy low-carbon fuel, at scale, for long enough and at a bankable price?

Offtake structures are the hinge on which first-of-a-kind projects turn – without credible demand signals, low-carbon fuel plants remain at risk of languishing in the pre-FID valley of death. As suppliers strive to scale up production of low-carbon fuels, such as green hydrogen, e-ammonia and e-methanol, offtake strategies have emerged as the cornerstone for both project bankability and sector-wide decarbonization.

Three framing perspectives from discussions with low-carbon fuel suppliers set the stage:

- **Scale mismatch is pervasive.** Project sizes range from pilots producing a few thousand tonnes to initiatives targeting over a million tonnes annually. Offtake commitments often do not align with project diversity, creating further market uncertainty.
- **Market mechanisms**, including contracts for difference and book-and-claim systems, are emerging and offer promise, but are not yet mature or widely adopted.
- **Policy support is vital.** Even optimistic buyers seldom sign long-term contracts at volumes or prices that satisfy project-finance lenders.

With these observations in mind, two interlocking insights surface:

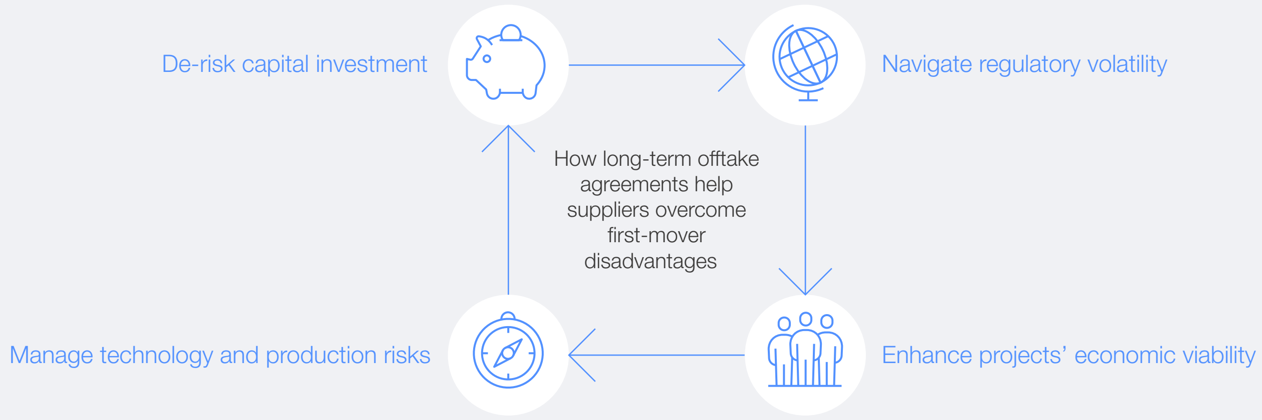
1. Long-term, risk-sharing offtake agreements form the backbone for scaling-up.
2. Flexible, aggregated demand models can overcome infrastructure and market fragmentation.

➔ **Insight:** Long-term, risk-sharing offtake agreements form the backbone for scaling-up

For low-carbon fuel suppliers in shipping, the ability to scale up is largely predicated on one thing: locking in long-term commitments from buyers willing to share risk. These offtake agreements are not merely supply contracts but financing backbones that can allow producers to reach FID and secure capital for new facilities. Without them, suppliers often face financial, regulatory and operational uncertainties that stall investment and keep innovative projects on the drawing board.

Four key "puzzle pieces" help illuminate why long-term, risk-sharing offtake agreements are crucial to help suppliers overcome first-mover disadvantages. Such agreements de-risk capital investment, while helping suppliers to navigate regulatory volatility, enhance the economic viability of their projects, and manage technology and production risks (see Figure 3).

FIGURE 3 Four puzzle-pieces explain why long-term offtake is crucial



De-risk capital investment

De-risking capital investment is an immediate function of such offtake agreements. Maritime green fuel projects, whether e-methanol, e-ammonia or advanced biofuels, typically require hundreds of millions of dollars in upfront capital expenditure. Investors and lenders often demand predictable cashflows, which are enabled by 10-year or longer agreements, paired with take-or-pay provisions and indexed pricing mechanisms.[19,20]

Demand aggregation initiatives pool commitments across shipowners and cargo owners to generate sufficient contracted volumes for FID.[21] Evidence from industry shows this dynamic at work: for example, Maersk's multi-year bio-methanol offtake with LONGi, tied directly to its expanding dual-fuel fleet, demonstrates how offtakes underpin both vessel capex and production investment.[22] This helps to lower risk for both suppliers and buyers.

These contracts often include price floors, volume guarantees and flexible clauses to adjust to regulatory or market shifts, thereby sharing both opportunity and risk. Suppliers can gain the confidence to finance and build capital-intensive plants, knowing they have committed customers and stable cash flow. Meanwhile, buyers can secure priority access to future low-carbon fuels and may lock in favourable pricing, hedging against future market volatility or regulatory compliance costs.

Navigate regulatory volatility

Regional regulatory measures are already reshaping economics: for example, the European Union (EU)'s Emissions Trading System (ETS) began covering maritime emissions in 2024,[23] while FuelEU Maritime has enforced greenhouse gas intensity limits since January 2025.[24] In parallel, the net-zero framework (NZF) of the International Maritime Organization (IMO), initially approved in April 2025, seeks to establish a binding global fuel-intensity target, a carbon pricing and credit-trading system and a net-zero fund to scale up zero- or near-zero fuels.[25,26] However, its realization has stalled following the Marine Environment Protection Committee's (MEPC) postponement of a decision until October 2026. With this, many NZF implementation details remain unsettled until at least 2026, leaving crucial factors in the business case for zero or near-zero fuels (ZNZs) uncertain.[27]

> **Today the rules/standards are still not predictable enough in some regions and completely lacking in others.**
>
> Vibeke Rasmussen, Senior Vice President, Product Management and Certification, Yara Clean Ammonia

For suppliers and buyers alike, this layering of regional and global rules intensifies exposure to shifting compliance costs. This is precisely where change-in-law provisions and pass-through clauses can matter: by allowing costs from ETS allowances, FuelEU penalties or prospective NZF compliance units to be contractually transferred or shared, they shield project economics from sudden regulatory shocks. Embedding these protections reduces the uncertainty premium applied by financiers and ensures offtake structures remain aligned with evolving global mandates.

Enhance projects' economic viability

Early supplies of low-carbon fuel alternatives remain more expensive than conventional marine fuels such as VLSFO.[28] For example, while e-methanol is a potential game-changer, its adoption requires carbon pricing, lifecycle standards and green corridors to close the cost gap.[29]

> **The buyers do not self-elect but only purchase when incentivized or are obligated to through regulation. Currently, the pricing disparity between e-fuel and traditional oil and gas is the largest issue facing scaling of e-fuel.**
>
> Talissa Mathieu, Business Development Manager, StormFisher Hydrogen

Offtake agreements can help mitigate this disadvantage by distributing the price premium through indexed formulas, floor/ceiling protections or consortium-based arrangements. Innovative structures such as "time-stacked offtakes"[30] enable phased commitments that ease buyer exposure while still anchoring supplier financing.[31]

Manage technology and production risks

E-fuels present new technological and production risks that need carefully managing. E-ammonia poses toxicity and handling challenges, while e-methanol blends must meet strict quality standards to ensure compatibility with engines and bunkering infrastructure.[32,33] Robust offtake agreements can help address this by:

- Aligning staged deliveries with commissioning milestones.
- Embedding performance guarantees and make-good provisions.
- Assigning responsibilities for safety and certification.

Synchronizing delivery schedules with the rapidly growing dual-fuel vessel orderbook and port terminal expansions mitigates the risk of supply-demand mismatches.

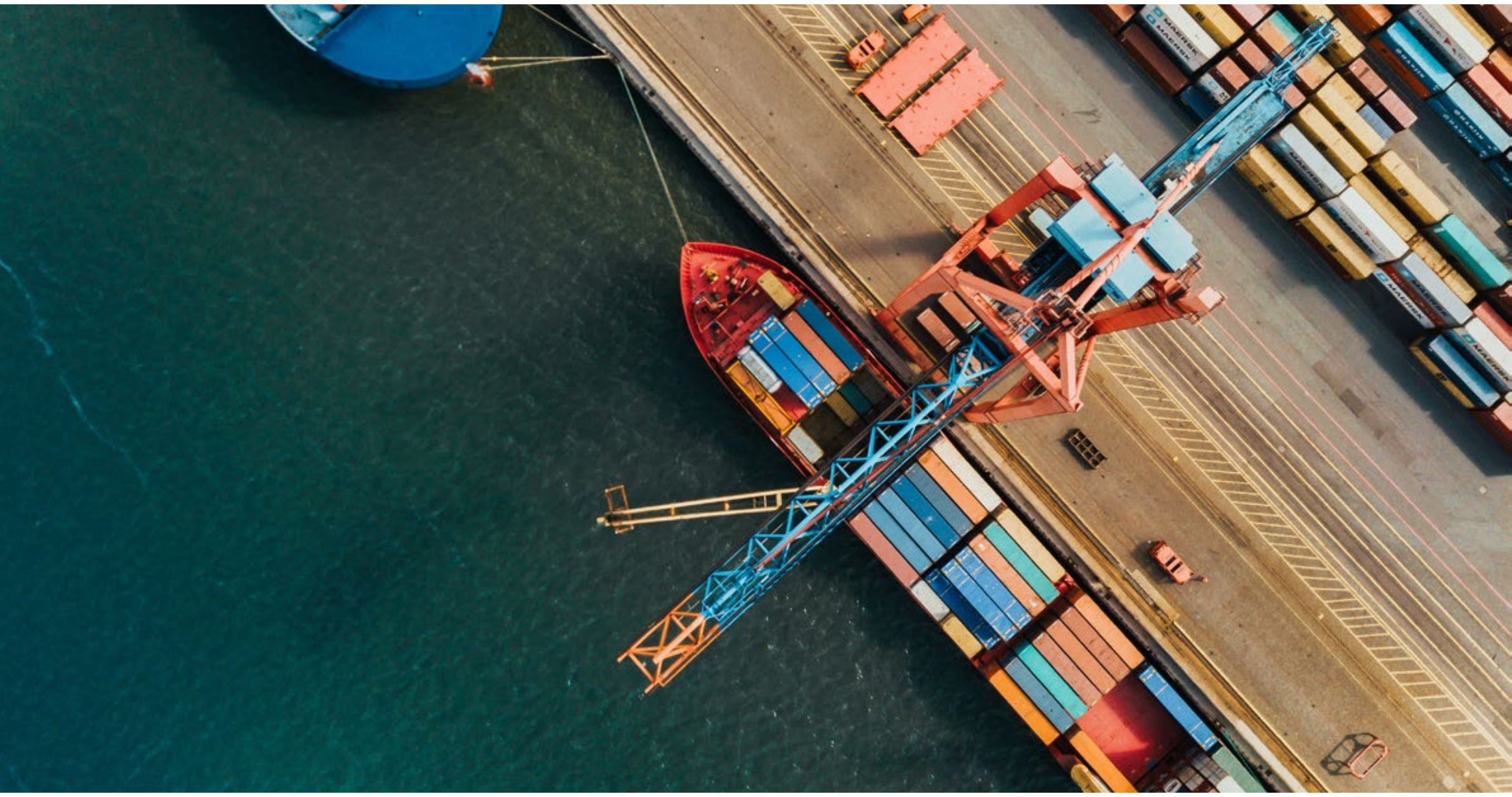
Taken together, these four pieces – de-risking capital investment, navigating regulatory volatility, enhancing projects' economic viability, and managing technology and production risks – illustrate why long-term, risk-sharing offtake agreements are valuable. They can provide some certainty needed not only for suppliers, but also for financiers and shipowners to invest at scale, enabling zero-emissions fuels to move from pilot projects and green corridors to global fleet deployment.

Smart solution: contracts for difference (CfDs)

While offtake agreements are a cornerstone, they are not a guaranteed solution. To further bridge the price gap and create a level playing field for first movers, policy-based mechanisms such as contracts for difference (CfDs) are emerging as a complementary tool, offering predictable revenue support where market-based offtakes alone cannot close the investment case.

Clean maritime fuels remain significantly more expensive than incumbent products. This green premium is one of the largest barriers to scaling-up. Contracts for difference offer a policy mechanism to directly bridge this price gap: governments or third-party entities commit to pay the difference between a reference fossil fuel price and the higher cost of a clean fuel. By stabilizing revenues for suppliers and capping exposure for buyers, CfDs de-risk investment in production and accelerate market uptake.

> **Without CfDs to anchor pricing, enable long-term financing and mitigate early-mover disadvantages, large-scale industrial offtake remains economically out of reach and the market will not scale. That said, production and consumption at scale is macroeconomically viable already at today's high prices.**
>
> Patrick Stein-Kaempfe, Principal and Project Director, Hyphen



How CfDs work in practice and their role in the transition

CfDs are well-established in the power sector, where they have driven down costs of offshore wind and solar in Europe. For example, the UK's renewable CfD scheme created stable revenue conditions that unlocked billions in project finance and reduced technology costs through predictable demand.[34] In a shipping context, they could operate similarly: if the cost of e-methanol or e-ammonia exceeds the reference fossil fuel benchmark, the CfD pays the supplier the difference; if the clean fuel price falls below the benchmark, the supplier pays back into the system.

The IMO's postponed yet anticipated NZF sets binding GHG intensity targets and compliance milestones in 2030 and 2040, effectively requiring significant uptake of low-carbon fuels.[35] Without complementary price-support mechanisms such as CfDs, first movers could face cost exposures that discourage investment.

Design considerations

Implementing CfDs in the maritime context will require tailoring them to sectoral dynamics in the following ways:

- Reference price or benchmark could be tied to regional fuel markets, for example the cost of VLSFO (the IMO's conventional reference fuel for compliance) in Singapore (the world's largest bunkering hub).
- Eligibility criteria should prioritize zero- and near-zero fuels (e-methanol, e-ammonia, synthetic fuels) to avoid transitional lock-in.
- Volume-tranching could allow both large and small suppliers to participate, reducing concentration risk.[36]
- Funding sources could include revenues from carbon pricing regimes such as the EU ETS.

CfDs should be seen as a bridge mechanism: not a permanent subsidy, but a tool to accelerate early deployment until scale-up and learning reduce costs. Importantly, low-carbon suppliers increasingly recognize CfDs as critical for making offtake agreements bankable. They reduce reliance on buyers alone to absorb the green premium and create a shared-risk framework between public and private actors. If designed well, CfDs can complement offtakes, aggregation models and book-and-claim systems, forming a comprehensive toolkit to bring clean shipping fuels from pilot scale up to mainstream adoption.

> **“ CfDs are critical for making offtake agreements bankable. They reduce reliance on buyers alone to absorb the green premium and create a shared-risk framework between public and private actors.**

➔ **Insight:** Flexible, aggregated demand models can overcome infrastructure and market fragmentation

Why flexibility and aggregation matter

Shipping's supply chain for low-carbon fuels is highly complex: production sites are often distant from ports, bunkering infrastructure remains uneven and suppliers themselves are fragmented, ranging from industrial-scale energy companies to emerging start-ups. On the demand side, buyers have diverse operational needs and fuel strategies. Rigid one-to-one offtakes do not fit this landscape. Instead, flexible, aggregated demand models that pool commitments, adapt to diverse supplier profiles and coordinate distributed logistics are important to make the transition commercially viable.

Addressing infrastructure gaps

Even if production costs fall and demand rises, the absence of adequate bunkering, storage and transport infrastructure can stall adoption. The uneven development of bunkering infrastructure is one of the biggest constraints on scaling-up clean marine fuels. Production of e-methanol, e-ammonia and synthetic fuels is geographically clustered near renewable energy hubs, but bunkering capacity is limited to a handful of ports. The cost of building a global fuelling network for these fuels is immense and will likely require coordinated action between suppliers, ports and shipowners to avoid stranded assets.

Aggregation is a key tool for bridging this gap. Green corridor models concentrate demand along specific trade lanes, pooling commitments to justify investment in storage, blending and fuelling infrastructure. The Global Maritime Forum notes that more than 60 corridor initiatives are now under development, serving as focal points for coordinated infrastructure investment and shared logistics.[37]

By aligning these initiatives with the IMO's NZF, which could introduce binding global fuel-intensity targets and compliance checkpoints in 2030 and 2040,[38] suppliers and ports can ensure that infrastructure build-out directly supports upcoming compliance milestones. Aggregation thus helps transform scattered demand into a coordinated signal that underpins infrastructure scale-up in line with global regulatory deadlines.

Overcoming market fragmentation

Equally critical is managing market fragmentation among suppliers. The emerging clean fuel landscape features a mix of large incumbents, such as oil majors moving into methanol and ammonia and smaller innovators piloting synthetic fuel plants at modest scale. This diversity creates coordination challenges: smaller producers often lack the capacity to meet the needs of large global carriers, while larger producers concentrate on major hubs, leaving gaps for regional operators. The patchwork of production pathways, certification regimes and delivery scales complicates buyers' ability to secure uniform offtake structures.

> **The ideal for a company like us, at our current scale, would be to sell our technology to a methanol offtaker, because what do you do with these small, not necessarily useful volumes of methanol?**
>
> – Jonny Lowndes, Head of Commercialization, Aircela

Aggregated demand models offer a solution by bundling multiple suppliers into joint procurement or platform structures, enabling buyers to access a diversified portfolio of fuels through a single channel. The Global Centre for Maritime Decarbonisation (GCMD) notes that collaborative procurement initiatives, such as Zero Emission Maritime Buyers Alliance (ZEMBA) and multi-supplier green corridor projects, are increasingly bridging small and large producers, giving shipowners confidence in resilient supply while ensuring smaller suppliers can participate in scaling-up.[39]

Crucially, as and when the IMO NZF moves towards its 2030 and 2040 checkpoints, diversified, aggregated supplier models provide flexibility: if one producer or technology pathway underperforms, others can step in to meet regulatory requirements. This makes supplier fragmentation not just manageable but a potential source of resilience when coordinated through aggregated demand platforms.

Smart solution: book-and-claim

Aggregation alone cannot fully overcome the friction of fragmented supply and uneven access to infrastructure. To unlock the next level of scale, policy-enabled mechanisms such as book-and-claim systems are emerging as a complementary solution – creating traceable, tradable certificates that allow fuel use and emissions reductions to be decoupled from physical delivery.

Book-and-claim is not new: it has been widely used in electricity (e.g. renewable energy certificates), aviation (e.g. sustainable aviation fuel credit systems) and corporate decarbonization markets. In shipping, it has been tested by initiatives such as ZEMBA and port-led pilots in Singapore and Rotterdam, which are exploring traceable certificates linked to fuel lifecycle emissions.[40]

What is new is the robust and growing support for the idea from low-carbon suppliers themselves. As producers of e-methanol, e-ammonia and synthetic fuels struggle to reach diverse buyer segments across multiple geographies, they increasingly view book-and-claim as a commercial enabler rather than a mere accounting tool. This approach enables suppliers to access a broader and more diverse pool of buyers, including those from both within and outside the maritime sector. It removes the constraint of matching physical fuel delivery to immediate operational needs, allowing even non-maritime buyers, who are interested exclusively in the environmental benefits of the fuel, such as emissions offsets, to participate in the market.

> **Book-and-claim turns non-fuel purchasers into financial supporters of early volumes.**
>
> Talissa Mathieu, Business Development Manager, StormFisher Hydrogen

How book-and-claim can accelerate expansion of green maritime fuels

Book-and-claim mechanisms complement flexible, aggregated demand models in three pivotal ways (see Figure 4):

- **Infrastructure bypass:** By decoupling fuel use from fuel location, book-and-claim mitigates the unevenness of bunkering infrastructure. For example, a shipowner in Africa or South America can purchase clean fuel certificates, even if the nearest port lacks supply.
- **Supplier diversity:** Book-and-claim integrates fragmented suppliers into a common marketplace, allowing large and small producers to issue credible claims for their volumes, widening participation and reducing market concentration.
- **"Financeability":** Traceable, third-party-verified certificates generate confidence for investors and regulators, making offtake commitments more bankable even in early, geographically limited markets.

FIGURE 4 **Book-and-claim – three pivotal advantages**

Book-and-claim: design considerations

- Attribute boundaries should be clearly defined, specifying fuel type, lifecycle emissions covered (well-to-wake), geographic origin and certificate validity period.
- Allocation and retirement rules should ensure units can only be claimed once, with transparent retirement events accounted for by established registries to prevent double counting.
- Auditing and registries should be standardized, with third-party verification, unique certificate IDs and interoperability across registries; consider building on lessons from SAF pilots.
- Accounting alignment should map claims to accepted GHG reporting frameworks and disclosure standards, enabling both shipowners and cargo owners to credibly integrate claims into scope 3 accounting.
- The credibility of book-and-claim depends on robust governance. Concerns remain over double counting, registry interoperability and ensuring that claims correspond to actual lifecycle emissions reductions.

Industry initiatives – such as the Maersk Mc-Kinney Møller Centre for Zero Carbon Shipping's work on transparency frameworks and the GCMD's trials on digital verification (in this case specific to biofuels) – are actively tackling these issues.[41] Regulators are also starting to recognize its role: the EU has explored the use of book-and-claim for synthetic fuels under FuelEU Maritime, provided that robust traceability is in place.[42]

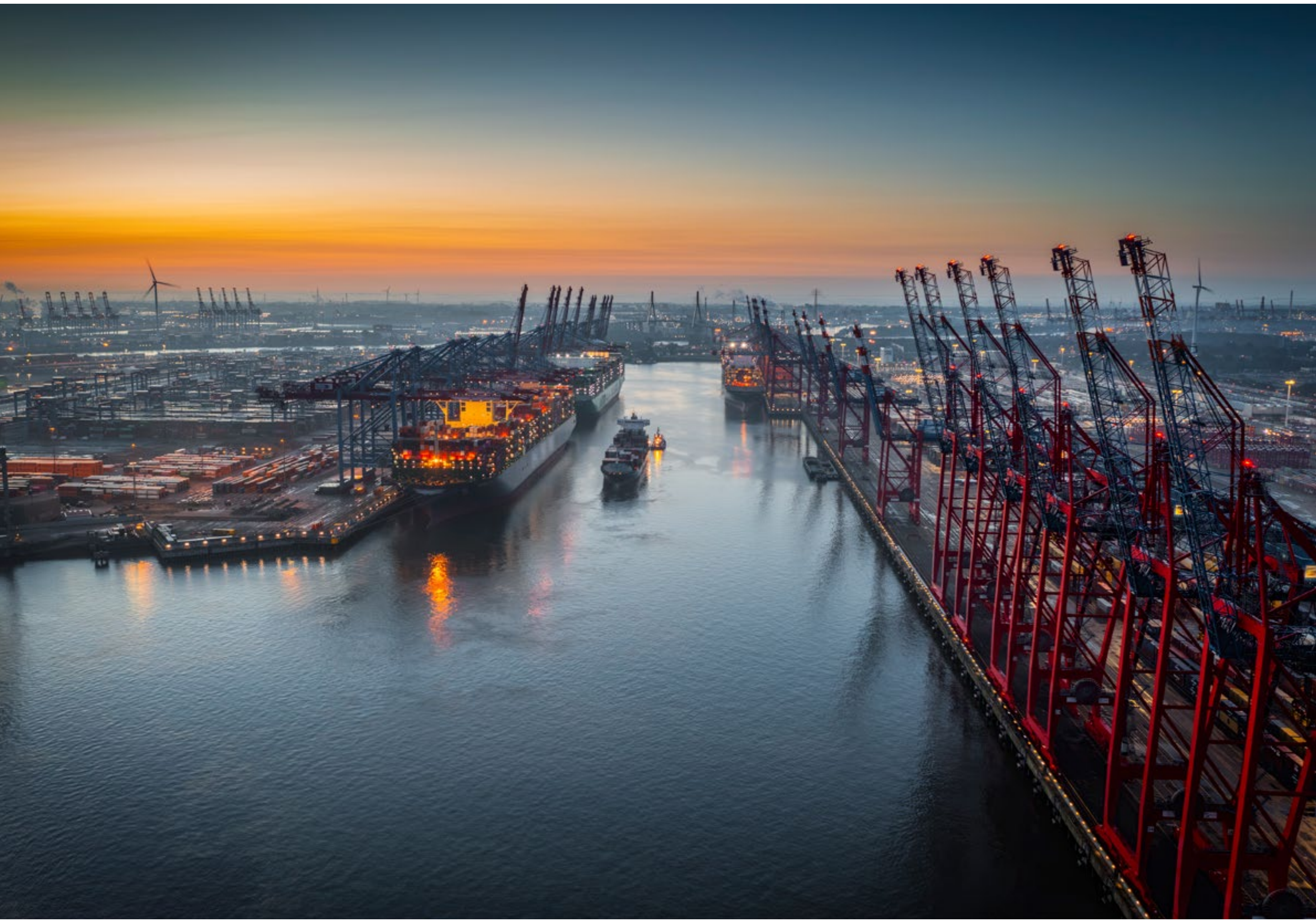
Book-and-claim is best seen as a near-term enabling mechanism, not a silver bullet. It will not replace the need for physical infrastructure build-out, but it can accelerate market formation by allowing buyers and suppliers to transact now, even in the absence of global bunkering coverage. Crucially, with suppliers now advocating for book-and-claim as part of their commercial strategy, the mechanism has shifted from a buyer-driven accounting workaround to a mutually reinforcing solution.

Conclusion

Shipping's low-carbon fuel transition hinges on translating intent into bankable demand signals and coordinated market architecture. Long-term, risk-sharing offtakes, possibly reinforced by targeted CfDs, can unlock first-of-a-kind projects and pull investment through to scale, while flexible, aggregated models such as credible book-and-claim systems may overcome infrastructure gaps and supplier fragmentation.

As regulatory frameworks develop towards 2030 and 2050 objectives, early movers that combine contractual resilience with portfolio flexibility may be best positioned to navigate cost volatility, technology learning curves and evolving standards.

The imperative now is execution: align green corridor demand with production ramp-up, embed change-in-law protections and certificate integrity into offtakes, and mobilize blended finance to shorten timelines from pilots to system-wide adoption. This integrated approach will convert today's pocketed progress into durable market pull, accelerating the shift from niche deployments to mainstream decarbonization across global fleets.



1.3 Trucking – electrification realities: scaling-up, barriers and the road to decarbonization

Introduction

Trucking contributes

5%

of global CO_2e emissions.[43]

The decarbonization of medium- and heavy-duty (MHD) trucking[44] sits at an intersection of technology, infrastructure and capital deployment. With the range of battery-electric vehicles (BEVs) improving, power grids becoming more resilient and various policy-makers tightening diesel regulations, fleet operators are shifting from the theoretical aspects of decarbonization strategy to the practical question of implementation. This chapter explores this mindset shift from the vantage point of the supplier — from planning to operationalizing change.

This chapter presents the perspectives of a small but diverse set of trucking and logistics pioneers who are not only committing to the offtake of zero-emission trucks but, more importantly, leading their real-world operations. While what follows is in no way an exhaustive industry census, it does represent a curated scan of the pathways that credible actors, across various regions and global supply chains, believe can lead to the widespread decarbonization of medium- and heavy-duty trucking. The framing is region-agnostic but region-aware. Rather than crown a single "right" model, a more useful way forward is to ask the question: What would have to be true, operationally, financially and institutionally, for a respective fleet's decarbonization to scale up?

Two convictions run through these interviews. First, the interviewed subset of suppliers largely finds electrification emerging as the anchor pathway for decarbonizing their medium to heavy road freight services — not because alternatives are unviable, but because advances in batteries, power electronics and grid integration are compounding faster than competing options. Second, a strong supplier consensus that electrification is not simply a truck problem — it's a systems problem, encompassing utilization, corridor charging density, interconnection timelines, software-driven orchestration and the financing of the actual "steel in the ground".

Two main bottlenecks stand out:

- **Infrastructure versus timeframe:** Charging infrastructure deployment and grid upgrades remain opaque, fragmented and slow relative to corporate targets.
- **Utilization versus economic viability:** Total cost of ownership (TCO) parity depends heavily on consistent BEV utilization; idle assets can erase expected savings overnight.

The state of electrification of medium- and heavy-duty (MHD) trucking

The electrification of MHD trucking is growing globally, but it remains in the early adoption phase compared to light commercial vehicles. In 2024, over 90,000 electric trucks were sold globally with year-on-year growth of almost 80% from 2021.[45] In the EU, sales of zero-emission heavy-duty vehicles increased from 11,000 in 2023 to 14,000 in 2024; meanwhile, light- and medium-duty trucks accounted for 6% of the bloc's zero-emission truck sales in 2023, growing to 10% in 2024.[46] China is also showing strong uptake, with sales of electric MHD trucks doubling between 2023 and 2024. In 2024 China sold over 80% of the total number of electric trucks sold globally.[47] Forecasts generally remain bullish: one recent analysis projected the global heavy-duty EV truck market would expand at ~20 % CAGR up to 2030, as expected policy incentives, falling battery costs and shipper sustainability commitments converge.[48]

> “ **We believe electrification is the optimal solution for Europe, while regions like Sub-Saharan Africa face challenges such as road quality and security that currently limit adoption. However, with rapid advances in batteries, especially from China, combined with microgrid technologies, I'm convinced that Sub-Saharan Africa could leapfrog ahead and surpass Europe in vehicle electrification within the next five years if action begins now.**
>
> Nicholas Mazzei, Vice President Sustainability, DP World

For MHD applications, vehicle capability is crossing more useful thresholds: next-gen long-haul tractors slated for release are targeting ~600-800 km (e.g. Tesla Semi) on a single charge, enabled by the “e-axle” that frees battery space without fully sacrificing payload[49] (e.g. Volvo’s FH Aero Electric can now carry eight batteries). Meanwhile, technological advancement of infrastructure is promising: 350-500 kW depot charging is already scaling-up and real-world megawatt-class pilots are demonstrating that sub-hour turnarounds are now technically feasible.[50] However, expanding this infrastructure is complex and varies by region.

A chicken-and-egg dilemma persists where operators are reluctant to invest without charging certainty, while investors hesitate to fund charging without guaranteed utilization. Moreover, trucking services and logistics players interviewed for this report stressed that the decisive factor for MHD electrification is not only the truck but the orchestration of vehicles, charging and operations. Digital tools for route planning, charging schedules and energy optimization are emerging as potential complements to vehicles themselves, helping providers maximize utilization and protect margins. In short, the MHD trucking landscape is shifting from whether electrification technology works to how fast systemic bottlenecks in infrastructure and integration can be removed.

➲ **Insight:** Electrification is the primary technological pathway — but it is not without hurdles

First suppliers – from pilot to scale

In 2025, several logistics players made significant commitments to and investments in battery-electric truck (BET) deployment, proving the operational viability of zero-emission freight:

- **Kuehne+Nagel** aims to have a 60% representation of low-emission vehicles in its owned fleet by 2030, focusing strongly on electric trucks. The company works closely with customers and carriers to advance electrification. In September 2025, for example, Kuehne+Nagel and Siemens eMobility launched an all-electric route linking Germany and Portugal.[51]
- **Toll Group** announced a AU$67 million investment in a battery-electric heavy vehicle and charging programme, co-funded by the Australian Renewable Energy Agency (ARENA)’s Driving the Nation Program. In August 2025, Toll delivered the first electric Volvo FM prime mover (HDT) for Woolworths Group’s logistics operation at Moorebank Distribution Centre in New South Wales, supported by a 980 kW onsite charger.[52]

- **DP World** reported deploying the largest electric freight-mobility fleet in the Middle East through its partnership with Einride, as part of its equipment-electrification programme. In March 2025, DP world expanded electric freight operations at Jebel Ali Port with Einride, rolling out an electric, digitally orchestrated road-freight solution to decarbonize port-related trucking.[53]

Battery-electric holds the edge on efficiency and early adoption

The supplier calculus is pragmatic: for those seeking to decarbonize, battery-electric trucks are the most efficient pathway available to reduce emissions in the near-term, not because other pathways are impossible, but because electrification combines fast-improving vehicle availability, clear energy-efficiency advantages and a developing infrastructure trajectory that eases future planning. Additionally, the broader EV passenger-vehicle industry's scale supports BET adoption via improvements in cell density, thermal control and cost reduction that spill into the MHD segments.

When suppliers compare pathways, system efficiency is a key discriminator: electricity is used directly in BETs, translating into motion with substantially fewer conversion losses than routes that convert electricity into hydrogen or e-fuels before it reaches the wheels. Moreover, BEVs' "power-to-wheels" efficiency is placed far above hydrogen and e-fuels – fewer megawatt-hours must be generated and delivered per tonne-km moved.[54]

A recent analysis concluded that drivetrain efficiency for BEVs reached 70-90%, compared to substantially lower efficiency for fuel-cell systems due to hydrogen production and conversion processes, once the end-to-end energy pathway is considered.[55] That efficiency edge compounds with falling battery costs and improved power electronics to create a powerful case for BETs – specifically when duty cycles are repeatable (hub-to-hub, back-to-base) and where depot charging can be sequenced with operations.[56]

> **The road freight ecosystem continues to grapple with well-known challenges: limited charging infrastructure, difficult grid connections, high cost of new assets and insecurities regarding total cost of ownership.**
>
> John De Dryver, Strategy and Sustainability Manager, Kuehne+Nagel

Navigating roadblocks

Interviews with suppliers illuminate that a dominant limiting factor for electric adoption in 2025 is not whether an electric truck can move freight – it is whether there is enough powerful, well-placed infrastructure to keep it moving.

Coverage is improving but still thin on long corridors, reflecting a need for public tenders – or for coalitions between OEMs and utility providers to move first and fill obvious gaps. However, adding plugs is only half the job: multi-megawatt depots and high-throughput hubs increase strain on the grid, dragging substation upgrades, interconnection queues and tariff exposure into the critical path – unless utilities are able to co-plan from day one.

Even when steel is in the ground, operations can decide the economics. Many fleets are treating charging as a software-defined flow problem – coordinating arrivals, state-of-charge and price signals across trucks and nodes. In a large-scale simulation of Sweden's road network, a distributed truck-station coordination scheme cut average waiting times materially – this dictates the difference between making or missing utilization targets.[57] Complementary analyses show that managed charging and onsite distributed energy resources (DERs) can trim fleet power bills by up to 30%, while depot-level optimization can avoid majority on-peak charging, cut peak load rates and reduce variable energy costs.[58,59] As previously highlighted, vehicle capability continues to improve – yet range, payload, climate and route profile still define what's bankable, which is why hub-to-hub and back-to-base lanes keep leading early scale.

Finally, the maths of adoption still leans on utilization. Logistics providers and truck operators voice concern about a material TCO gap and capex premium versus diesel in many long-haul cases, without incentives. This gap closes as trucks run hotter, batteries get cheaper and tariffs are optimized. The through-line for operators is not simple but becoming clearer: design lanes for utilization, co-plan sites with the grid and use policy tailwinds to pull parity forward – the trucks are ready enough, but the system around them decides the pace.

➔ **Insight:** For utilization and economics, the business case lives or dies on asset productivity

> **For logistics companies operating on extremely thin margins, even a slight increase in pricing can be prohibitive. Addressing the green premium remains a significant challenge.**
>
> Manosij Ganguli, Group Chief Sustainability Officer, Aramex

For MHD fleets, electrification only pays off when trucks stay busy, maintain payload margins and power is bought optimally. In other words, fixed costs are high, variable savings are real and utilization is a key fulcrum. The TCO gap is often material versus diesel for long-haul use cases in the short-term, without incentives. That gap narrows as miles stack up, batteries and power electronics become cheaper and electricity is procured on smarter tariffs.

> **If the truck is doing over roughly 70,000 kilometres a year, we can make it the same price as the diesel. Utilization really is the key to success on this.**
>
> Nicholas Mazzei, Vice President Sustainability, DP World

In real operations, the fleets that make the maths work design lanes for repeatability (hub-to-hub, back-to-base), deepen daily mileage and avoid under-using large-capacity battery packs. Field analysis of 91 electric tractor-trailers in 2025, conducted by the International Council on Clean Transportation, found that battery under-utilization (e.g. ~44% average depth of battery discharge) increased TCO, while higher daily distances plus off-peak pricing or lower utility cost for electricity improved economics.[60]

An additional utilization lever is time. When a supplier evaluates the upfront cost of procuring an electric truck relative to purchasing a diesel internal combustion engine at time of purchase, they are deterred by the BET's premium. This cost discrepancy narrows as the time interval in which the BET operates grows. However, this highlights the suppliers' dilemma and the temptation to hesitate before procuring BETs – given that second- or third-generation BET technology may shorten the time interval of this payback period further.

> **While the upfront cost of acquiring an electric truck is roughly double that of a conventional diesel truck, the lower operating expenses over a seven-year period result in a full payback. However, ongoing advancements in battery technology may affect future cost and performance considerations.**
>
> Shaun O'Flaherty, Global Head of Products & Solutions, Toll Group

Moreover, a powerful near-term utilization lever is not necessarily a new connector (the physical charging interface and its standard) but "orchestration" of the charging system itself. In practice, charging system orchestration for BETs means systematically coordinating when, where and how trucks charge to reduce demand peaks, minimize wait times and lower per-mile energy costs. When fleets and stations coordinate charging as a system, under-utilization rates and power costs can decrease. Additionally, joint routing and charging (JRC) optimization for heavy trucks shows the potential for synchronizing stops with station capacity and charger power to lower system cost, which is exactly what many utilization-driven operators want.[61]

Inside the fence, depot scheduling has delivered outsized wins without touching hardware: one 2024 optimization model of an MHD depot comparing optimized to managed scenarios found a reduction in peak-hour energy demand of 64-75% monthly, corresponding to roughly 53-63% reduction in variable costs – these are savings that carry to the P&L.[62] At portfolio scale, pairing managed charging with onsite distributed energy resources (DERs), such as solar power and battery storage, can reduce fleet electricity bills by up to 30% while easing interconnection stress, turning "the power bill" from a risk into a controllable line item.[63]

The US Government's National Renewable Energy Laboratory has documented how actively managed charging (direct load control) can avoid or defer costly grid and distribution upgrades by controlling when and how vehicles charge to keep depot load under electrical capacity limits – another way that orchestration moves the economics.[64]

Taken together, the economic playbook for electrification can be pragmatic, not theoretical: lock in utilization, orchestrate charging to slash peaks, buy off-peak and support tightening policy to close the TCO gap – because the trucks typically save on energy and maintenance when they are moving and the rest is sequencing lanes, sites and tariffs to keep them moving.

➔ **Insight:** The critical role of partnerships and policy

Across interviews, suppliers converged on a simple operational sentiment: medium- and heavy-duty electrification scales up as a shared-risk programme, not as a sequence of siloed procurements. According to these suppliers, the partnerships they value are those that couple vehicle roadmaps and diagnostics access (from OEMs) to utility-backed sites and interconnection plans (from charging providers/utilities) and to anchored lane commitments (from shippers), so that power, places and predictable demand come online together.

Suppliers pointed to “coalition” models that map to real corridors rather than aspirational dots on a slide – such as MAN and E.ON’s cross-border build-out, on path to equal roughly 170 locations – which together create concrete waypoints around which route design and utilization plans can be built.[65]

> **Right now, the overall capital cost remains high when compared to the cost of purchasing a conventional diesel fleet. Without sustained policy support and programmes like ARENA, it’s difficult to de-risk early projects and accelerate the transition at scale. We anticipate the cost to acquire a BEV fleet to reduce in line with increased demand, especially as 2nd and 3rd generation BEV fleets enter the market in the near future.**
>
> Shaun O’Flaherty, Global Head of Products & Solutions, Toll Group

Policy is seen by many of those interviewed as a key factor – useful for underwriting early sites and shifting long-run costs, but too variable to “hard-code” without contingencies. Given the disparate global landscape, electrification policies will look different across countries and regions. For example, Australia’s ARENA seeks to de-risk early heavy-duty electrification via its Driving the Nation focus areas; it recently issued a grant for AU$12.3 million to Mondo Power to build the country’s first shared electric-truck hub in Melbourne.[66] Meanwhile, The EU’s ETS2 will price road-transport fuels upstream from 2027, with a built-in option to postpone to 2028 if energy prices are exceptionally high, so that teams model timing risk rather than assuming a single start date.[67,68] In parallel, the EU’s Alternative Fuels Infrastructure Regulation (AFIR) sets mandatory targets for truck-capable recharging along the TEN-T network and at safe/secure parking areas, creating a planning scaffold for where public charging should progressively materialize.[69,70]

Suppliers also highlighted the complexity of contradictory regulatory signals in some regions, such as the EU. For example, while CO_2 standards and AFIR push zero-emission trucks, current weight and axle rules, in certain locations, can still penalize battery-electric payloads, eroding the business case on weight-limited lanes. Generally, today’s framework still grants a constrained threshold limit for zero-emission combinations without increasing the drive-axle limit, which can blunt the benefit for heavier battery packs.[71] However, the European Parliament took steps to address this, by backing a revision of the Weights & Dimensions Directive in March 2024. This proposed up to +4 tonnes for ZEVs and additional axle flexibility, but implementation and cross-border harmonization remain in motion, which many logistics providers view as a practical risk to near-term utilization and revenue.[72]

Conclusion

On the weight of evidence and with many suppliers’ operating realities in view, electrification emerges as a scalable near-term pathway, but its advantage is conditional rather than absolute. Its economics and reliability improve rapidly when lanes are repeatable, charging is orchestrated as a system (not a site) and interconnection is planned alongside vehicle orders. However, when these conditions slip, the TCO edge softens and confidence erodes. The slope of adoption is therefore a function of utilization discipline, grid and siting readiness and policy considerations – each a moving part with real sensitivity. If these contributing factors line up, many suppliers expect their electrification to transition from pilots to durable programmes on core corridors. If they do not, scale will lag – not because these suppliers’ trucks cannot perform, but because the surrounding system is not sequenced to let them.

1.4 Mobility cross-sector – converging realities across low-carbon mobility suppliers

Across the mobility ecosystem, suppliers face distinct emissions reduction pathways, but recurring themes emerge that cut across aviation, maritime and trucking alike. This chapter explores those cross-sector dynamics, highlighting shared structural challenges – including policy design, infrastructure readiness and financing constraints – that lead to prospective opportunities for coordinated solutions. The analysis intentionally remains high-level, respecting each sector's unique regulatory and operational context while identifying common enablers that could accelerate progress collectively. By comparing experiences across these sectors, the goal is not to conflate them, but to illuminate where alignment could make the entire system move faster towards viable, scalable low-carbon supply.

Policy-driven demand floors are globalizing – reach and shape vary by geography

Across the mobility ecosystem, suppliers interviewed for this report characterized regulatory policy as a principal way to convert emissions reduction ambition into bankable demand. However, the consistency, durability and scope of policies diverge by sector and geography.

The shipping sector has demonstrated global vision with the IMO's Net-Zero Framework (NZF) – a regulatory push to combine mandates on emissions limits and GHG pricing across an entire industry sector. While its realization was postponed by 12 months in a vote of MEPC IMO members in October 2025 – carrying significant impacts – the NZF nevertheless marks the sector's ambition to transition from disparate policy coordination and voluntary efficiency schemes to a first-of-a-kind form of enforceable climate governance.

By contrast, aviation and trucking suppliers described parallel but more geographically bounded trajectories – robust domestic and/or regional policies that seek to anchor demand but lack cross-border harmonization.

In aviation, policy obligations are growing and mandates have reached operational specificity. Examples include the following:

- European Union's ReFuelEU Aviation, mandating a minimum of 2% SAF share in all EU airports starting in 2025, increasing to 70% SAF in all EU airports from 2050.[73]
- Japan stated its objective for SAF to reach a minimum of 10% of airline jet fuel by 2030.[74]
- Singapore's Ministry of Transport introduced the Civil Aviation Authority of Singapore (CAAS) Amendment Bill, which imposes a levy on departing flights to facilitate SAF usage, passed in October 2025.[75]

In trucking, regulatory drivers are growing increasingly sustainability-orientated but are still regional and mixed in design. For example, the EU's revised tightening of CO_2-emission standards for heavy-duty vehicles and its extension of ETS2 to road transport from 2027 create a carbon price signal, but not yet a coordinated fuel or fleet mandate.[76,77] At the same time, emerging national low-carbon fuel standards and renewable-fuel quotas, seen in regions such as Scandinavia, Latin America and parts of East Asia, sustain localized demand for renewable diesel, biomethane and hydrogen, but do not translate into a cross-border compliance market in which many logistics providers operate.

Trucking logistics providers, especially those operating within global markets, therefore navigate a dense constellation of programmes without harmonized accounting, which complicates credit trading and offtake structuring for multinational fleets.

Mobility sectors, particularly those operating across global supply chains, share a common challenge derived from asynchronous policy certainty – even with many strong local anchors, disparate global coordination is difficult to navigate. The combined effect is a patchwork of demand floors without ceilings: enough to justify early projects, but generally insufficient for requisite scaling-up. The shipping sector is emerging as the policy prototype for a globalized compliance market in which the obligation spans jurisdictions. Its success will need to be considered in determining whether this approach is feasible across neighbouring industrial mobility sectors.

Infrastructure is a governor of growth

During supplier interviews across each sector – aviation, shipping and trucking – infrastructure readiness emerged as a shared determinant of scale. Technologies for low-carbon fuel production and zero-emissions mobility are advancing quickly, yet the systems that store, blend, transport, deliver and certify these fuels and electrons remain uneven and sometimes lag behind demand. Across mobility, infrastructure – from tanks, blending and bunkering to charging and grid connections – strongly influences the near-term limit on volumes in each sector.

In particular, mobility suppliers flagged first-mile and last-mile logistics as critical chokepoints – linking the fuel/energy production to the point of use. Whether that is SAF being delivered to airport hydrants, electricity and hydrogen to truck stops, or e-ammonia and e-methanol bunkering at ports, the absence of seamless integration with the legacy infrastructure of production, transport, storage and dispensing creates a frequent break in the chain.

Across mobility, demand growth is not simply constrained by the premium of the clean alternative process, but by the capital, permitting and coordination needed to build the supporting network. Many suppliers likened this to “flying the airplane while building the airport”. Moreover, the required geography of infrastructure differs widely from sector to sector. Shipping requires bunkering at global port hubs and along major shipping lanes; trucking demands hubs at highway corridors, border crossings and terminals; aviation calls for fuel blending, delivery and storage off- and on-airports – all of which are vital nuances that must be considered.

In summary, infrastructure is not simply a sector-specific issue – its opportunity and limitations are pervasive across the mobility sectors where creating solutions is just as important as demand signals.

Financing opportunities and challenges

Even when policies and infrastructure align, the transition to low-carbon supply is ultimately a capital-intensive endeavour. Across aviation, shipping and trucking, suppliers consistently recounted the following current and structurally similar financial findings:

- **Upfront capital intensity and stranded-asset risk:** Building new plants, modifying refineries, installing tanks and pipelines and retrofitting vessels and trucks require large upfront capital before significant cash flows begin. While this can be mitigated via advanced offtake, milestone-based grants and concessional finance, the risk that shifts in policy, demand or technology may render assets partially stranded is a constant concern.

- **Uncertain offtake:** Since compliance demand – through mandates, pricing or credits – is still evolving, offtake agreements are not fully guaranteed. Suppliers fear volume risk and buyer default.

- **Technical and operational risk:** New technologies generally introduce engineering and performance risk, increasing perceived risks by lenders and requiring higher returns.

- **Currency, policy and regulatory risk:** Particularly in global supply chains, suppliers face risks from policy changes, cross-border trade and tariffs, exchange rates and differing tax regimes.

Conclusion

Despite distinct regulatory and operational contexts, low-carbon mobility suppliers across aviation, shipping and trucking share some common challenges in policy alignment, infrastructure readiness and financing. Disparate policy frameworks globally and uneven infrastructure development currently limit the scalability of low-carbon solutions, while capital intensity and financial risks further constrain progress.

However, coordinated approaches to policy design, infrastructure investment and financial structuring present significant opportunities to accelerate sector-wide decarbonization. By leveraging shared experiences and fostering cross-sector collaboration, the mobility ecosystem may move more rapidly towards scalable, viable low-carbon supply.

2 Materials sectors

2.1 Cement and concrete – reimagining procurement practices to reward low-carbon innovation

Cement contributes

6%

of global CO_2e emissions.[78]

Introduction

Cement and concrete provide the foundations of modern infrastructure, but are one of the hardest sectors to decarbonize. Suppliers interviewed for this report consistently returned to one point above all others: bankable, long-dated demand is the gatekeeper to capital. In a commodity business with thin margins and exacting standards, first-of-a-kind (FOAK) projects struggle to attract project finance without credible, durable offtake. Near-zero solutions lack economies of scale and both demand and market awareness are relatively nascent – underscoring the need for demand creation and deployment support.[79]

Deep decarbonization will likely require a portfolio approach, including clinker substitution (supplementary cementitious materials and novel binders), carbon capture, utilization and storage (CCUS), alternative raw materials and chemistries, fuel switching and efficiency.[80]

This chapter captures the supplier perspective: innovators and producers at the leading edge of low-carbon cement and concrete who are learning, often painfully, how to move from pilot-scale demonstration projects to commercial-scale production.

Offtake as the backbone of scale

Across supplier interviews, a key constraint kept resurfacing – no offtake, no debt; no debt, no plant.

> **Startup innovators have very limited access to finance in this capital-intensive, cyclical commodity industry where everything is sold on the spot market. A substantial balance sheet, a long track record and economies of scale really matter here.**
>
> Cindy McLaughlin, CarbonBuilt

Norway's Longship programme shows how public support can catalyse bankable supply that buyers can contract against. In June 2025, the Norwegian government launched the world's first full-scale carbon capture and storage (CCS) value chain. It brought Heidelberg Materials' Brevik capture facility online, which is designed to capture ~400,000 tonnes CO_2/year (≈50% of plant emissions) with transport and storage via Northern Lights. This is precisely the type of policy scaffolding that converts nascent intent into financeable volumes – critically, it creates the confidence for longer-tenor offtake that lenders will recognize.[81]

> **First-mover decarbonisation projects also need to be economically successful to take off… and that's why we work closely with governments to create that business case.**
>
> Winston Beck, Heidelberg Materials

Low-carbon cement developers often find themselves in a loop: buyers want proven volumes, financiers want guaranteed cashflows and innovators cannot build plants without both. Only a handful of buyers – large technology firms (notably hyperscalers) and public procurement channels – are currently willing to anchor multi-year commitments that lenders recognize as bankable.

> **We've signed multiple offtake LOIs and run testing, but demo production is a bottleneck – moving from costly demo to large-scale is the hard gap.**
>
> Oscar Hållén, Cemvision

Recent deals hint at the emerging playbook. Microsoft's 2025 agreement with Sublime Systems secured up to 623,000 tonnes of ultra-low-carbon cement over nine years, designed explicitly to bridge the pre-FID gap. Similarly, the Sustainable Concrete Buyers Alliance aggregates buyers such as Amazon and Meta to create pooled, demand signals across multiple regions – a concrete parallel to green corridors in shipping.[82,83]

Digital offtake, such as book-and-claim models, are seen as an attractive option because they open up new customers and sources of revenue in a market where buyers of low-carbon materials are geographically dislocated from production sites. This provides liquidity to suppliers, which in turn helps to finance new projects.

Customer acceptance

Technical readiness means little without market acceptance. Cement products have changed little over time and therefore the introduction of new low-carbon cement products presents new challenges to buyers, who must ensure those new products have the correct performance characteristics before committing to large-volume purchases.

Codes, engineering standards and public procurement guidelines lie at the heart of cement procurement decisions. Suppliers interviewed for this report repeatedly cited product standards and customer acceptance of novel cement products as critical friction points. The lack of a cohesive and uniformed set of standards is a significant deterrent for potential buyers of low-carbon cement products.

However, there are several examples of new performance standards emerging which could help drive customers to low-carbon products – such as ASTM C1157 in the US, EN 197-5 and EN 206 in the EU and EPCC/BS 8500 in the UK.

> **We're at deployment stage… certification is the really big focus. We've got ASTM C1157 for our product in the US; the longer pathway is concrete acceptance (from buyers) – state DOT testing etc. None of that is super fast, but it's happening.**
>
> Susan McGarry, Ecocem

Real progress will likely require buyers to be willing to seek out and try new low-carbon products and not just rely on traditional products and traditional procurement practices.

> **In any given geography, we need a diverse array of buyers… cement is a commodity; acceptance across the value chain clicks when customers ask for it.**
>
> Joe Hicken, Sublime Systems

> **A robust system of carbon monetization with a portion paid upfront can get a company some of the additional capital it needs to make necessary investments in infrastructure. Furthermore, long-term forward carbon offtake commitments can help mimic contracted revenue for the material, which might help some lenders get comfortable enough to provide project finance.**
>
> Cindy McLaughlin, CarbonBuilt

Monetizing carbon

Suppliers increasingly frame environmental attribute certificates (EACs) and carbon credit structures as revenue instruments, not just marketing tools. Properly structured, these can offer pre-paid, contract-backed income that will support financing. In 2024-25, Microsoft and partners published science-based criteria for high-quality EACs in low-carbon concrete and steel intended to be verifiable, additional and catalytic. Such standards matter because they support lender diligence and mitigate fears of double counting.[84]

Carbon monetization and upfront capital can turn early demand intent into tangible, financeable cashflow. It can unlock buyers beyond traditional local markets, including customers who may not be physically close to low-carbon suppliers' production facilities. Furthermore, it can bring in buyers who are willing to pay a premium for low-carbon products. This is clearly aligned with lenders' appetites for contracted revenue streams, making the financing process easier.

Policy certainty and public procurement to spur demand

Europe is seen as an attractive market for the suppliers interviewed for this report, for a number of reasons:

- Carbon pricing through the EU ETS and the CBAM can create a clear market floor for low-carbon materials.[85,86]
- Public procurement rules increasingly reward EPD (Environmental Product Declaration)-verified low-GWP (Global Warming Potential) mixes.
- Suppliers interviewed indicated that permitting and approvals are predictable and streamlined for near-zero materials. In Europe the sector is well-funded, but funding is overwhelmingly skewed towards CCS/CCU at incumbent plants, with far less capital flowing to alternative binders and processes, such as calcined clay, novel chemistries or electrified routes.[87,88]

> **The cement sector [in Europe] is extremely well-funded… the problem is you're not seeing the same level of commitment go to the alternative technologies.**
>
> Susan McGarry, Ecocem

In the US, the federal energy policy landscape is shifting, with federal policies which had been supportive rolled back in 2025.[89,90,91] At the state level, several public policies are providing support:

- Colorado's Buy Clean Colorado Act now enforces environmental production declaration (EPD)-based maximum global warming potential (GWP) limits for cement and concrete on Colorado Department of Transportation (CDOT) projects. These limits, effective from January 2025, operationalize disclosure into hard thresholds.
- New York State's Low Embodied Carbon Concrete Leadership Act (LECCLA) requires state entities to procure low-carbon concrete for state projects, resulting in the Office of General Services (OGS) Buy Clean Concrete Guidelines, which establish EPD reporting and emissions standards with bid preferences for compliant mixes.
- California's Department of Transportation (Caltrans) requires EPDs for concrete and asphalt and is standing up advance procurement tools to lock in low-carbon cement and concrete supply.[92,93,94]

These state rules have the potential to translate ambition into measurable procurement criteria for companies in this sector looking to decarbonize. Despite this progress at state level, companies interviewed describe a harder path from pilot to plant in the US, with grant uncertainty and sparse offtakes outside a handful of hyperscalers.

Enabling solutions

Book-and-claim and EAC platforms

The creation of credible registries to track and retire digital attributes tied to certified low-carbon volumes allows customers and public agencies to “buy impact” even when logistics and distance may prevent physical delivery.

Public procurement

Buyers can embed embodied-carbon thresholds and EPD-based scoring in infrastructure tenders. Strong public procurement policies send a strong demand signal that can help support FOAK plants.

- In the US, federal procurement efforts are waning.[95] Some state programmes now institutionalize EPD-based purchasing and, in several cases, binding GWP thresholds.[96][97]
- In the EU and UK, stronger green public procurement and industrial carbon capture (ICC)/CCS business models are channelling public money towards verifiably low-GWP cement.[98]

Standards and acceptance hubs

Regional consortia and open data platforms are proving effective at turning low-carbon mix innovation into standardized, EPD-verified specifications.

Conclusion

For suppliers, decarbonizing cement is not a chemistry problem – it is a finance problem disguised as one. The technologies exist. The constraint is turning good intentions into long-term, contract-backed cashflows that suppliers can leverage to finance their projects. Offtake commitments, carbon monetization, upfront capital and procurement reform are not side issues; they are the enabling infrastructure that will determine whether the next decade delivers scattered pilots or an investable, scalable industry.

> **The book and claim mechanism creates liquidity in an economic market where buyers of low-carbon materials are geographically dispersed from sites of production. The mechanism allows for buyers of sustainable value and sellers of low-carbon building materials to concentrate demand and supply efficiently and exchange value directly. The publicly announced commercial contract between Microsoft and Sublime Systems would not have been possible without this book and claim mechanism.**
>
> Joe Hicken, Sublime Systems

2.2 Steel – Commercializing pioneering technologies in an evolving policy landscape

Steel contributes

7%

of global CO_2e emissions.[99]

Introduction

Steel is one of the most polluting industrial sectors, contributing approximately 7-9% of global CO_2 emissions, a share that keeps the industry central to national climate strategies and competitiveness debates.[100] In 2024, the International Energy Agency (IEA) helped develop an emerging consensus on practical definitions for near-zero and low-emissions steel and outlined the underlying measurement methodologies needed for interoperability across markets.[101]

The policy environment is shifting in ways that directly affect suppliers' investment cases. The European Union's Carbon Border Adjustment Mechanism (CBAM) entered a transitional reporting phase in October 2023 and moves to its compliance phase in 2026, paced with the phase-out of free allowances in the EU Emissions Trading System (ETS) up to 2034. This transition raises the effective carbon price exposure of conventional industrial production routes while rewarding verifiable low-emissions pathways.[102]

In parallel, buyers' initiatives – from coalitions and certification schemes to sustainable public procurement – are beginning to signal demand and reduce uncertainty. However, suppliers still encounter a fragmented landscape of standards, offtake structures and permitting regimes.[103]

Against this backdrop, leading steel suppliers interviewed for this report consistently underscored both the urgency and complexity of the transition. For suppliers in the vanguard, the transition represents both strategic reinvention and existential pressure. Suppliers voiced caution that capital markets and customer commitments remain limiting factors in attempts to decarbonize the industry.

> “For suppliers in the vanguard, the transition represents both strategic reinvention and existential pressure.

What emerges from these perspectives is a picture of an industry that recognizes its centrality to global decarbonization yet grapples with system-level friction. Suppliers are navigating an investment landscape that is partially incentivized, partially penalized and heavily dependent on the alignment of regulation, finance, buyer commitment and input materials.

This chapter distils the insights shared by suppliers who are operating at the frontier of low-emissions steel, triangulated with credible secondary sources.

Sector landscape and the maturity curve

Technology is shifting

The core technological storyline is clear: steel production is advancing away from high-emissions blast furnace/basic oxygen furnace (BF/BOF) technology towards lower-emissions alternatives, including scrap-based electric arc furnaces (EAF), hydrogen-fuelled direct iron reduction (DRI) with EAF and carbon capture, utilization and storage (CCUS)-enabled transitional pathways – albeit at different paces and with different regional fits.

However, suppliers emphasized that technology readiness is no longer the only challenge – financing, permitting, energy system integration and credible demand are also key variables.

Supply has plateaued

On the supply side, IEA tracking shows that primary near-zero steel projects in the 2030 pipeline have plateaued at ~10 million tonnes (Mt), against more than 100 Mt needed by 2030 on a net-zero pathway, highlighting the gap between ambition and bankable projects.[104] Hydrogen-DRI can close a meaningful share of the emissions gap, but its cost competitiveness hinges on low-cost, reliable renewable power and hydrogen. IEA's comparative cost analysis illustrates the sensitivity of hydrogen-DRI steel costs to electricity and hydrogen price trajectories.[105]

Demand is slowly growing

Demand is nascent but growing. Buyers' platforms and coalitions have begun to aggregate early volumes. Several global and regional initiatives – including the First Movers Coalition[106] and the Rocky Mountain Institute (RMI)[107] – are assembling future demand commitments to underwrite first-of-a-kind plants this decade. Yet as one supplier cautioned, buyers' long-term commitments have softened with shifting macro conditions, even while the technology trajectory remains intact.

On the policy front, CBAM's 2026-2034 phase-in/phase-out with the EU ETS is the fulcrum for Europe's investment logic; complementary lead-market ideas such as standardized definitions and green public procurement criteria are being actively developed to stabilize demand and price signals.[108]

Supplier perspectives: key themes and insights

Offtake and bankability are critical

Bankability is the binding constraint. Many suppliers repeatedly stressed that moving from demonstration scale to commercial scale is fundamentally a financing problem linked to demand visibility. In iron-making projects especially, the development cycle is longer and more capital-intensive than incremental retrofits. This financing reality is reshaping commercial structures. Some suppliers are experimenting with new multi-party configurations, extending beyond traditional steelmaker-supplier relationships to include downstream OEMs and logistics partners. As one project start-up supplier commented, a project like theirs needs to be financed and pre-sell a very large portion of their books through offtake contracts.

Permitting defines pathway

Permitting and "time-to-grid" define the critical pathway. Access to suitable and affordable gigawatt-scale renewables, hydrogen and industrial interconnection requirements are colliding with permitting and local planning processes. Suppliers seeking to co-locate industrial loads with renewable resources also flagged grid congestion, land availability and community acceptance as variables that decide site selection and sequencing.

Demand needs policy support

Demand signals exist but are uneven and often conditional and not guaranteed. Where credible policy backstops and procurement standards are emerging, offtakes are advancing. One European supplier reported substantial future sales across sectors and tied these to buyers' upstream raw material strategies. Still, several suppliers emphasized that policy certainty is as important as private coalitions.

Early market offerings validate willingness to pay, albeit at limited volumes. Producers piloting low-emission grades in select markets are using these runs to test price premium, logistics and other operational and marketing parameters.
This experimentation is essential for learning, yet suppliers noted that premium recovery seldom covers previous cost expenditures without policy support.

> **We can make [our low-carbon steel product] commercially available, even if [volumes are] limited… to open up the market and test willingness to pay a premium.**
>
> Supplier

Policy shields often matter across the entire value chain. Many suppliers argued that CBAM and trade protection policies only work if they cover downstream goods, not just primary steel, so that European producers of green finished goods are not undermined by carbon-intensive imports.

Steel suppliers interviewed for this report highlighted key systemic challenges, opportunities and recommendations in relation to decarbonizing steel production, summarized below.

Systemic challenges

Fragmented standards and accounting

Suppliers see an urgent need for interoperable definitions and measurement rules that take into account complex supply chains. IEA calls for clarifying principles for near-zero definitions and harmonizing greenhouse gas accounting methodologies, to avoid market fragmentation and double counting.[109]

Policy gap between targets and bankability

Europe's CBAM and ETS reforms can raise the floor for high-emitting imports and domestic production, yet lead markets for green steel are still patchy. Germany's Low Emission Steel Standard (LESS) and EU-level efforts to incorporate non-price criteria in procurement are promising templates, but they remain early-stage or non-binding in many jurisdictions.[110]

Energy-system dependencies

The competitiveness of hydrogen-DRI is a function of power prices, electrolyser utilization and hydrogen logistics. Cost parity improves materially with low-cost renewables and hydrogen, but many regions are far from that equilibrium.[111]

Permitting and infrastructure sequencing

Industrial siting, grid interconnects, water and CO_2 transport (where CCUS is relevant) are bottlenecks that reset project-critical paths and delay financial close – an experience echoed across supplier experiences in multiple regions.

Macroeconomic challenges and buyer caution

Several suppliers observed a softening in multi-year offtake appetite amid macro uncertainty – even among historically forward-leaning buyers – complicating financing for first-of-a-kind assets.

Trade and leakage exposure across finished goods

Some trade policies do not sufficiently address the full steel value chain, which can unintentionally erode green producers' market share via finished goods imports embedding high-emissions steel.

Emerging opportunities and enabling levers

Harmonized definitions and verification

Swift convergence on near-zero and low-emissions thresholds, embodied in clearly auditable cradle-to-gate metrics aligned with IEA's measurement guidance, would unlock cross-border recognition and simplify contracting.[112]

Procurement-led markets

Procurement can create price-discoverable segments where green premiums can be observed, benchmarked and gradually competed down.[113] The EU is exploring non-price procurement criteria to value low-emissions attributes in public purchases, while Germany's LESS aims to provide a universal standard for transparent segmentation of low-emissions steel.

Sequenced CBAM and ETS incentives

With CBAM's definitive phase starting in 2026 and ETS's free allowances phasing out up to 2034, policy in Europe provides a time-bound business case: the cost of unabated routes will rise while verified low-emissions routes gain relative advantage. Suppliers are preparing by locking in offtakes and calibrating investment timing to this arc.[114]

> **Policy in Europe provides a time-bound business case: the cost of unabated routes will rise while verified low-emissions routes gain relative advantage.**

Value chain risk-sharing

Innovative contracts, flexible volume offtakes, pay-for-attribute certificates alongside physical shipments and multi-buyer coalitions help spread risk and accelerate FIDs. Early market testing campaigns show that limited volumes can command partial premium recovery and provide learning for both sides.

Geography-smart siting

Suppliers emphasized the importance of multi-site portfolios close to demand centres and advantaged resources (e.g. access to affordable power), rather than single mega-sites. This reflects some of the technology innovations attempt to offer flexible modular upgrades.

Near-term pathways that bank scope 3 gains

Several strategies (e.g. high-quality scrap programmes, low-carbon raw material sourcing, renewable fuels in logistics) are already lowering embodied emissions and are financeable today. One producer noted that coupling the use of biocarbon in steel production and utilization of renewable fuels in shipping could deliver market-ready low-emissions grades at meaningful (if limited) volumes.

Market protection paired with downstream alignment

Suppliers consistently argued that tariff-rate quotas or CBAM-like mechanisms must account not only for primary steel but also for downstream products, to keep pricing signals intact across the chain.

> **You need to protect the whole value chain… up through the end use.**
>
> Fernando Pessanha, Chief Strategy Officer, Hydnum Steel

Strategic recommendations

Adopt common standards to make environmental attributes bankable

Suppliers recommended that governments, buyers and producers converge on near-zero and low-emissions steel definitions, agree common accounting rules and couple these with a single verification passport that travels with the steel coil/plate across borders. This could help reduce transaction costs and turn environmental attributes into bankable collateral for lenders.[115]

Make demand signals investable

Proposals already in place across public and private sectors need strengthening.

- **Public procurement:** Governments can introduce mandatory non-price sustainability criteria for steel-containing public projects above a threshold value, phased by product class, with auditable emissions benchmarks mirroring the EU's emerging direction and Germany's LESS concept.[116]

- **Private sector demand:** Coalitions can expand buyers' voluntary initiatives into multi-year, multi-buyer contracts that include a floor-price, which will help suppliers' financing efforts.[117]

Align CBAM with decarbonization roadmaps

Producers can use the 2026-2034 period (when EU ETS credits phase out) to sequence and accelerate shifts in technology as follows:

- BF/BOF retirement or relining decisions with clear carbon price visibility.
- DRI-EAF conversions where renewable power and hydrogen economics work.
- CCUS build-out where geological and cluster infrastructure exists.

To support this, governments can publish national siting maps that overlay power, hydrogen, CO_2 storage/transport and logistics to reduce developer risk.[118]

Streamline the critical path on permitting and grids

Governments can create ways to streamline industrial permitting with statutory timelines; they can also facilitate grid interconnection milestones for projects meeting near-zero criteria.

Create ways to reduce risk for hydrogen and power inputs

IEA analysis indicates that reaching low electrolytic hydrogen costs is decisive for hydrogen-DRI parity.[119] Government-backed contracts for difference (CfDs) on green hydrogen and renewable power purchase agreements (PPAs) for near-zero steel projects can stabilize opex in early years, tapering support as markets mature.

Protect the full value chain against leakage

Governments can extend CBAM-like treatment or embedded-carbon criteria to downstream products (e.g. autos, appliances, machinery) so green steel signals are not diluted by finished-goods imports. This echoes suppliers' repeated calls to "protect the whole value chain".

Conclusion

Suppliers are unequivocal: the technology is advancing, but the keys to unlocking capital for low-carbon steel include definitions, demand and delivery infrastructure.

Alongside these primary insights, certain policy timelines are forthcoming: the EU's CBAM becomes financially binding in 2026, free ETS allowances decline up to 2034 and definitions for near-zero are converging under IEA's guidance. The project pipeline remains far short of what is required for net-zero pathways by 2030, but specific levers – procurement-led markets, standardized verification, opex de-risking for hydrogen and power, streamlined permitting and value chain-wide leakage protections – can help turn intent into bankable demand.[120]

2.3 Aluminium – powering low carbon aluminium: achieving parity with traditional supply

Aluminium contributes

2%

of global CO_2e emissions.[121]

Introduction

Aluminium demand growth is driven by the transportation sector, power sector, solar frames and cables, buildings and packaging. Producers interviewed for this report emphasized that market conditions and policy design, not technology readiness alone, will determine the pace of decarbonization over the next three to five years.

Two overarching messages come through clearly:

- Near-term economics are challenging. Several interlocutors described thin margins and buyers that still prioritize lowest delivered price, with little room for a green premium.

- Nascent carbon-accounting practices on the buyer side are often based on recycled content rather than the carbon footprint because it is easy to measure, even when a kilogramme-of-scrap proxy says little about the lifecycle footprint of the final product. This misalignment stalls investment in deeper process innovations.

A recent full lifecycle (cradle-to-gate) accounting by the International Aluminium Institute (IAI) places average global emissions at roughly ~14.8 tonnes of CO_2-equivalent per tonne of primary aluminium (tCO_2e/t) produced in 2023, with electricity use in smelting dominating the footprint.[122] The latest industry reporting estimates ~1.10-1.12 gigatonnes (Gt or billion tonnes) CO_2e of sectoral emissions in 2023 (≈2% of global emissions). Meanwhile, total demand for aluminium is showing sustained growth, with producers accelerating low-carbon power sourcing, inert-anode pilots and expansions in recycling.[123]

This chapter reflects insights from leading suppliers operating across primary and recycled aluminium value chains. Their collective perspectives reveal both the technological readiness of the industry and the structural barriers that continue to slow investment. Suppliers agree that the sector's challenge is no longer invention but value-building policies and markets that reward verifiable decarbonization rather than proxy indicators.

Sector landscape and maturity curve

Emissions reality

Globally, the aluminium sector's emissions intensity has been declining, but not fast enough to meet net-zero targets. Recycled routes are dramatically less carbon-intensive on a process basis (~0.3-0.6 tCO_2e/t), although totals depend on electricity and scrap logistics. This puts decarbonization of primary aluminium production to the top of industrial priorities, where electricity remains the dominant driver of primary smelting emissions – offering 70% of decarbonizing potential.[124]

Power is key

Suppliers stressed that electricity not only determines their carbon footprint but also accounts for a major portion of operating cash costs. IEA underscores that decarbonizing power is a "key complement" to reducing aluminium's indirect emissions; it is also the swing factor in siting decisions for both primary smelters and low-carbon smelters.

Decarbonization levers

Commercially deployed levers today include energy efficiency (e.g. line losses, anode/cathode improvements), renewable power purchase agreements (PPAs) for smelters and casthouses, and high post-consumer scrap remelting with improved sorting.

Stepping-up tier includes electrified or hybrid calciners for alumina refining, biomass/co-firing for anode baking and fuel-switching to gas or hydrogen where infrastructure exists.

Breakthrough level technology includes inert-anode smelting (e.g. ELYSIS) that eliminates direct process CO_2 by producing oxygen at the anode; and point-source CO_2 capture on alumina calciners that can push intensities down towards 2.0 tCO_2e/t or below, when paired with clean power. Multiple recent announcements confirm industrial-scale demonstrations of inert anodes, with producers and governments financing pilots now.[125]

Ambition ladder

Interviewees proposed an ambition ladder to target 3.0 tCO_2e/t or less:

- "3.0 by 2030" is achievable with current technology, such as upgrading boilers and calciners.
- To achieve 2.0 tCO_2e/t, carbon capture on refining and pre-bake steps is needed.
- Below 2.0 tCO_2e/t requires CCUS and/or zero-emissions smelting (with inert anodes) for new lines.

Supplier perspectives: key themes and insights

Market dynamics and pricing gaps

Suppliers report that low-carbon primary aluminium does not yet command a consistent market premium outside Europe, limiting their ability to justify new investment. They note that a carbon price or equivalent signal roughly aligned with the European Union's Emission Trading System (ETS) range would be necessary to close the cost gap between conventional and decarbonized products.

Despite early traction in the automotive and packaging sectors, demand remains largely voluntary. Suppliers stress that until buyers integrate carbon costs into procurement, decarbonization will depend on first-mover partnerships and niche offtake agreements.

Policy and regulatory misalignment

Many suppliers are welcoming new border adjustment and trading mechanisms but emphasize that incomplete carbon accounting distorts competitiveness. They highlight that the EU's current Carbon Border Adjustment Mechanism (CBAM) excludes emissions from scope 2 (electricity) and alumina refining – an omission that disadvantages suppliers utilizing renewable power.

> **It's impossible to produce aluminium without power and alumina… [if you exclude them from emissions accounting] you won't reduce emissions.**
>
> Leandro Faria, Sustainability General Manager, Companhia Brasileira de Alumínio (CBA)

Suppliers advocate for harmonized global methodologies to comprehensively measure emissions under the IAI and for integrating all relevant scopes into carbon border frameworks to ensure that policies can reward true abatement. The European Commission's public guidance confirms that, during CBAM's transitional phase, indirect emissions are not yet included for several CBAM product groups, leaving treatment for aluminium unsettled today – a cause of considerable concern for suppliers.[126]

Technology and investment constraints

Suppliers agreed that decarbonization technologies are becoming increasingly available but remain economically out of reach without stable policy support. Near-term efficiency upgrades are self-financing, but breakthrough investments require shared risk through public-private mechanisms. One supplier noted that they had already implemented all profitable improvements.

> **The next stage of investments requires that the market start paying for the greener aluminium.**
>
> Rafael Fuertes, Vice President & Head of Hydro Strategic Partnerships, Hydro Aluminium

Capital intensity remains high

CCUS and hydrogen fuel-switching could increase production costs significantly. Access to renewable energy and permitting timelines for grid or transmission expansion are equally decisive factors for competitiveness.

Buyer behaviour and education on primary vs. recycled

A recurring challenge is internal misalignment within buyer organizations. Sustainability teams set ambitious targets, but procurement departments often stick to conventional requests for quotes (RFQs). According to interviewed suppliers, there is no internal alignment within the customer between procurement and top management. For more information on this, see the World Economic Forum's report, *Green Procurement Playbook: The CPO's Guide to Delivering Value for Business and Planet*, published in October 2025.

Discussions fluctuate between requests for low-carbon primary aluminium or for recycled content, without understanding the overall lifecycle carbon footprint. Suppliers acknowledged the market confusion caused by labelling both low-carbon primary and recycled products under the same "low-carbon" umbrella – and noted their own push to define recycled aluminium as low-carbon when it is produced specifically from post-consumer scrap. Customer education on the topic remains a high priority.

Many suppliers encourage the development of standardized procurement templates and buyer education programmes coordinated through initiatives such as the First Movers Coalition, to ensure that purchasing decisions reflect verified carbon data rather than simplified proxies.

Systemic challenges

Across both primary and secondary segments, suppliers identified five interdependent structural barriers to aluminium industry decarbonization:

- **Uneven carbon pricing and absent market premiums**, which deter long-term investment.
- **Infrastructure and energy limitations**, as renewable power and transmission lag technology readiness.
- **Fragmented standards and accounting methodologies**, creating verification costs and distortions.
- **First-of-a-kind financing gaps**, with high-capex projects unable to access debt without policy backstops.
- **Procurement misalignment**, where buyers prioritize recycled percentage over total verified footprint.

These constraints reinforce each other, sustaining a confidence gap between what suppliers can technically deliver and what markets and regulations currently enable.

To address these constraints, suppliers interviewed for this report identified the following opportunities, enabling levers and recommendations.

Emerging opportunities and enabling levers

Converging on "3.0 by 2030" as a credible anchor

Technical roadmaps are converging around a near-term 3.0 tCO_2e/t target (cradle-to-gate, including power and refining). Suppliers consistently maintained that the 3-tonne target is deliverable this decade with retrofits to refining and smelting, and with cleaner power – but *only if* buyers send the demand signals.

That narrative gives purchasers and financiers a concrete stepwise trajectory: 3.0 tCO_2e/t this decade, 2.0 in the 2030s for existing assets and sub-2.0 for new builds with inert anodes and CCS.

> **3.0 we can achieve with present technology… for 2.0, then we need carbon capture.**
>
> Supplier interviewee

Carbon intensity-based procurement – move from "% recycled" to "tCO_2e/kg Al"

The industry should adopt standardized, third party-verified environmental production declarations (EPDs) or product greenhouse gas disclosures that report cradle-to-gate intensity. These calculations must use consistent boundaries (including the entire bauxite > alumina > smelting > casting process), while defining the share of post-consumer scrap.

Existing guidance, such as IAI's product-level carbon footprint methodology,[127] can reduce ambiguity and enable consistent evaluation across suppliers. Buyers could potentially set target bands (e.g. ≤3.0 or ≤2.0 tCO_2e/t) rather than single points and align them with contract price escalators.[128]

> **Buyers could potentially set target bands (e.g. ≤3.0 or ≤2.0 tCO_2e/t) rather than single points and align them with contract price escalators.**

Clarify CBAM boundaries and recognition

Suppliers proposed aligning the EU's and UK's approaches to measure and include indirect emissions and alumina refining. In the EU, suppliers urged clarity on the timeline and methodology for including indirect emissions and for recognizing carbon costs already paid in producer countries. In the UK, the government's intent to price both direct and indirect emissions should be paired with robust mechanisms to recognize clean power procurement and upstream carbon cost exposure. Done properly, convergence would reward genuinely low-carbon metal and avoid arbitrage.[129]

Power-contract innovation as a decarbonization lever

Since electricity dominates both cost and footprint, aluminium offtake should be coupled with *power* offtake solutions (e.g. sleeved PPAs). The objective is to hedge power-price risk and to lock in the carbon reduction benefits that buyers are paying for. IEA's analysis reinforces that power-sector decarbonization is inseparable from aluminium's low-carbon trajectory.[130]

Strategic recommendations

For purchasers and OEMs

- Set explicit, carbon-intensity thresholds in RFQs, disclose the boundary (cradle-to-gate) and specify minimum post-consumer shares with measurement guidance.
- Replace "% recycled" as the headline proxy with intensity-plus-scrap and book into multi-year offtakes that index price premiums to recognized carbon prices (EU ETS, UK ETS) and certified intensity reductions.
- Build internal coherence by aligning sustainability targets with procurement scorecards – supplier interviews suggest the gap between C-suite intent and RFQ language is a prime blocker today.

> **Supplier interviews suggest the gap between C-suite intent and RFQ language is a prime blocker today.**

For policy-makers

- Close CBAM boundary gaps: include electricity (indirect) in chargeable emissions with robust recognition of clean power contracts; consider bringing alumina into scope or otherwise recognizing refining emissions; and harmonize with UK design to avoid arbitrage.
- The European Commission's ongoing work to simplify and strengthen CBAM and to explore downstream coverage provides an opportunity to correct known distortions before full charging starts.
- Use ETS revenues to fund material CfDs that bridge the step-change to 3.0 tCO_2e/t and first wave to 2.0 tCO_2e/t.[131]

For financiers

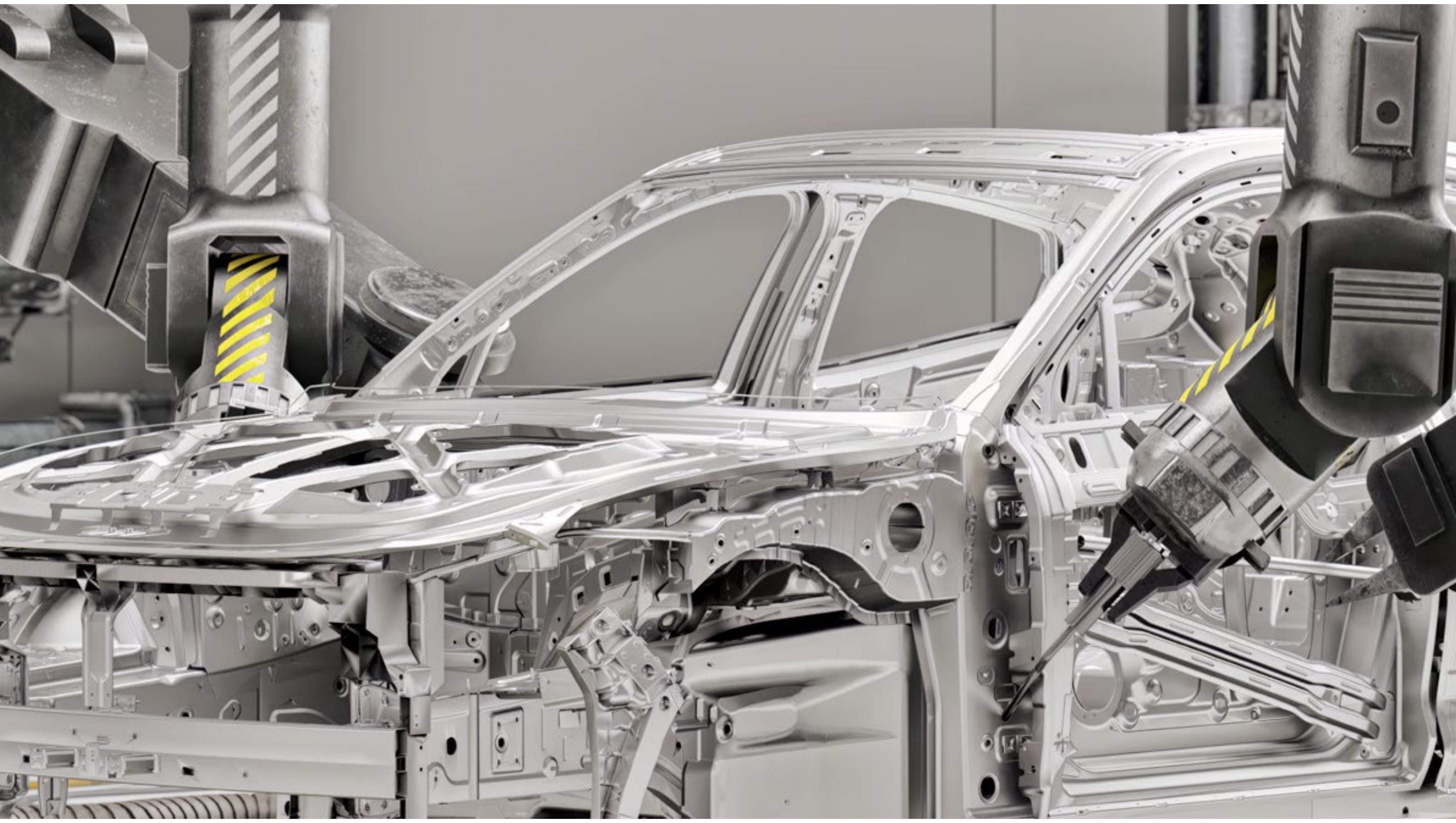
- Underwrite "3.0 by 2030" packages that combine:
- Customer offtake with minimum carbon floors and step-up volumes.
- Indexed pricing or CfDs.
- Dedicated power hedges (e.g. renewable PPAs + storage).
- Prioritize projects in grids where marginal electricity emissions are falling fast and CO_2 transport/storage options are bankable.

Conclusion

The suppliers interviewed for this report were clear: technology is not the bottleneck, the market signal is.

Where price signals exist as a result of ETS-linked obligations or buyers willing to pay for verified intensities, capital can move from efficiency retrofits into deeper process upgrades. Where policy boundaries exclude electricity and alumina, where RFQs conflate recycled content with carbon performance and where offtake stops at one- or two-year pilots, the result is predictable: projects stall in the pre-FID valley of death.

The near-term path is practical and specific. Buyers can unlock scale by specifying intensity bands, rewarding post-consumer scrap and signing bankable tenors. Policy-makers can help to repair boundary gaps in CBAM and recycle carbon revenues into CfDs that bridge the next tranche of capex. Financiers can syndicate risk across offtake, power and carbon revenue so that suppliers can underwrite calciners, anode plants and power-switching at pace. Meanwhile industry platforms can keep score publicly on contracts that actually move tonnage.



2.4 Carbon dioxide removal (CDR) – creating a market structure to commercialize proven technologies

Introduction

Carbon dioxide removal (CDR) has increasingly become a key pathway for many global companies' net-zero strategies. While mitigation and avoidance remain core aspects of addressing emissions, durable carbon removal is a critical pathway.

This chapter presents insights from suppliers working across three principal CDR pathways – biochar, direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS). Their experiences highlight an industry driven by public policy, yet constrained by regional variations in those policies, inconsistent demand and limited access to finance.

Early corporate buyers, emerging compliance signals and government investment are bringing carbon removal from the small pilot scale projects towards the mainstream. Still, suppliers describe a market in need of a coherent market structure. They face inconsistent pricing in voluntary markets, shifting standards and uncertain incentives. Beneath these operational issues lies a deeper challenge: maintaining societal and investor confidence in the value of removal itself.

> **We are fighting against apathy as much as we are fighting against carbon.**
>
> Josiah Hunt, Pacific Biochar

Sector landscape and maturity curve

Three distinct pathways dominate the CDR sector today, outlined below.

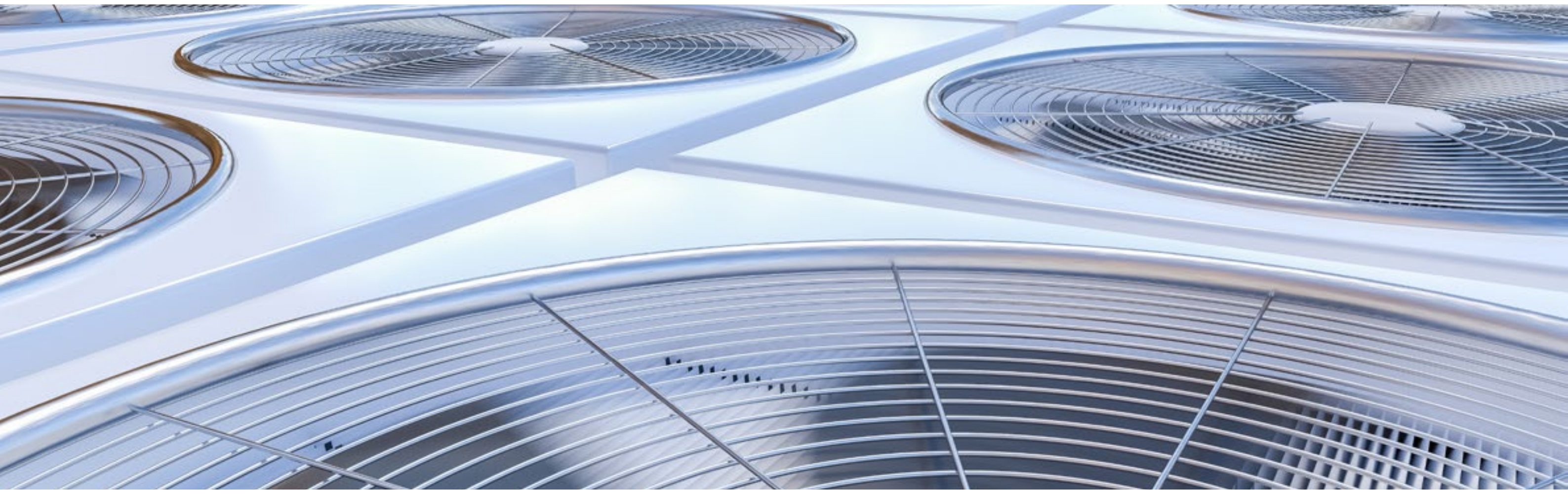
Biochar

Biochar producers convert agricultural residues and organic waste into a stable, carbon-rich material that can lock away carbon for centuries while improving soil fertility. Recognition of biochar in many leading carbon-credit frameworks has transformed what had been a small agricultural input business into a climate-solution industry. Yet credit prices fluctuate, methodologies are evolving and the cost of verification remains high. Long-term confidence depends on stable credit valuation and sustained buyer demand for high-durability removal.

Direct air capture (DAC)

DAC systems use chemical and mineral processes to capture CO_2 directly from ambient air. The technology has proven viable; however, the economics remain a key challenge. Capital expenditure and energy intensity remain formidable barriers.

> **DAC solutions like Heirloom's are ready to scale — the real challenge is deploying them fast enough with affordable power and permitted carbon storage.**
>
> Max Scholten, Head of Commercialization, Heirloom



Developers are pursuing modular designs and locating projects near renewable energy hubs, but financing and permitting continue to slow expansion.

Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage integrates capture technology into existing biomass facilities, producing renewable energy while permanently removing CO_2. The technology is mature, but deployment is limited by feedstock logistics and the slow build-out of storage and pipeline infrastructure. In Europe, cluster-based initiatives – such as the North Sea storage network – illustrate how shared assets can improve bankability. In the US, policy uncertainty around the long-term future of supportive tax credits remains a concern.

> **We can deliver clean power and carbon removal at once, but only one of those has a clear market price.**
>
> Dawn Whitworth, Vice President, Communications and Business Development, Elimini, Drax Group

Although the three approaches differ in scale, permanence and maturity, all often confront the same structural paradox: proven capability without stable market architecture.

Suppliers interviewed for this report identified the following key themes, insights and opportunities.

Supplier perspectives: key themes and insights

Economic viability

Suppliers operate amid volatile demand and fluctuating buyer expectations. Biochar and BECCS rely on dual revenue streams – product sales and carbon credits – but the latter dominates financial planning. DAC remains capital-intensive and dependent on a limited set of advance-purchase buyers. Across technologies, suppliers called for long-term offtake agreements that mimic power-purchase contracts to stabilize revenues.

Inconsistent markets

Limited liquidity and sporadic demand cause price fluctuations that discourage investment. The same tonne of CO_2 can trade at $10 or $600 depending on buyer sentiment.

Policy uncertainty

The current global policy landscape is varied and lacks global cohesion. While some policies are supportive – including the EU's Carbon Removal Certification Framework (CRCF) and certain US tax credits – suppliers were concerned about the evolving geopolitical landscape and the fear that this could undermine investor confidence. Suppliers maintained that regulation should evolve towards consistency across jurisdictions and remain durable over the long term.

Financing limitations

Without standardized offtake structures, lenders hesitate to provide debt financing. Many projects rely on equity or grants, which help get the project started, but cannot sufficiently finance large-scale capacity. Suppliers repeatedly compared their predicament to early renewable energy developers before standardized power purchase agreements (PPAs) created bankability. They support blended finance – combining public guarantees with private capital – to bridge the first-of-a-kind funding gap.[132]

Infrastructure gaps

DAC and BECCS require CO_2 transport and storage networks; biochar depends on reliable biomass supply chains. Permitting delays for critical infrastructure pose a key risk to projects and can potentially extend timelines by years. Suppliers viewed shared infrastructure as a public good – analogous to power grids – which could therefore be a target for public investment.

Buyer behaviour

The buyer base remains limited, dominated by forward-leaning technology firms and philanthropic coalitions. Hard-to-abate industries have yet to engage meaningfully. Suppliers emphasized that buyers with in-house carbon expertise are the most effective partners, underscoring the need for corporate capacity building.

> **We can work within strict frameworks – but timely implementation is important.**
>
> Dawn Whitworth, Vice President, Communications and Business Development, Elimini, Drax Group

Emerging opportunities and enabling levers

Suppliers interviewed for this report expressed guarded optimism that the building blocks of a durable market are taking shape, as outlined below.

Policy coherence

Some initiatives, such as the EU's CRCF and the UK's Emission Trading Scheme (ETS) review, indicate growing governmental commitment in some jurisdictions. The next step is harmonization – establishing common criteria for permanence, measurement and additionality so that credits are interchangeable globally.

Financial innovation

Suppliers highlighted the need for standardized long-term offtake contracts (e.g. renewable energy PPAs) and blended finance instruments that share early-stage risk between public and private actors. These mechanisms could replicate the cost-reduction trajectory once achieved in the wind and solar industries.[133]

Infrastructure collaboration

The North Sea and Nordic industrial clusters illustrate how shared CO_2 transport and storage can de-risk projects. Biochar producers propose regional feedstock alliances to coordinate sourcing and logistics.

Cross-sector partnerships

Suppliers are increasingly collaborating across industries – linking removers with emitters, farmers with biochar producers and energy utilities with BECCS operators – to integrate removal into existing value chains. Such partnerships can blur the line between mitigation and removal and accelerate normalization of CDR as infrastructure.

Conclusion

Interviews with CDR suppliers made one message clear: the technologies are ready, but the supporting systems are not there yet. The next decade will determine whether carbon removal becomes a permanent fixture of the global economy or remains a fragmented experiment.

Suppliers envision a future where CDR is treated as essential infrastructure – planned, financed and regulated alongside energy, water and transport. Achieving this vision will likely require converting belief into durable systems: common policy that can endure, finance that values permanence and markets that reward integrity.

> **Five years ago, we were explaining what carbon removal was. Now, we're explaining how fast we can build it.**
>
> Dawn Whitworth, Vice President, Communications and Business Development, Elimini, Drax Group

2.5 Materials cross-sector – converging realities across low-carbon materials suppliers

Across the cement and concrete, steel, aluminium and carbon dioxide removal (CDR) sectors, suppliers related many similar challenges that stand in the way of faster decarbonization. While technologies and market structures differ sector by sector, some common barriers to progress continue to dominate supplier feedback:

- Policy differences.
- Weak market signals.
- Divergent standards.
- Unresolved financing.

This chapter addresses how suppliers interviewed for this report viewed these themes from the perspective of cross-sector solutions and future stakeholder collaboration.

Policy: differences and fragmentation impact demand visibility

Across all three materials sectors plus CDR, greater policy harmonization and predictability offer potential ways to support progress in decarbonization. Regulatory approaches, carbon pricing mechanisms and incentive schemes differ not only between countries, but often within a single market.

For example, many aluminium and steel producers said the limited scope and shifting parameters of instruments such as the EU Carbon Border Adjustment Mechanism, which may exclude certain processes or emissions sources, creates an uneven playing field. Similarly, CDR project developers must navigate a global patchwork of credits and eligibility rules, such as evolving tax incentives and nascent standards for carbon removals, which create uncertainty and impact investments.

Cement/concrete suppliers reported similar challenges, especially as the strength of policy signals varies by jurisdiction. For all materials, policy changes globally can be frequent or abrupt, further destabilizing forward planning. Many suppliers described significant resources being spent on tracking and interpreting these changes, rather than innovating or scaling-up solutions.

This disparate and evolving policy landscape makes long-term planning extremely challenging and often dampens the appetite for capital-intensive decarbonization projects.

Market signals: weak, unpredictable or misaligned with industrial perspective

A second, closely connected barrier is the lack of reliable, value-driving market signals aligned with actual decarbonization impact. Suppliers observe that, while there is growing support for “low-carbon” procurement, real-world buyer behaviour often fails to support the required technology transitions.

Weak or inconsistent product premiums mean firms that invest in breakthrough carbon reduction methods rarely see these rewarded in contract prices or long-term market access. For instance, aluminium and steel suppliers highlighted that contracts often prioritize recycled content or cost savings, rather than lifecycle carbon intensity, dampening incentives for process innovation.

Cement/concrete and CDR suppliers similarly pointed out that offtake arrangements rarely extend beyond short-term purchase cycles. The absence of multi-year, standardized contracts means lenders and investors often view such projects as risky – given there is no secure revenue base to underwrite plant financing.

Many suppliers describe a tendency among buyers to select the minimum viable option, rather than partnering on shared investment in truly novel solutions. The result is that projects remain stuck in pilot or demonstration phases, as suppliers are forced to chase near-term or marginal requirements rather than investing boldly in long-term breakthroughs.

Standards and accounting: divergent metrics create market friction

Suppliers from the four industries highlighted serious consequences from the lack of unified accounting and standards. What constitutes a “low-carbon” or “sustainable” product may vary across governments, industries and buyers, with each applying different definitions and emission boundaries.

For example, a steel product may qualify as “net zero” under one regime if it leverages renewable electricity, yet be excluded under another that does not count scope 2 emissions reductions. CDR and cement/concrete suppliers face shifting verification targets, with evolving criteria on issues such as permanence and additionality that change between project types, buyers and geographies.

The proliferation of reporting systems and certification schemes often brings high administrative costs, particularly for smaller suppliers who lack dedicated compliance teams. Many must prepare multiple sets of documentation for different buyers, jurisdictions and purposes – from environmental product declarations for cement/concrete to managing a portfolio of carbon credits for a removals project – adding both direct and indirect costs.

This friction ultimately delays market entry for new technologies and sows uncertainty that can discourage both buyers and investors. Suppliers interviewed for this report indicated that without a globally recognized standard for verification, the environmental integrity of these claims is also undermined, making it harder for leaders in decarbonization to differentiate themselves.

Financing: demand risk is the dominant blocker

Financing constraints, especially related to demand risk, are seen by suppliers as the most pivotal barrier across all sectors. Decarbonizing major industrial processes or establishing new CDR facilities requires enormous upfront investment and long payoff horizons, which are only feasible when there is reliable, multi-year demand for the resulting lower-carbon products or services.

However, as highlighted above, the combination of changing policy signals, lack of standardized offtake agreements and inconsistencies in product certification all compound the sense of risk for lenders and investors. In practice, this means many such projects must rely on limited public grants, philanthropic capital or equity investment – resources that are often neither large enough nor reliable enough to deliver a genuine scale-up.

Multiple suppliers in steel, cement/concrete and CDR described an urgent need for new financial structures that blend public and private capital and share risk more evenly. Some proposed contracts-for-difference, insurance instruments or pooled buyer syndicates to guarantee revenues or underwrite early offtake. Others stressed the necessity of harmonized finance terms and the creation of standardized, investable contract templates for all buyers and suppliers in the value chain.

Until investors have confidence that the products can be sold, at scale, with a clear premium or stable offtake, transformative capital will likely remain on the sidelines and most projects will remain at early-stage scale.

Conclusion: foundation for unified progress

Many suppliers in aluminium, CDR, cement/concrete and steel interviewed for this report were aligned in their call for greater policy clarity, robust and reliable market signals, common standards and accessible financing models that shift risk-sharing and rewards towards first movers.

Overcoming historic fragmentation demands collaboration across governments, buyers and financiers as well as industry actors. By focusing on these shared challenges, stakeholders can unlock new scale and speed for decarbonization – and help move heavy industries beyond pilot projects towards system-wide transformation.

Conclusion

Decarbonization in hard-to-abate industries is advancing. But it is uneven – shaped as much by coordination and trust as by cost curves or mandates.

Across high-emitting sectors and regions, the low-carbon supplier stands at the centre of industrial decarbonization's most immediate realities. Their perspectives shared in this report have revealed that progress is not defined solely by technology maturity or emissions reduction ambitions, but by the strength of the networks that link them – policy durability, infrastructure readiness and access to finance.

This report has aimed to highlight the views of industrial actors on the ground, leading the retrofit of refineries and smelters, spearheading fuel conversion or piloting new electrolyser technology. Through extensive supplier dialogue across the seven high-emitting sectors of the First Movers Coalition and First Suppliers Hub, one insight resounds – transition is advancing, but unevenly, shaped as much by coordination and trust as by cost curves or mandates.

The sectoral deep-dives illustrate the specificity and nuance of each market. Yet, when viewed together, common patterns are clearly visible. Low-carbon product suppliers confront fragmented policies that can complicate long-term planning, infrastructure gaps that cap achievable volumes and financing structures that often remain misaligned with emerging risk profiles.

These shared challenges also point to shared opportunities. Cross-sector collaboration, for example through multi-modal infrastructure nodes,[134] standardized measurement and certification systems and blended finance mechanisms, may offer pragmatic routes to efficiency and scale. Such collaboration will not erase sectoral nuances, but it can compress learning curves and lower capital costs across the broader ecosystem.

For many policy-makers, financiers and corporate buyers alike, the voice of the low-carbon supplier is not background noise but a diagnostic signal. It pinpoints the place where ambition meets challenge, where targeted coordination could unlock tangible progress. The next stage of the transition will largely depend on elevating that voice from consultation to co-design, embedding supplier experience into how markets, mandates and financing mechanisms are built.

Appendix

First Suppliers Hub technology readiness level (TRL) tables

Note: IEA's technology maturity level (TML) 10 and 11 go beyond the traditional technology readiness level (TRL) by addressing large-scale system integration and broader market deployment.

However, to remain consistent with widely recognized definitions, such as those in ISO 16290, the EU Horizon framework and the US Department of Energy, this report consolidates these advanced TMLs under TRL 9. Consequently, in the frameworks below, TRL 9 denotes a technology that has been fully demonstrated in an operational environment. Aligning IEA's maturity levels with TRL 9 ensures clarity and comparability across international technology assessment standards.

Aluminium

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Electric calcination during alumina refining	Natural gas use in the calcination process is replaced by electric heating.	7	IEA, 2025. ETP Clean Energy Technology Guide	Calix has developed a technology called ZEAL (Zero Emissions Alumina), which is an indirectly heated electric calciner designed to replace combustion-based calciners in alumina refining. Calix has signed a memorandum of understanding (MoU) to jointly develop scalable electric alumina calcination systems (based on ZEAL) with an alumina company.	Calix, 2023. Decarbonising alumina with Calix technology
Heat exchangers during smelting	Heat exchangers control the loss of heat during aluminium smelting, allowing electricity consumption to be ramped up or down without impacting the production process. This allows smelters to consume electricity when prices are low, or store energy in molten aluminium when prices are high.	8	IEA, 2025. ETP Clean Energy Technology Guide	ALUVATION is a developer of a mobile heat-treating system designed to optimize aluminium component usage and minimize CO_2 emissions. The company's system is connected to a data network and consists of standardized furnace modules for annealing and cooling down materials, enabling clients to get flexibility in application.	Aluvation, 2015. Aluvation: modular heat treatment for aluminium
Hydrogen calcination during alumina refining	Natural gas use in the calcination process is replaced by renewable hydrogen.	4	IEA, 2025. ETP Clean Energy Technology Guide	Rio Tinto, in partnership with Sumitomo Corporation (via Summit Hydrogen Gladstone), is executing a Yarwun hydrogen calcination pilot demonstration programme. They are retrofitting one of their calciners to be able to run (partially or fully) with hydrogen burners, replacing natural gas in the calcination step. They are installing a 2.5 MW electrolyser on site to produce hydrogen (≈ 250–300 tonnes/year) to fuel the retrofit calciner.	Rio Tinto, 2024. Yarwun hydrogen calcination pilot for low-carbon alumina
Inert anode during smelting	Inert anodes replace carbon anodes which, when used, react with oxygen to produce CO_2. A non-consumable (inert) anode avoids the formation of this CO_2, producing only pure oxygen.	7	IEA, 2025. ETP Clean Energy Technology Guide	ELYSIS is a joint venture between Alcoa and Rio Tinto focused on replacing carbon anodes with inert anodes in aluminium smelting. They are commissioning industrial prototype cells (450 kA) using inert anode technology.	Alcoa, 2018. ELYSIS: zero-carbon aluminium smelting technology

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Mechanical vapour recompression during alumina refining	Wastewater vapour is captured at relatively low pressures and is recompressed through a series of fans and compressors, to bring it up to the temperature and pressure required.	7	Deloitte analysis First of its kind demonstration facility for alumina; large-scale deployment at food grade temperatures.	The Alcoa mechanical vapour recompression (MVR) for low carbon alumina refining project seeks to demonstrate the feasibility of integrating MVR, powered by renewable energy, to electrify steam production in the alumina refining process thus displacing fossil-fuelled boiler steam. Upon success, the plan is to install a 4 MW MVR module integrated into the evaporation circuit at Wagerup, powered by renewable energy.	Australian Renewable Energy Agency (ARENA), 2022. mechanical vapour recompression for low-carbon alumina refining
Multi-polar cells during smelting	Multi-polar cells are an advanced technology used in aluminium smelting. In traditional aluminium smelting, a single anode is used to produce aluminium from aluminium oxide, which requires a large amount of energy and releases significant amounts of CO_2. Multi-polar cell technology uses multiple electrodes, which reduces the energy consumption and CO_2 emissions of the process. This technology operates at a higher current density and reduces the cell voltage, making the process more efficient with fewer emissions.	5	IEA, 2025. ETP Clean Energy Technology Guide	It is a relatively niche/future-oriented cell architecture.	INCARBZERO, 2023. Primary smelting with multipolar cell: clean energy technologies

Aviation

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)	Conversion of cellulosic or starchy alcohols (isobutanol and ethanol) into a drop-in fuel occurs through a series of chemical reactions – dehydration, hydrogenation, oligomerization and hydrotreatment. The alcohols are derived from cellulosic or starchy feedstocks via fermentation or gasification. Ethanol and isobutanol produced from lignocellulosic biomass (such as corn stover) are considered favourable feedstocks, although other potential sources (not yet approved by American Society for Testing and Minerals (ASTM)) include methanol, iso-propanol and long-chain fatty alcohols. ASTM approval was granted in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit.	7-8	IEA, 2025. ETP Clean Energy Technology Guide	LanzaJet is a leading player in the ATJ technology space. Renowned for its proprietary processes that convert various low-carbon alcohols – including ethanol and isobutanol – into SAF, LanzaJet's Freedom Pines facility in Georgia, USA, is set to become the first small-scale commercial ATJ plant. The company participates in multiple projects worldwide, such as the LanzaTech DRAGON SAF project in the UK and Project Ulysses in Australia.	IEA Bioenergy, 2024. Progress in commercialisation of biojet/sustainable aviation fuels (SAF)
Catalytic hydrothermolysis synthesized kerosene	Also known as hydrothermal liquefaction (HTL), this process combines clean free fatty acid oil from processing waste oils or energy oils with preheated feed water, which is then passed through a catalytic hydrothermolysis reactor. Feedstocks for the CH-SPK process include a range of triglyceride-based materials, such as soybean oil, jatropha oil, camelina oil, carinata oil and tung oil. ASTM approval was given in February 2020 with a 50% blend limit.	4-5	IEA, 2025. ETP Clean Energy Technology Guide	Project Firefly (Firefly Green Fuels, UK) intends to convert treated human sewage (biosolids) into SAF using HTL, producing biocrude that is subsequently hydroprocessed to jet fuel. A pilot project is planned for Haltermann Carless's Harwich refinery in Essex. Applied Research Associates (ARA) developed the Biofuels ISOCONVERSION (BIC) process, which utilizes catalytic hydrothermolysis to produce sustainable fuels. They have partnered with Chevron Lummus Global (CLG) to further develop and commercialize the BIC process.	Firefly Green Fuels, 2024. Significant progress made towards commercialisation Advanced Biofuels USA, 2020. ASTM approves ARA's synthetic kerosene process for the production of sustainable aviation fuel
Fats, oils and greases (FOG) co-processing	ASTM has approved 5% fats, oils and greases co-processing with petroleum intermediates as a potential SAF pathway. Used cooking oil and waste animal fats are among the popular sources for co-processing. The UK fuel specification DEF STAN 91-091 currently allows co-processing for up to 30%, an increase from the previous 5% limit.	9	Deloitte analysis ASTM-approved, commercially available, actively used by major refiners.	OMV produces SAF by co-processing used cooking oil (UCO) in the Schwechat refinery's existing hydroprocessing units, supplying the resultant SAF via pipeline to Vienna Airport for Austrian Airlines. The companies delivered approximately 1,500 tonnes in 2022, marking the first Austrian production and use of SAF, with ongoing deliveries planned. Honeywell UOP offers co-processing technologies such as hydrotreating and hydrocracking to produce renewable diesel and partial SAF from diverse FOGs.	OMV, 2021. OMV and Austrian Airlines are taking off with sustainable aviation fuel Honeywell UOP, 2024. Fuel a change for the better, co-processing technologies

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Fischer-Tropsch (FT) synthetic paraffinic kerosene (SPK)	Woody biomass is converted to syngas through gasification, after which a Fischer-Tropsch synthesis reaction transforms the syngas into jet fuel. Feedstocks include a variety of renewable biomass sources, primarily woody biomass such as municipal solid waste, agricultural residues, forest waste, wood and energy crops. ASTM approval was granted in June 2009 with a 50% blend limit.	7-8	IEA, 2025. ETP Clean Energy Technology Guide	Honeywell UOP's FT Unicracking® technology enables the conversion of liquids and waxes from various waste sources into Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), an ASTM D7566-approved form of SAF. Velocys has produced 2,366 litres of ASTM D7566 Annex A1-certified FT-SAF from woody biomass, which was used on a Japan Airlines commercial flight in their first integrated end-to-end demonstration in Japan.	Honeywell UOP, 2024. FT UniCracking™ technology for renewable fuels Velocys, 2024. Proving sustainable aviation fuel from woody biomass in Japan
FT co-processing	In association with the University of Dayton Research Institute, ASTM approved the co-processing of 5% Fischer-Tropsch syncrude with petroleum crude oil to produce SAF.	7-8	Deloitte analysis Demonstrated at scale, ASTM-approved, early commercial deployment underway.	Honeywell is also active in FT co-processing via their hydrocracking technology, recently announcing advancements that combine hydrocracking with the Fischer-Tropsch process to broaden SAF feedstock options. DG Fuels has selected Honeywell's FT Unicracking technology for its biofuels manufacturing facility in Louisiana.	Honeywell, 2024. Honeywell technology helping to produce sustainable aviation fuel with lower cost and waste
FT-SPK with aromatics	Biomass is converted to syngas, which is subsequently converted to synthetic paraffinic kerosene and aromatics by Fischer-Tropsch synthesis, with the addition of aromatic components. This process was ASTM-approved in November 2015 with a 50% blend limit.	7-8	Deloitte analysis FT-based SAF is cited as nearing commercial rather than fully mature.	Virent is progressing an application under ASTM D4054 for a pure aromatic stream – synthetic aromatic kerosene (SAK) – which can be blended with synthetic paraffinic kerosene (SPK) derived from pathways such as HEFA or FT. A blend of HEFA-SPK (88%) and Virent SAK (12%) was recently used on Virgin Atlantic's 100% SAF transatlantic flight, preparing the path for drop-in alternative jet fuel. Virent is nearing the final stage of required testing.	IEA Bioenergy, 2024. Task 39: sustainable aviation fuel (SAF) report
Hydroprocessed esters and fatty acids (HEFA)	Triglyceride feedstocks such as plant oil, animal oil, yellow or brown greases, or waste fats, oils and greases are hydroprocessed to break apart the long fatty acid chains, followed by hydroisomerization and hydrocracking. This pathway yields a drop-in fuel and was ASTM-approved in July 2011 with a 50% blend limit.	9	IEA, 2025. ETP Clean Energy Technology Guide	Neste and World Energy have been producing SAF for several years and there is now a growing number of facilities aiming for SAF production, largely encouraged by supportive policies in the US and EU. Numerous new facilities have been announced for SAF production through the hydrotreatment of fats and oils, although some recent HEFA projects have been cancelled by major oil and gas companies.	IEA Bioenergy, 2024. Task 39: sustainable aviation fuel (SAF) report

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Hydroprocessed fermented sugars to synthetic isoparaffins (HFS-SIP)	Microbial conversion of sugars into hydrocarbons is also used; feedstocks include cellulosic biomass (such as herbaceous biomass and corn stover). Pretreated waste fats, oils and greases can also serve as eligible feedstocks. This approach was ASTM-approved in June 2014 with a 10% blend limit.	Prototype – lignocellulosic sugars: 5 Pre-commercial – conventional sugars: 7	Deloitte analysis DSHC routes using conventional sugar feedstocks are at TRL 7-8, while the same processes based on cellulosic feedstocks are at TRL 5.	Amyris is a prominent company in the HFS-SIP pathway, specializing in genetically engineered yeast to produce farnesene, which is then hydroprocessed into a jet fuel component. Amyris is currently enhancing its fermentation processes for complex lignocellulosic sugar streams, collaborating closely with the US National Advanced Biofuels Consortium. TotalEnergies, another major player in HFS-SIP, has contributed to developing and promoting SAF solutions across multiple pathways. As a co-developer and commercial partner with Amyris, TotalEnergies announced its readiness to market up to 10% farnesane blends following ASTM approval.	de Jong, S. & Hoefnagels, R., 2023. Overview of different production pathways for sustainable aviation fuels. ScienceDirect TotalEnergies (2024). Total and Amyris' renewable jet fuel ready for use in commercial aviation

Carbon dioxide removal (CDR)

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Biochar production using pyrolysis	Biochar is the conversion of biomass into a charcoal-like product that can displace fossil fuel use in heat generation. It is one example of bioenergy with carbon capture & storage (BECCS).	9	IEA, 2025. ETP Clean Energy Technology Guide	NetZero is a provider of climate biochar intended to remove carbon from the atmosphere. The company's platform specializes in long-term carbon removal from the atmosphere by turning agricultural residues extracted from residual plant matter and buried in the soil, enabling farmers with higher yields and lower fertilizer use in agriculture and companies to neutralize their unavoidable emissions and co-generate renewable energy.	NetZero, 2022. NetZero: carbon removal and biochar solutions
Biodiesel and biokerosene from gasification (Fischer-Tropsch)	Biomass is gasified by heating it in a high temperature, low oxygen environment. The resultant gas is processed to increase its hydrogen content, then a catalyst (e.g. iron) is used to convert carbon monoxide and hydrogen into hydrocarbons.	8	IEA, 2025. ETP Clean Energy Technology Guide	Raven SR is a developer of waste-conversion technology intended to create environmentally friendly, efficient and clean hydrogen and synthetic fuels. The company's technology transforms biomass, municipal solid waste, bio-solids, industrial, sewage, medical waste and natural gas into hydrogen, sulphur and nitrogen-free liquid fuels, additives, solvents and electricity, thereby providing clean technology to convert waste into renewable fuels and energy.	Raven SR, 2018. Raven SR: renewable fuels from waste and CO_2.

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Bioethanol from enzymatic fermentation	Sugars are decomposed into bioethanol using micro-organisms. This produced a biofuel that can be blended up to 15% with ethanol for standard engines, or higher percentages for dedicated ethanol engines.	9	IEA, 2025. ETP Clean Energy Technology Guide	Edeniq is a developer of cellulosic and biorefining technologies designed to produce low-cost cellulosic sugars and cellulosic ethanol. The company's cellulosic ethanol products can be easily integrated into existing biorefineries that produce ethanol, other biofuels, biochemicals and bio-based products, enabling biorefineries to produce valuable cellulosic ethanol while also increasing throughput, yields and corn oil production.	Edeniq, 2008. Edeniq: advanced biofuel and cellulosic ethanol technologies
Biogas from anaerobic digestion	Microorganisms break down organic materials, such as food scraps or animal manure, in the absence of oxygen. This produces biogas consisting of methane, CO_2 and small amounts of other gases.	9	IEA, 2025. ETP Clean Energy Technology Guide	Perpetual Next is a developer of a climate technology designed to reuse waste streams and upgrade organic waste streams to quality raw materials. The company's technology prevents climate change by reducing CO_2 emissions and extracting CO_2 from the atmosphere which is converted into renewable bio-based products as well as facilitating a reduction in the use of fossil raw materials, enabling companies to reduce their carbon footprint and minimizing the impact on the environment.	Perpetual Next, 2019. Perpetual Next: biomass carbonization and green carbon solutions
Biomass sequestration	Biomass sequestration involves removing carbon using biomass crops, harvesting and drying the crops, and burying the carbon underground. The correct storage conditions need to be met in terms of humidity and temperature to avoid anaerobic decomposition.	4	Deloitte analysis Technology undergoing early prototyping and testing.	Graphyte's technology sequesters carbon-containing biomass waste underground, avoiding the energy intensity of other engineered carbon removal that allows the company to offer low-cost removals to carbon credit buyers, enabling users to combine the low cost of nature-based approaches with the lasting impact of engineered removal.	Graphyte, 2022. Graphyte: permanent carbon removal through biomass transformation
Carbon injection wells (e.g. mineral storage)	Vast quantities of carbon are naturally stored in geological formations (rocks). Streams of pure CO_2 can be absorbed into rocks and stored underground or alternatively can be pumped underground to be naturally absorbed by certain geologic formations.	8	Deloitte analysis Dozens of demonstration plants.	Charm is a developer of carbon removal technology designed for environmental sustainability. The company's technology converts agricultural residues into bio-oil through fast pyrolysis, which is then sequestered underground, enabling industries to achieve long-term carbon offsetting and contribute to climate change mitigation.	Charm Industrial, 2018. Charm Industrial: carbon removal via bio-oil sequestration

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Deep water sequestration of biomass (e.g. krill, macroalgae, terrestrial)	Carbon that is trapped in biomass is sunk to the bottom of the ocean and eventually buried by sediment. In an oxygen free environment, the biomass does not decompose, permanently trapping carbon.	5	Deloitte analysis Currently operating field trials.	Rewind is a biomass carbon removal and storage company intended to capture CO_2 in agricultural waste at the bottom of the Black Sea. The company aims for climate stability for future generations by storing organic carbon in anoxic water where plants decompose slowly to restore the earth's carbon balance, enabling businesses to effectively store carbon for a longer period in an affordable manner.	Rewind, 2021. Rewind: ocean-based carbon removal with biomass
Direct air capture – liquid	CO_2 is absorbed from ambient air in an aqueous solution. This solution is then heated, releasing a pure stream of CO_2. This pure CO_2 can then be stored or sold.	6	IEA, 2025. ETP Clean Energy Technology Guide	AVNOS is a developer of HDAC (hybrid direct air capture) technology designed for CO_2 removal service that captures both CO_2 and water from the atmosphere in a single system. The company offers CO_2 geographic potential available, lowers costs, uses less energy and produces water, enabling clients to operate the system from water-scarce environments and eliminate heat consumption.	Avnos, 2021. Avnos: hybrid direct air capture and water harvesting technology
Direct air capture – solid	A pure stream of CO_2 is created from ambient air through adsorption/desorption onto a solid adsorbent. This pure CO_2 can then be stored or sold.	7	IEA, 2025. ETP Clean Energy Technology Guide	Climateworks is a developer of carbon dioxide removal (CDR) services designed for companies to advance their net-zero roadmaps and fight global warming. The company offers direct air capture (DAC) facilities combined with storage installation in commercial operation, modular collectors designed for scalability and facilities running on clean energy, enabling companies to combat climate change.	Climeworks, 2009. Climeworks: direct air capture of CO_2
Electro-swing adsorption	Ambient air is passed through an electrode, which absorbs CO_2 when positively charged and releases pure CO_2 when negatively charged.	4	IEA, 2025. Direct Air Capture – A key technology for net zero	Svante is a developer of proprietary solid-sorbent filter and rotary contactor technology designed to capture and remove CO_2 from hard-to-decarbonize industrial point-source emissions and directly from the air. The company's technology captures and concentrates CO_2 to pipeline-grade purity, which can be safely transported and stored underground or used to make other products, enabling enterprises to cut capital costs and reduce energy regeneration.	Svante, 2007. Svante: solid sorbent carbon capture technology
Enhanced rock weathering	Pulverized silicate and/or carbonate minerals are spread over large areas of warm, humid land. The pulverization of these minerals increases their surface area, increasing the amount of CO_2 that they naturally absorb from the atmosphere.	7	Deloitte analysis Commercial demonstration, full-scale deployment in final condition.	44.01 is a provider of CO_2 mineralization services intended to help companies eliminate their captured CO_2. The company's services use technology to accelerate the natural weathering process to turn CO_2 into rock, enabling industries to accelerate the safe and natural process of mineralization, turning carbon into harmless rock.	44.01, 2020. 44.01: mineralizing CO_2 in peridotite rocks

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Water alkalinization	Pulverized silicate and/or carbonate minerals are introduced to the surface of water bodies, such as seas, rivers and ponds. The pulverization of these minerals increases their surface area, enhancing the natural absorption of CO_2 from the water.	3	Deloitte analysis Multiple initiatives are actively stimulating research to enable field testing in the ocean, rivers, ponds and water bodies.	Captura is a developer of a carbon removal system designed to extract excess CO_2 from the atmosphere through ocean-based processes. The company offers proprietary electrodialysis technology that removes measurable carbon streams without generating waste or requiring feedstocks, enabling carbon credit buyers and producers of low-carbon products to access scalable, ocean-safe carbon removal.	Captura, 2021. Captura: ocean-based carbon dioxide removal

Cement & Concrete

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Alkali-activated binders (geopolymers)	Geopolymer cement is a low carbon alternative to typical Portland cement. Geopolymers remove limestone from the chemical equation, a high embodied CO_2 mineral that is released during cement manufacture.	9	IEA, 2025. ETP Clean Energy Technology Guide	Terra CO_2 is a manufacturer of low-carbon geopolymer cement alternatives intended to serve the construction industry to reduce emissions in concrete production. The company offers scalable supplementary cementitious materials made from abundant silicate rocks, enabling clients to replace Portland cement, lower CO_2 emissions and maintain cost and performance efficiency.	Terra CO_2 Technologies, 2016. Terra CO_2: next-generation cement alternatives
Bio-cement	Bio-cement is a type of cement made from natural materials, such as calcium carbonate, that are renewable and sustainable. Unlike traditional cement, which is made from limestone and clay, bio-cement is produced using less energy and generates fewer emissions, making it a more environmentally-friendly alternative. Bio-cement can be used in construction, paving and other applications, and can improve the sustainability and resiliency of buildings and infrastructure.	5	Deloitte analysis Lab scale R&D.	Biomason is a developer of a building materials technology designed to harness biology to produce high-quality concrete, replace Portland cement and cut carbon emissions. The company's technology combines natural microorganisms and chemical processes to develop masonry materials at room temperature, which helps replace traditional clay and concrete and the energy consumption associated with standard manufacturing them, enabling builders to acquire alternative building materials that are produced carbon-free.	Biomason, 2012. Biomason: biologically-grown masonry materials for construction

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Calcined clay	Calcined clay is a material that is produced by heating raw clay to high temperatures in a kiln. This process removes moisture and organic material and causes the clay to undergo chemical and physical changes that improve its properties, such as porosity, particle size distribution and surface area. Calcined clay can be used as a building material, filler, or additive in various industries, including ceramics, plastics, rubber and construction. In the construction industry, calcined clay can be used as a replacement for Portland cement in the production of low-carbon concrete. This results in a reduction in the carbon footprint of concrete and improved mechanical properties, such as strength and durability.	9	IEA, 2025. ETP Clean Energy Technology Guide	Materrup is helping to reduce the carbon footprint of the construction sector. The company uses a rupture technology that converts excavated earth and clay into low-carbon concrete for construction and urban planning, enabling on-site developers to decarbonize construction and establish a sustainable city.	Materrup, 2018. Materrup: low-carbon cement solutions
Chemical absorption	Chemical absorption involves the reaction between CO_2 and a chemical solvent. Amine-based solvents are the most advanced CO_2 separation technique.	9	IEA, 2025. ETP Clean Energy Technology Guide	Heidelberg Materials (Norcem Brevik, Norway) using Aker Carbon Capture's post-combustion amine scrubbing to capture 400,000 tonnes of CO_2 annually from kiln flue gas; the facility is part of Norway's Longship programme and was officially opened in mid-June 2025, with CO_2 sent to Northern Lights for storage.	Aker Solutions, 2020. Awarded contract for the Brevik carbon capture project
CO_2-based building materials	Carbon dioxide captured can be used to produce building material such as concrete.	9	IEA, 2025. CO_2 Capture and Utilisation	CarbonCure is a developer of CO_2 utilization technology designed to help solve climate change and reduce carbon footprint. The company's retrofit technology chemically sequesters waste CO_2 during the concrete manufacturing process to make greener and stronger concrete, enabling ready-mix producers to make low-carbon concrete, gain a competitive advantage, grow their business with the green building market and reduce the embodied carbon footprint in the environment.	CarbonCure, 2012. CarbonCure: carbon mineralization technologies for concrete
CO_2 curing in concrete (carbon sequestration)	Carbon dioxide is injected into an absorption chamber where it reacts with steel slag within concrete to permanently capture and convert that CO_2 into carbonates.	9	IEA, 2025. ETP Clean Energy Technology Guide	Fortera is a manufacturer of cement products intended to contribute to the global goal of reducing CO_2 emissions. The company's cement is made through the process of capturing industrial CO_2 emissions from kilns and mineralizing it. This provides improved performance characteristics compared to the traditional ones, enabling industries to lower the overall carbon footprint in construction.	Fortera, 2010. Fortera: low-carbon cement innovation and manufacturing

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Direct separation	Direct separation is a technology in cement production where CO_2 from process emissions is captured by indirectly heating the limestone using a special calciner. This technology strips CO_2 directly from the limestone, without mixing it with other combustion gases, thus considerably reducing energy costs related to gas separation.	7	IEA, 2025. ETP Clean Energy Technology Guide	Furno intends to produce zero-emission ordinary Portland cement. The company's technology leverages oxyfuel combustion and a novel design to develop plants, providing the cement industry with agile, scalable, carbon-neutral, energy-efficient and less capital-intensive cement technology, enabling clients to have carbon-neutral technology.	Furno, 2020. Furno: decarbonizing cement manufacturing with modular kilns
Low-carbon aggregates	Low-carbon aggregates are a sustainable alternative to traditional aggregates used in concrete production. These aggregates are typically made from recycled materials such as crushed concrete, glass and ceramics, or from industrial by-products such as fly ash and slag. By using low-carbon aggregates, concrete producers can significantly reduce the carbon footprint of their operations while also promoting circular economy principles.	4	IEA, 2025. ETP Clean Energy Technology Guide	Neolithe is a developer of a fossilization technology designed to transform non-recycled, non-inert and non-hazardous waste that can be reused in the construction sector. The company's technology offers a service for reclaiming the waste material produced either by recycling raw materials extracted, which enables more precise sorting of small-sized waste or an alternative to landfill or incineration and aims to transform the waste treatment sector, which is currently highly polluting, into a circular sector, by the transformation of waste into aggregate, enabling construction companies to utilize mineral granulates based on the fossilization of waste and reduce waste, traditional construction-associated CO_2 emissions.	Neolithe, 2019. Neolithe: fossilization of waste and carbon-negative aggregates
Low-carbon clinker substitutes	Clinker is the chief component of conventional cement (known as ordinary Portland cement), causing it to harden when reacting with water. Substitute materials (supplementary cementitious materials, or SCMs) can be used to decrease clinker to cement ratio (on a mass basis). The most common substitutes today are fly ash from coal furnaces and blast furnace slag from the production of pig iron and steel.	7	IEA, 2025. ETP Clean Energy Technology Guide	Carbon Upcycling is a carbon-tech company intended to deliver technology to decarbonize hard-to-abate industries. The company's patented technology permanently stores CO_2 in industrial by-products and minerals, transforming them into high-performance alternative materials for cement and concrete, reducing the carbon impact of industrial processes and diverting industrial materials from landfills, enabling cement manufacturers to produce more sustainable products.	Carbon Upcycling, 2014. Carbon upcycling: turning CO_2 into advanced materials
Low-carbon kilns	The use of lower-carbon kilns includes using pre-calciners/pre-heaters, dry kilns, electric or hydrogen powered kilns, or electrochemical kilns.	5	Deloitte analysis Dry process kilns are commercial, while hydrogen and electrified kilns are TRL 2 and 5, respectively.	Fortera's cement is made through the process of capturing industrial CO_2 emissions from kilns and mineralizing it and provides improved performance characteristics compared to the traditional ones, enabling industries to lower the overall carbon footprint in construction.	Fortera, 2010. Fortera: low-carbon cement innovation and manufacturing

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Magnesium oxide binders	Cement is produced from magnesium oxides derived from magnesium silicates, resulting in a lower CO_2 footprint.	3	IEA, 2025. ETP Clean Energy Technology Guide	Brimstone is a developer of a decarbonized construction material intended to reduce carbon emissions in cement production significantly. The company's platform uses a process to create cement that meets industry standards, drastically lowering CO_2 emissions, while maintaining cost-competitiveness at scale, enabling the construction industry to replace traditional processes with a cost-effective and clean electrochemical system.	Brimstone, 2019. Brimstone: carbon-neutral cement from alternative minerals

Shipping

Technology type	Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)	Engine type
Battery	Redox flow batteries (RFBs)	Flow batteries, also known as redox flow batteries, are a type of rechargeable battery that uses two separate liquid solutions, called electrolytes, to store energy chemically. The solutions are stored in tanks and the energy is generated by the movement of ions between the solutions through a membrane. Flow batteries have the potential to have a much larger energy storage capacity than traditional batteries.	Stationary/grid applications: 8-9 Maritime applications: 6	Deloitte analysis Stationary/grid applications have been deployed and commercially available. Within maritime applications, technology is demonstrated in relevant environment, early prototypes and pilot projects.	Conoship in the Netherlands and Vega Reederei in Germany are utilizing technology from Vanadium Corp in Canada to develop a next-generation redox flow battery stack. It will use a high energy-density vanadium electrolyte specifically formulated for marine applications.	eMobility Engineering, 2024. Redox flow battery has ships in sight	Hybrid electric propulsion systems: these combine conventional internal combustion engines (typically diesel or gas) with electric motors and energy storage, most commonly batteries. This integration enables vessels to operate using either the engine, the electric motor, or both, managed by an advanced energy management system (EMS).
	Lithium-ion batteries (Li-ion)	Lithium-ion batteries are rechargeable energy storage devices that operate by moving lithium ions between a positive electrode (cathode) and a negative electrode (anode) through a liquid or gel electrolyte.	9	Deloitte analysis Li-ion batteries are widely deployed in commercial marine vessels, from ferries to support ships. Li-ion batteries are the current workhorse for maritime electrification, suitable for short-sea shipping, ferries and hybrid vessels.	A123 Systems has developed a range of lithium iron phosphate (LFP) batteries optimized for marine transportation applications. A123's marine LFP batteries feature advanced thermal management systems that maintain optimal operating temperatures even in challenging marine conditions. CATL has developed advanced LFP batteries specifically designed for marine applications. CATL's LFP batteries for marine use feature enhanced thermal management systems to prevent overheating in confined spaces and utilize a proprietary cell design that increases energy density by up to 30% compared to traditional LFP cells. Corvus Energy offers a comprehensive range of marine battery energy storage and fuel cell systems. Many of the world's first hybrid and electric-powered maritime vessels use a Corvus system, including the first all-electric fast ferry, the first hybrid cruise ship and the world's largest fully electric lightweight Ro-Pax ferry.	Eureka, 2024. Lithium iron phosphate battery applications in marine transportation Corvus Energy, 2024. Cruise and ferry segment overview	

Technology type	Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)	Engine type
Battery	Solid-state batteries (SSBs)	Solid-state batteries replace the liquid or gel electrolyte in conventional Li-ion batteries with a solid electrolyte.	5-7	Deloitte analysis System prototype demonstration in operational environment. SSBs are being manufactured and tested, with promising results in energy density and cyclability. Widespread deployment in shipping is pending; mass production and operational integration are still in development.	SOLiTHOR is developing lithium metal solid-state batteries for maritime and aviation, with milestones in energy density and cyclability. Solid State M-Oceans (SSC) batteries offer an efficient, light-weight battery oriented towards both commercial and leisure maritime applications.	Maritime Battery Forum, 2024. Solithor reaches 1000 charging cycles with over 80% capacity retention – a key milestone in its development of solid-state batteries for the aviation and maritime sectors M-Oceans, 2024. The future of solid-state batteries	Hybrid electric propulsion systems: these combine conventional internal combustion engines (typically diesel or gas) with electric motors and energy storage, most commonly batteries. This integration enables vessels to operate using either the engine, the electric motor, or both, managed by an advanced energy management system (EMS).
E-ammonia	Green Haber-Bosch process	Haber-Bosch is the century-old, globally dominant process for ammonia synthesis. The mature, decarbonized pathway uses green hydrogen, produced by water electrolysis powered by renewable electricity, instead of hydrogen from fossil fuels. The process combines green hydrogen and nitrogen under high pressure and temperature in the presence of an iron-based catalyst to produce ammonia (NH_3).	9	Deloitte analysis Green hydrogen and nitrogen are fed into a Haber-Bosch reactor to synthesize ammonia. All components are commercially available and proven at industrial scale.	Some shipping companies have already begun trials with hydrogen and ammonia-powered vessels. NYK Line and Maersk are testing ammonia-fuelled ships, while others are examining hybrid vessels that combine green fuels and batteries. DNV is partnering with Wärtsilä, MSC, C-Job and CNR on the Ammonia24 project, which aims to develop both two- and four-stroke marine engines that run safely and efficiently using ammonia as fuel.	Carbon Credits, 2024. Green hydrogen and ammonia drive maritime decarbonization DNV, 2024. Ammonia 24	Ammonia internal combustion engines: these are modified marine engines designed to burn ammonia directly, either as the sole fuel or in dual-fuel mode with a small amount of pilot fuel – such as diesel or hydrogen – for ignition.
	Integrated green ammonia plants (Haber-Bosch + renewables)	Integrated green ammonia plants are large-scale facilities where the entire ammonia production chain is co-located and directly coupled with dedicated renewable energy assets.	9	Deloitte analysis Several large projects are operational or under construction globally (e.g. in Australia, Saudi Arabia, Chile and Europe. Several large-scale integrated plants are under construction or have recently started operations, marking the transition to commercial readiness.	ACWA Power (Saudi Arabia) is developing the world's largest integrated green ammonia plant in Yanbu, targeting 2.8 million tonnes per year by 2030, powered by 4 GW of wind and solar. Envision Energy (China) conducted the world's first green marine ammonia bunkering at Dalian Port, using green ammonia from their integrated wind, solar and energy storage plant.	Global Business Outlook, 2024. Go green with GBO: Sinopec joins Saudis' energy diversification with green hydrogen plans Renewables Now, 2024. Envision Energy delivers green ammonia for world-first bunkering	

Technology type	Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)	Engine type
E-methanol	Power-to-methanol (PtM)	The power-to-methanol (PtM) pathway is a process that synthesizes e-methanol, a renewable, carbon-neutral fuel, by combining green hydrogen (H_2) with captured CO_2. This process is central to decarbonizing shipping, offering a sustainable alternative to conventional marine fuels.	8-9	Deloitte analysis Methanol is moving towards initial scale, with around 60 methanol-capable vessels on the water, more than 300 further ships on order and just under 20 ports offering green methanol bunkering. Methanol engines are commercially available and in use. Retrofitting and new builds are well-established.	Earlier this year, Ørsted and Maersk took another decisive step and signed a landmark green fuels agreement to boost global e-methanol production. The 675 MW facility in Texas will produce a further 300,000 tonnes, which Maersk will use in its newly ordered fleet of 12 methanol-powered vessels by 2025, bringing green shipping and global trade a step closer to reality.	Renewable H_2, 2024. Decarbonising shipping globally with e-methanol	Dual-fuel methanol engines: these are internal combustion engines designed to operate on both methanol and conventional marine fuels (such as diesel or heavy fuel oil). This flexibility allows vessels to switch between fuels based on cost, availability and regulatory requirements.
Hydrogen	Electrolysis – alkaline electrolysis (using freshwater)	Water is split into hydrogen and oxygen via the application of an electric current, using a porous diaphragm and an alkaline electrolyte.	9	IEA, 2025. ETP Clean Energy Technology Guide	Sunfire (Germany), an electrolyser manufacturer, presents a cutting-edge solution in the form of its ultra-reliable pressurized alkaline electrolyser. This advanced electrolyser is specifically designed for applications where steam availability is limited or absent.	Green H_2 World, 2024. Electrolysers	Hydrogen internal combustion engines (HICEs): these are modified conventional engines designed to burn hydrogen directly. They can operate solely on hydrogen or in dual-fuel mode with a pilot fuel such as diesel. HICEs leverage familiar engine technology, can accept lower purity hydrogen and produce no CO_2 emissions when running on pure hydrogen.

Technology type	Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)	Engine type
Hydrogen	Electrolysis – polymer electrolyte membrane (PEM) (using freshwater)	Water is split into hydrogen and oxygen via the application of an electric current, using an acidic solid polymer electrolyte membrane.	9	IEA, 2025. ETP Clean Energy Technology Guide	ITM Power (UK) specializes in proton exchange membrane (PEM) electrolysers that convert renewable electricity and freshwater into ultra-high-purity hydrogen (up to 99.999%) and oxygen. Their modular, compact systems are designed for rapid response to variable power inputs, making them ideal for integration with renewable energy sources and applications such as shipping, industrial decarbonization and hydrogen refuelling. ITM Power's manufacturing facility in Sheffield currently has an annual capacity of 1 GW, with plans to scale up further, supporting both small-scale and large-scale green hydrogen projects.	ITM Power, 2024	Hydrogen internal combustion engines (HICEs): these are modified conventional engines designed to burn hydrogen directly. They can operate solely on hydrogen or in dual-fuel mode with a pilot fuel such as diesel. HICEs leverage familiar engine technology, can accept lower purity hydrogen and produce no CO_2 emissions when running on pure hydrogen.
	Methane pyrolysis plasma thermal decomposition	In the absence of oxygen, methane is decomposed into hydrogen and elemental carbon at high temperatures, usually in the presence of a catalyst. In plasma thermal decomposition pyrolysis processes, the energy demand is supplied by electricity. The electric energy ignites the plasma (an ionized gas), which reaches temperatures of 1,000–2,000°C and splits methane into hydrogen and carbon black, a by-product that can be used commercially.	8	IEA, 2025. ETP Clean Energy Technology Guide	Plenesys's HyPlasma is a methane pyrolysis process that uses renewable electricity and (bio) methane as feedstocks. Unlike SMR, HyPlasma does not produce any CO_2, as it uses the clean heat generated by plasma torches to crack the methane molecule (CH_2) into hydrogen and solid carbon powder, a by-product that can be valorised on the market. HyPlasma also uses electricity, similar to water electrolysis, but at the same production scale, it uses five times less electricity than electrolysis, making operational costs more than 50% lower than electrolysis, while remaining competitive with the low costs of SMR.	Plenesys, 2024. Plasma methane pyrolysis	
	Steam methane reforming (SMR) with carbon capture, utilization and storage (CCUS)	Natural gas is mixed with steam (and/or CO_2) in the presence of a catalyst at high temperatures and moderate pressure to produce syngas.	9	IEA, 2025. ETP Clean Energy Technology Guide	Shell develops and licenses the "Shell Blue Hydrogen Process", integrating natural gas reforming with advanced CCUS technologies, and claims up to 99% CO_2 capture.	Shell, 2024. Shell Blue Hydrogen Process: Cost-effective technology avoiding CO_2-emissions	

Steel

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Green steel: direct reduced iron (DRI) steel with attached carbon capture	Plants where iron ore is reduced to iron without melting can be equipped with carbon capture technology. This can be physical adsorption technology, where molecules are captured by an adsorbent, or chemical absorption, where CO_2 is reacted with a chemical solvent.	9	IEA, 2025. ETP Clean Energy Technology Guide	Emirates Steel (in Abu Dhabi) operates a direct reduced iron and electric arc furnace (DRI + EAF) route and has one of the world's only commercial CCUS facilities tied to an iron/steel plant (the Al Reyadah project). This plant is capable of capturing 800kt of CO_2 per year, which is compressed, dehydrated and then pumped through 50 km of pipeline to be injected into a mature onshore oil field for enhanced oil recovery (EOR) operations.	SAISI, 2024. Carbon capture & storage fact sheet
Green steel: direct reduced iron steel with blended hydrogen	Direct reduction occurs when iron ore is reduced to iron without melting. Natural gas fuel in this process can be replaced by a blend of natural gas and electrolytic hydrogen. Current technology is suited to up to 30% hydrogen content.	7	IEA, 2025. ETP Clean Energy Technology Guide	GravitHy is an operator of a sustainable iron plant intended to reduce carbon emissions in steel production. The company offers green hydrogen-based direct reduced iron production and operates a zero-carbon hot briquetted iron (HBI) facility with electrolyser capacity, enabling steel manufacturers to transition towards low-emission steelmaking.	GravitHy, 2025. GravitHy initiative: green hydrogen-based steelmaking
Green steel: direct reduction of iron oxide to pig iron using natural gas	This climate technology involves green steel produced through direct reduction of iron oxide to pig iron using natural gas, rather than coal, as a reducing agent. This process occurs in a direct reduction reactor, where the iron oxide is heated in the presence of the reducing agent natural gas to produce the pig iron. The resulting pig iron can then be used in the production of steel. The use of natural gas in the direct reduction process reduces the dependence on traditional fossil fuels, such as coal and coke, and decreases greenhouse gas emissions.	9	Deloitte analysis 24% of global steel production of pig iron is through direct reduced iron using natural gas.	ArcelorMittal Hamburg plant operates a DRI-EAF facility, where natural gas is currently used to reduce iron ore into DRI before feeding it into an electric arc furnace. The plant is now planning a transition to hydrogen (the Hamburg H_2 project), but as of now the base reduction is via natural gas.	ArcelorMittal, 2023. Hydrogen-based steelmaking to begin in Hamburg

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Green steel: replacement of coal in the steelmaking process with biomass	Biomass injection into blast furnaces is already applied commercially in Brazil, as it can be used as a reductant. However, not all types of biomass are suitable for direct injection, and some types require small-scale, less efficient blast furnaces due to the lower compressive strength of charcoal compared to coke. A less mature technology route is the conversion or upgrading of biomass to a coal-like material through torrefaction or pyrolysis, in which biomass is heated to temperate in the range of 200 °C to 400 °C in the absence of oxygen. The 'bio-coal' has characteristics more similar to coal than the original biomass. Such bio-coal can be used in standard blast furnaces to replace a portion of injected coal.	9	IEA, 2025. ETP Clean Energy Technology Guide	Rio Tinto is developing a process called BioIron™, which uses raw biomass (instead of coal) plus microwave energy to convert iron ore into iron (or reduce iron oxide) in a low-carbon route.	Rio Tinto, 2025. Decarbonizing steel making: innovative solutions and progress
Green steel: replacement of coal in the steelmaking process with inorganic waste	Green steel could be produced by substituting coal with inorganic waste. This includes paper, plastic and other waste. The inorganic waste is gasified and used as a reducing agent, replacing coal, to produce the necessary heat and reducing gases for the steelmaking process.	7	Deloitte analysis Piloting and scaling-up various waste materials that can replace coal.	Nippon Steel has published a report aiming to import carbonized products from waste and use those as a substitute for coal in iron/steelmaking. Their technical report states that by using the carbonized product derived from waste, they can substitute 1 tonne of coal and avoid significant CO_2 emissions.	Nippon Steel, 2022. Advanced technologies for steel and sustainability
Steel: blast furnace – converting off-gases into chemicals	Waste gases from steel plants have contaminants removed, then a catalyst is used to produce chemicals (e.g. ammonia, methanol) from these gases.	7	IEA, 2025. ETP Clean Energy Technology Guide	Thyssenkrupp Carbon2Chem project (Germany) aims to take steel mill gases/blast furnace off-gases (SMGs/BFG) and use them to produce chemicals such as methanol, ammonia, or synthetic fuels/plastics. At their Duisburg steelworks, they run pilot-scale demonstration of chemical utilization of steel mill gases. The process involves capturing/conditioning the off-gases (CO, CO_2, H_2) and feeding them to catalytic synthesis steps to make basic chemical building blocks.	Thyssenkrupp, 2025. Carbon2Chem: turning industrial gases into valuable resources
Steel: blast furnace – converting off-gases into fuels	Steel produced by the conversion of gases into fuels with a blast furnace is a method of steel production that involves the use of waste or surplus gases, such as CO_2, as a fuel source in the blast furnace. The gases are converted into a fuel, such as syngas, which is then used to replace traditional fossil fuels, such as coal, in the steelmaking process. This helps reduce waste and minimize emissions from the blast furnace. Utilizing these off-gases as fuels can provide a more sustainable and efficient steel production process, helping to reduce the carbon footprint of the industry.	8	IEA, 2025. ETP Clean Energy Technology Guide	The company Utility has developed H_2Gen, a process that produces hydrogen directly from blast furnace off-gases (BFG) + other steel plant gases, in one reactor step under field conditions. This essentially converts the off-gas into H_2 fuel (a clean fuel) rather than flaring or waste.	PR Newswire, 2025. Industry-first hydrogen production from steel manufacturing off-gases

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Steel: blast furnace – hydrogen fuel injection (blending)	Steel produced by hydrogen fuel injection (blending) in a blast furnace is a method of steel production that involves the use of hydrogen as a fuel source in the blast furnace. The hydrogen is blended with traditional fuels, such as coal, to replace a portion of the fossil fuels used in the steelmaking process. Blast furnace hydrogen fuel injection is a promising technology for reducing the carbon footprint of the steel industry and supporting sustainable production.	7	IEA, 2025. ETP Clean Energy Technology Guide	ThyssenKrupp Steel conducted the world's first test of hydrogen injection into an operating blast furnace (blast furnace No.9 (BF9)).	Thyssenkrupp Steel, 2021. First test phase successfully concludes for green steel technologies
Steel: coke dry quenching in BF-BOF steel for waste heat recovery	Coke dry quenching (CDQ) is a waste heat recovery process in blast furnace-basic oxygen furnace (BF-BOF) steel production. In CDQ, the hot coke from the blast furnace is cooled rapidly using air, which generates steam that can be used for power generation. This process helps reduce energy consumption, lower greenhouse gas emissions and improve overall efficiency of the BF-BOF production process. CDQ is an important step in the development of more sustainable and environmentally friendly steel production practices.	9	IEA, 2023. Iron and Steel Technology Roadmap	Tata Steel's Jamshedpur plant has installed new coke dry-quenching (CDQ) plants (for their new coke oven batteries COB-10 & 11) with waste heat recovery boilers, as part of their expansion and efficiency improvements. With the CDQ plus waste heat boiler setup, surplus high-pressure steam is to be used in a steam turbine to generate ~40 MW of power.	Tata Consulting Engineers, n.d. Engineering excellence for sustainable power generation from coke oven plant
Steel: top-pressure recovery turbines (TRTs) in blast furnaces	Steel top-pressure recovery turbines (TRTs) use waste heat from the blast furnaces during the steelmaking process to generate additional electricity, improving energy efficiency and reducing emissions. The hot gas from the blast furnace is fed through a TRT, which drives a turbine to produce electricity. The use of TRTs can lead to significant energy savings for steel producers and reduce their carbon footprint.	9	IEA, 2023. Iron and Steel Technology Roadmap	Mitsui E&S, a Japanese equipment firm, reports having supplied more than 70 TRT units to steel plants globally.	MES, 2024. Top pressure recovery turbine (TRT) technologies for steel plants

Trucking

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Battery electric trucks (BET)	Vehicles such as semi-trucks and delivery trucks that run on electric batteries.	9	IEA, 2025. ETP Clean Energy Technology Guide	Volvo Trucks is a leading provider in the heavy-duty electric truck market, offering a growing range of battery-electric models for applications such as urban distribution, construction, waste management and regional hauling. These trucks are fully electric and produce zero tailpipe emissions, supporting cities in meeting air quality goals, complying with zero-emission zone regulations and reducing noise pollution.	Volvo Trucks, 2024. Electric trucks
Battery swapping for heavy trucks	Trucks exchange depleted battery packs for fully charged ones at dedicated swapping stations. Swaps can be completed in minutes, drastically reducing downtime compared to conventional charging.	7-8	Deloitte analysis Early commercialization and rapid growth, especially in China. Rapid adoption and scaling-up in specific markets.	CATL is advancing battery swapping for heavy-duty trucks through its QIJI Energy project. The company has introduced standardized swappable battery packs, such as the #75 model, and is building a network of battery swapping stations across China. CATL plans to open more than 300 stations by the end of 2025 and is targeting a nationwide network by 2030.	Electrek, 2025. CATL battery swap: electric semi tech cleans up the messy middle
Dynamic & static inductive charging	Wireless power transfer uses electromagnetic fields between coils in the ground and coils on the vehicle: – Static: vehicles charge when stationary over a pad (depots, docks, parking spots). – Dynamic: vehicles charge while moving over coils embedded in the roadway.	Static inductive charging: 7-8 Dynamic inductive charging: 4-5	Deloitte analysis Static inductive charging: commercially available for buses; heavy truck systems entering pilot deployment. Dynamic inductive charging: concept proven, but large-scale deployment for heavy trucks is still in early research/demonstration.	Static wireless charging: WAVE Charging provides high-power wireless charging solutions to support commercial electric vehicle adoption. At the Port of Los Angeles, WAVE is powering ten class-8 yard trucks with 125kW wireless chargers. Additionally, nearby facilities use WAVE's 250kW and 380kW systems to charge Hyster-Yale electric top-loaders. A separate project is planned to supply 500kW wireless fast charging for a Cummins battery-electric drayage truck. Dynamic wireless charging: Smartroad Gotland, a project on the island of Gotland in Sweden, demonstrated dynamic wireless charging for long-haul electric trucks. Developed by ElectReon, the project enabled a truck to receive power continuously while driving at speeds up to 80 km/h over a 1.65 km public road segment. The system used coils embedded in the roadway to wirelessly transfer energy to a receiver on the truck.	WAVE Charging, 2024. Wireless charging ports Electreon, 2024. Smartroad Gotland project: dynamic wireless charging for electric vehicles

Technology	Technology description	Technology readiness level (TRL)	TRL rationale	Use cases	Use case source(s)
Hydrogen fuel-cell heavy-duty vehicles	Vehicles such as semi-trucks and delivery trucks that run on hydrogen fuel cells. These fuel cells convert hydrogen and oxygen into electricity, water and heat. This process produces zero emissions, making them a clean and eco-friendly alternative to traditional gasoline- or diesel-powered heavy-duty vehicles. The hydrogen can be stored in tanks on the vehicle and refilled at hydrogen fuel stations.	8-9	IEA, 2025. ETP Clean Energy Technology Guide	A prototype H_2Rescue truck, developed and powered by Accelera, set a world record by traveling 1,806 miles on a single tank of hydrogen fuel.	U.S. Department of Energy, 2024. Hydrogen-powered heavy-duty truck establishes new threshold by traveling 1,800 miles on a single fill
Overhead catenary/ in-motion charging	Hybrid or battery-electric trucks use a pantograph to connect to overhead electrical wires (catenary lines) installed above dedicated highway lanes. Trucks draw electricity directly while driving, enabling dynamic charging and propulsion. Off the electrified lanes, trucks switch to an onboard battery or hybrid powertrain.	7-8	Deloitte analysis Demonstration in relevant environment. Proven in pilot projects on public roads, but not yet commercially deployed at scale. Multiple field trials in Germany (ELISA, FESH, eWayBW), Sweden and California with positive technical results.	Siemens Mobility specializes in eHighway systems that use overhead catenary infrastructure to electrify roads for trucks and other vehicles. The company provides expertise in overhead lines, pantographs and power supply systems. Siemens' eHighway technology is currently in field trials on public roads in Germany, including the A5 and A1 autobahns and the B462 federal highway, and has also been demonstrated in Sweden and the United States.	Siemens, 2024. Siemens Mobility and Continental: supply trucks across Europe with electricity via overhead network

Contributors

Lead authors

Noam Boussidan
Programme Head, First Movers Coalition, World Economic Forum

Dilip Krishna
US Consulting Managing Director, Deloitte

Ben Hewson
US Manager, Deloitte

Williams Ahl
US Consultant, Deloitte

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World Economic Forum

Jelena Aleksić
Lead, Industry Decarbonization Metals (Steel and Aluminium)

Mette Asmussen
Lead, Maritime Sector Initiatives

Daniel Boero Vargas
Lead, Industrial Decarbonization Innovation, Supply and Concrete

Giorgio Parolini
Lead, Aviation Decarbonization

Nasim Pour
Lead, Climate Finance

Thibault Villien de Gabiole
Lead, Industrial Decarbonization (Trucking)

Deloitte

Milind Mahendra Malegaonkar
USI Senior Consultant

Rishabh Sharma
USI Consultant

Contributing organizations

Aluminium sector

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- DP World
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- Toll Group

Production

Jean-Philippe Stanway
Designer

Jonathan Walter
Editor

Endnotes

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org