Low-Carbon Hydrogen: Examining Decarbonization Potential and Commercialization Pathways Through 2035

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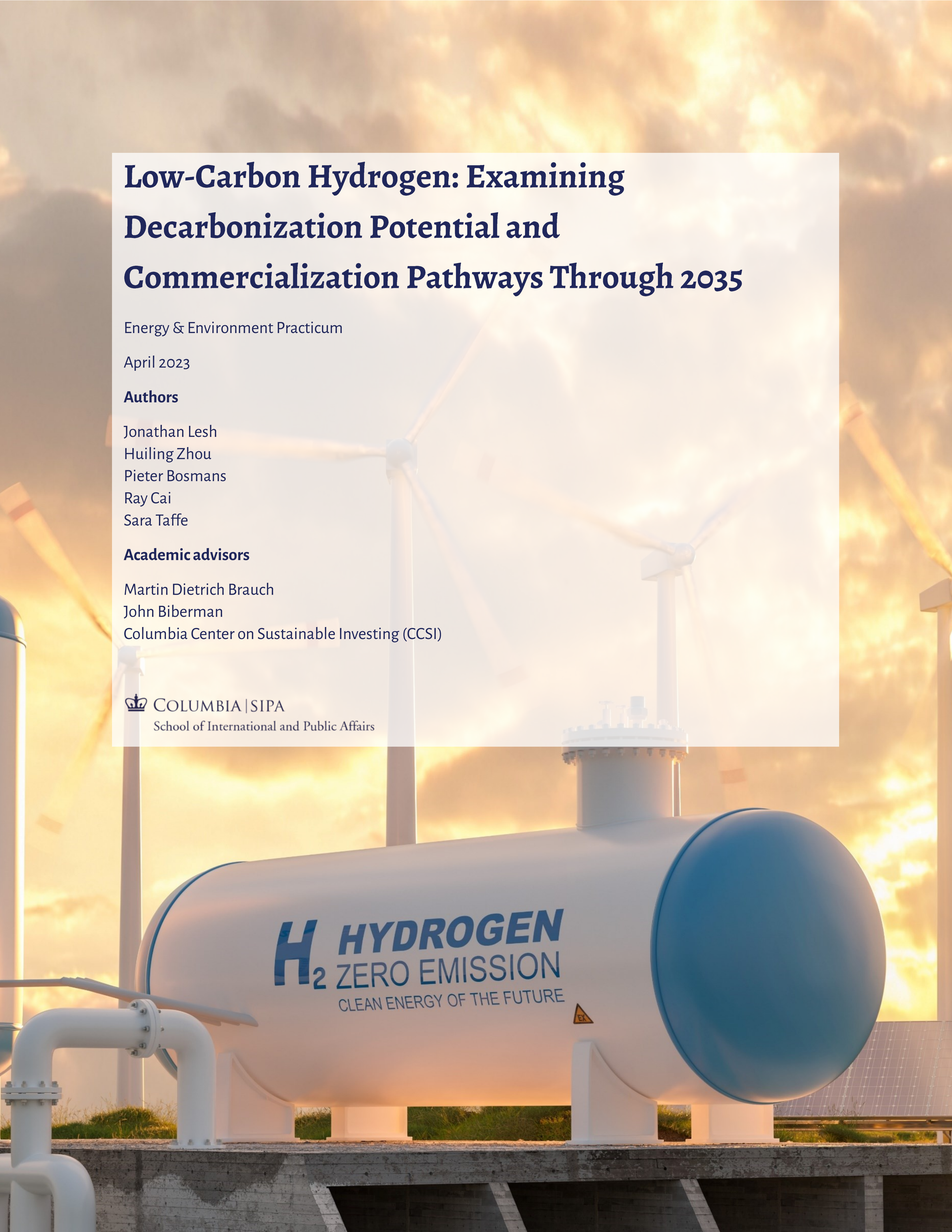

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Executive Summary

To decarbonize the global economy by 2050 and mitigate the most severe impacts of climate change, robust investment in new energy systems is urgently needed. **Hydrogen, an abundant and versatile element, has the potential to contribute to the energy transition** through its application in a number of different economic sectors. **This report will focus on the potential of low-carbon hydrogen in Europe and the United States**, where governments and the private sector have set ambitious goals and targets to scale up the use of low-carbon hydrogen technologies. However, **the market uptake of low-carbon hydrogen will depend on a range of enabling and inhibiting factors**, including technological feasibility, market structure, and cost concerns.

This study is based on an original survey of hydrogen industry stakeholders, expert interviews, and a comprehensive secondary literature review. It finds that, **by 2035, low-carbon hydrogen has the highest potential for commercialization in the ammonia and steel industries, as well as parts of the transportation sector**. Low-carbon hydrogen is likely to soon become cost-competitive in these industries and overcome a range of barriers to adoption as its technical maturity improves. **In the cement, maritime, and aviation sectors, the adoption of low-carbon hydrogen may be more limited through 2035.**

- As an existing consumer of hydrogen, the **ammonia** industry has high and immediate potential to transition from its carbon-intensive hydrogen feedstocks to low-carbon alternatives. Ammonia producers should take advantage of government incentives to overcome high upfront costs of building electrolyzers or carbon capture systems.
- A high proportion of **steel** plants in the United States and Europe, which currently are powered by fossil fuels, will require reinvestment in the next 10 years, presenting a significant opportunity for uptake of low-carbon hydrogen. However, the uncertain availability of low-cost renewable hydrogen and renewable energy could prevent this technology from gaining dominance. In regions with reliable access to hydrogen and electricity sourced from renewable energy sources, there is potential for hydrogen-based production to outcompete traditional steelmaking processes by 2035.
- In **commercial road transport**, diesel trucks lead the market given their affordability under current market conditions, but emissions regulations will move the market towards alternative powertrains. When accompanied by infrastructure investment, hydrogen fuel cell electric vehicles can replace diesel trucks in the long-haul segment if the technology achieves its expected cost reductions.
- Although the relevant technologies are still maturing, hydrogen could play a role in reducing the carbon intensity of **cement** production by serving as an alternative fuel source for high-heat processes. However, hydrogen fuel cannot fully decarbonize the cement industry by itself, as most emissions accrue from the chemical reaction that produces the cement mixture commonly used today.

- The **maritime transport** sector is considering decarbonization using hydrogen or hydrogen-based fuels, but the industry currently lacks adequate policy support and will have to overcome technical challenges and cost barriers to adopt low-carbon hydrogen into its supply chain.
- Hydrogen-powered **aviation** is associated with high capex and opex, significant technological hurdles, and a lack of infrastructure. Aside from hydrogen-derived sustainable aviation fuels, there are no targeted policies that can substantively address these obstacles.

There are similarities between the economic sectors where low-carbon hydrogen presents a viable market opportunity. As the upstream and midstream parts of the low-carbon hydrogen value chain mature, these industries will consider **cost competitiveness, policy inducements and penalties, and decarbonization potential** when determining how low-carbon hydrogen can factor into their strategic outlook. That said, there are **important differences in the decision sets that industries face**. For example, steel producers must select between investing in new infrastructure or retrofits of existing assets for low-carbon hydrogen; the choice is binary. In contrast, transportation sectors can make more nuanced decisions to adopt low-carbon hydrogen in specific sub-markets, such as long-distance commercial road transport; cement producers can blend hydrogen into their current fuel mix rather than convert their kilns to run on 100-percent hydrogen fuel. These factors are important for industry decision makers to consider when faced with a **range of decarbonization pathways** including electrification, carbon capture, and other fuels such as hydrogen. To avoid exposure to future regulatory scrutiny or stranded asset risk, **investors must ensure that current investments in capital-intensive assets are aligned with decarbonization** and determine how low-carbon hydrogen can play a role in these decisions.

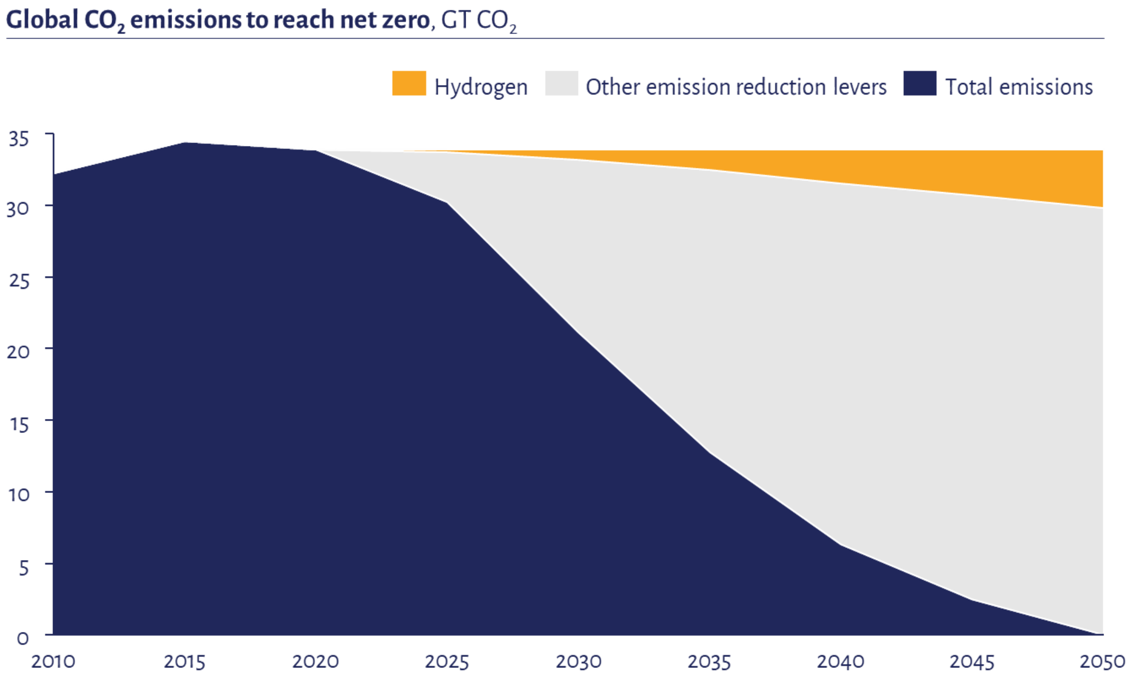
As diverse parts of the economy begin to integrate low-carbon hydrogen into their supply chain, they must monitor **factors that could further strengthen or weaken the case for hydrogen,** including technological innovations, sustained policy support, and new markets created by the proliferation of hydrogen.

Introduction

Global net anthropogenic greenhouse gas (GHG) emissions from fossil fuels have significantly increased since 1900. In particular, CO_2 emissions rose to their highest level ever in 2021.[1] To achieve the ambitious net-zero commitments set under the Paris Agreement to keep global warming under 2°C and support efforts to keep it below 1.5°C, the global financial sector must deploy transformative finance and nearly triple its current energy transition investments in the next decade.[2] Although energy and climate finance have accelerated in recent years, **many technologies – both nascent and mature – remain underfunded** compared to their abatement potential.

Low-carbon hydrogen is one such technology. Low-carbon hydrogen will be an important solution to a secure and affordable energy future due to its relative abundance, versatility, and lack of harmful direct emissions.[3] Estimates suggest that hydrogen could represent 9 percent of the cumulative emission reductions needed by 2050 [Exhibit 1], but the investments needed to unlock this potential are lagging.[4]

Exhibit 1: Global CO_2 Emissions to Reach Net Zero

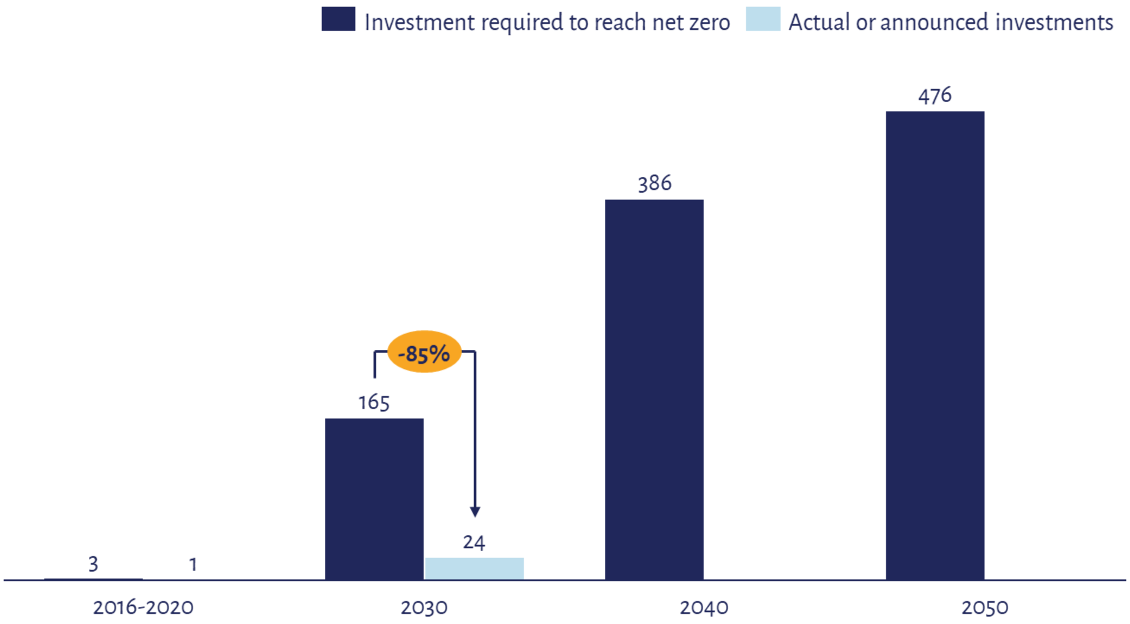


Source: IEA[5]

Current investment in hydrogen is estimated to be around USD 24 billion, compared to the roughly USD 165 billion needed across the value chain by 2030 to stay on track for 2050 net-zero commitments – **a total funding gap of USD 1.4 trillion** [Exhibit 2].[6] Ambitious and targeted action is therefore needed to overcome technological barriers and reduce costs to stimulate investment.

Exhibit 2: Hydrogen Investment Need vs. Actual or Announced Investment

Hydrogen investment net zero annual investment need vs. actual or announced investment, $B



Source: IEA.[7] PwC.[8] Hydrogen Council.[9]

Scope and Methodology

There are a number of high-level assessments of funding gaps in climate and energy finance, as well as discussions of investment pathways for new energy technologies. These reports have been published by international organizations like the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), as well as global consulting companies. With some variation, these studies all consider the current state of energy investment and discuss the additional investment required to achieve net-zero goals from their respective industries and viewpoints. However, these public reports have limited use for investors and analysts who require a more holistic and integrated view of the low-carbon hydrogen landscape to make critical, near-term decisions about when, where, and how to deploy capital.

Our project addresses this unmet need by developing a comprehensive view of the potential of low-carbon hydrogen and the enablers of future growth in Europe and North America by 2035. Specifically, this report provides a high-level overview of the low-carbon hydrogen value chain, as well as the current policy landscape. It then digs deeper into the market potential and commercialization pathways for the top potential downstream uses of low-carbon hydrogen: the heavy industry and transportation sectors.

The report takes a multidisciplinary approach to synthesize perspectives from across the low-carbon hydrogen value chain. Aside from extensive review of existing practitioner and academic literature, our findings are **informed by seven in-depth interviews with industry experts, as well as the results of an original industry survey** on the barriers to and opportunities for investment in low-carbon hydrogen with 30 respondents:

- Respondents are evenly-split geographically, with 13 respondents based in Europe, 13 others based in North America, and 4 respondents remaining anonymous.
- Respondents bring a diverse mix of expertise from across the hydrogen industry, including upstream (15 respondents), midstream (12 respondents), and various end uses such as transportation (14), heavy industry (14), power (12), and heating (8); respondents also represent viewpoints from the policy (12), investment (12), or academic (9) fields.
- Half of the respondents have 1-5 years of experience in hydrogen, while another one-third have 6-10 years of experience; the remainder have more than 10 years of experience.

Low-Carbon Hydrogen Value Chain

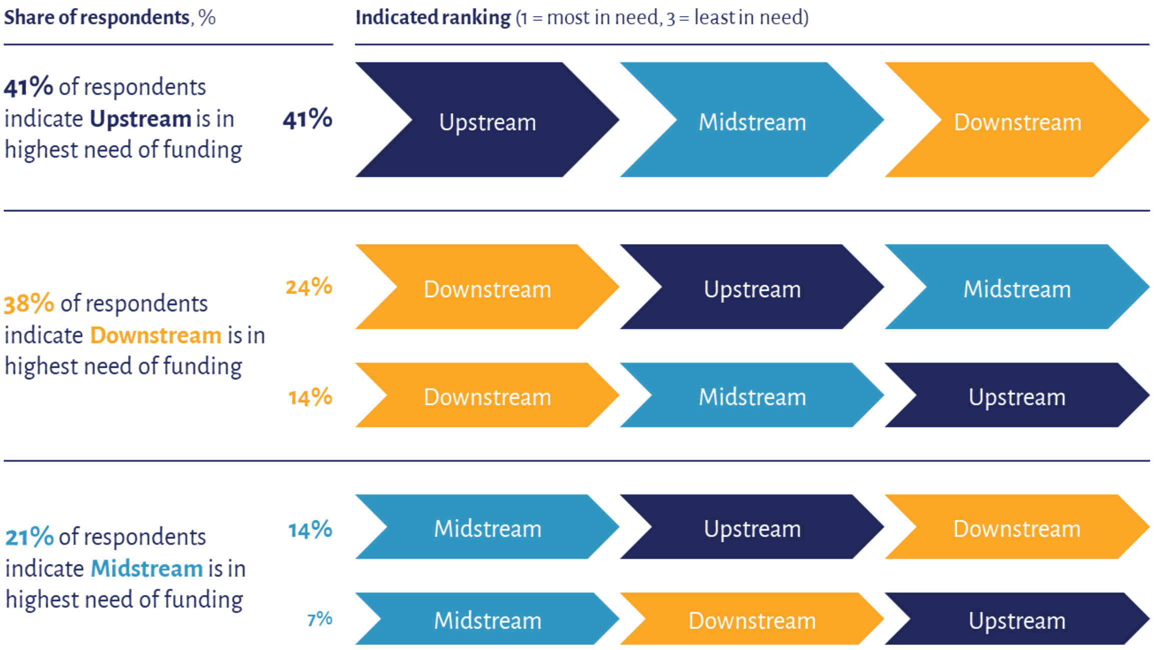
Hydrogen – the lightest and most abundant element on Earth – is a versatile source of energy. Its combustion does not emit CO_2, making it a potential solution for decarbonization across a range of applications.[10] The hydrogen value chain can be divided into three main segments: upstream, midstream, and downstream.

The upstream segment involves the production of hydrogen, which can be obtained from various sources such as natural gas through reforming and water through electrolysis. **The midstream segment involves both the physical infrastructure for the transportation and storage of hydrogen, as well as the market structure** that enables it to achieve economies of scale. **The downstream segment involves the utilization of hydrogen** through various end uses, such as heavy industry and transportation.

Each segment of the hydrogen value chain presents unique challenges and opportunities for innovation and optimization to make hydrogen a viable, efficient, and low-carbon energy source. For the most part, the value chain suffers from a **lack of coordination** between its component parts. There is an underlying tension between those who believe that investment should flow from upstream infrastructure and those who believe downstream investment should drive the market – in other words, there is **a "chicken and egg" problem**.[11] Our survey results reflect this dynamic [Exhibit 3]. A plurality of survey respondents (41 percent) indicate that upstream is in the highest need of immediate funding, followed by downstream (38 percent), and midstream (21 percent).

Exhibit 3: Hydrogen Supply Chain Funding Need

Which component of the low-carbon hydrogen supply chain is most in need of immediate funding?, %



Source: Original industry survey

Upstream: Producing Hydrogen

At present, there are three main ways to produce hydrogen:

- **Fossil-derived hydrogen** is derived from "fossil fuels with no CO_2 emissions control," and is sometimes referred to as gray hydrogen. More than three-quarters of fossil-derived hydrogen is produced through a process referred to as steam methane reforming (SMR), which involves a reaction between fossil fuel sources such as methane and high-heat steam. This process emits significant volumes of CO_2; the average SMR plant releases between 8 and 12 kg CO_2 per kg of hydrogen.[12] Today, 98 percent of hydrogen is produced as gray hydrogen.[13]
- **Fossil-derived hydrogen with carbon capture** combines the traditional process of making gray hydrogen with carbon capture, utilization, and storage (CCUS) facilities.[14] The hydrogen produced through this method is sometimes referred to as blue hydrogen. CCUS captures CO_2 from large point sources and transports it for use in other applications or for permanent storage in underground basins.[15] Currently, there are 7 CCUS hydrogen plants in Europe and 12 in North America.[16] Critics challenge the abatement potential of this technology, since fugitive methane (methane gas that escapes into the atmosphere during production and transportation) still contributes to significant GHG emissions and the potential of CCUS technology indefinitely storing CO_2 remains uncertain.[17]
- **Renewable hydrogen** derives hydrogen from water via electrolysis. Electrolysis refers to the process of splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) molecules by means of an electric current – a process that involves no direct GHG emissions. Electrolysis requires electricity; if this electricity is sourced from renewables such as wind or solar, the full process is zero-carbon and is referred to as green hydrogen.[18] However, indirect GHG emissions can still occur if the process uses electricity generated by fossil fuel combustion.

While the different types of hydrogen have historically been labeled according to the colors corresponding to the method of production, there has been **a recent push to instead designate hydrogen based on its carbon intensity**.[19,20] Assigning colors to hydrogen may confuse market participants and increase the risk of greenwashing, since different geographies may apply different standards and carbon accounting methods. **Given these ongoing discussions, we will refer to "low-carbon" hydrogen in this report instead of using specific color designations.**

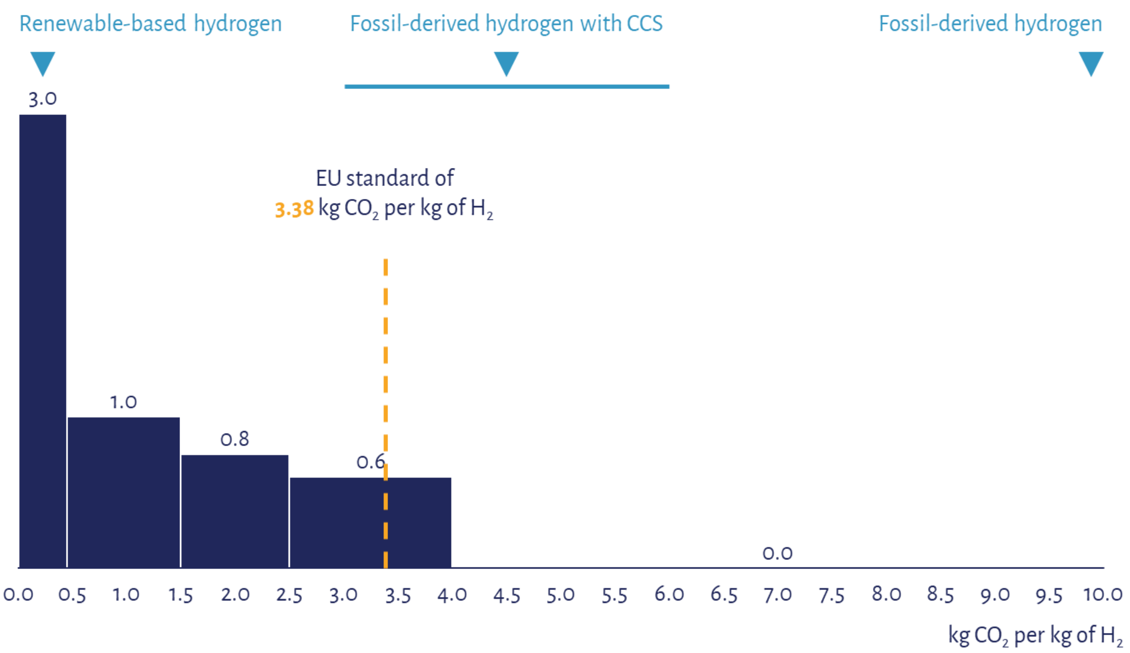
To create an international working definition of low-carbon hydrogen, **the European Commission and the US government have focused on carbon intensity**:

- **Europe** requires hydrogen to have emissions below 3.38 kg CO_2/ g H_2 (i.e., a 70 percent reduction compared to fossil-derived hydrogen) to be considered renewable under the Renewable Energy Directive.[21]

- The **United States** Inflation Reduction Act (IRA) scales hydrogen subsidies according to the carbon reduction potential of hydrogen [Exhibit 4]. The highest subsidies are reserved for hydrogen produced with emissions of less than 0.45 kg CO_2/kg H_2, while no subsidies remain for hydrogen with emissions over 4 kg CO_2/kg H_2.[22] It is worth nothing that both the European and US definitions include a lifecycle emission approach.[23,24]

Exhibit 4: IRA Subsidies Production Tax Credit by Carbon Intensity

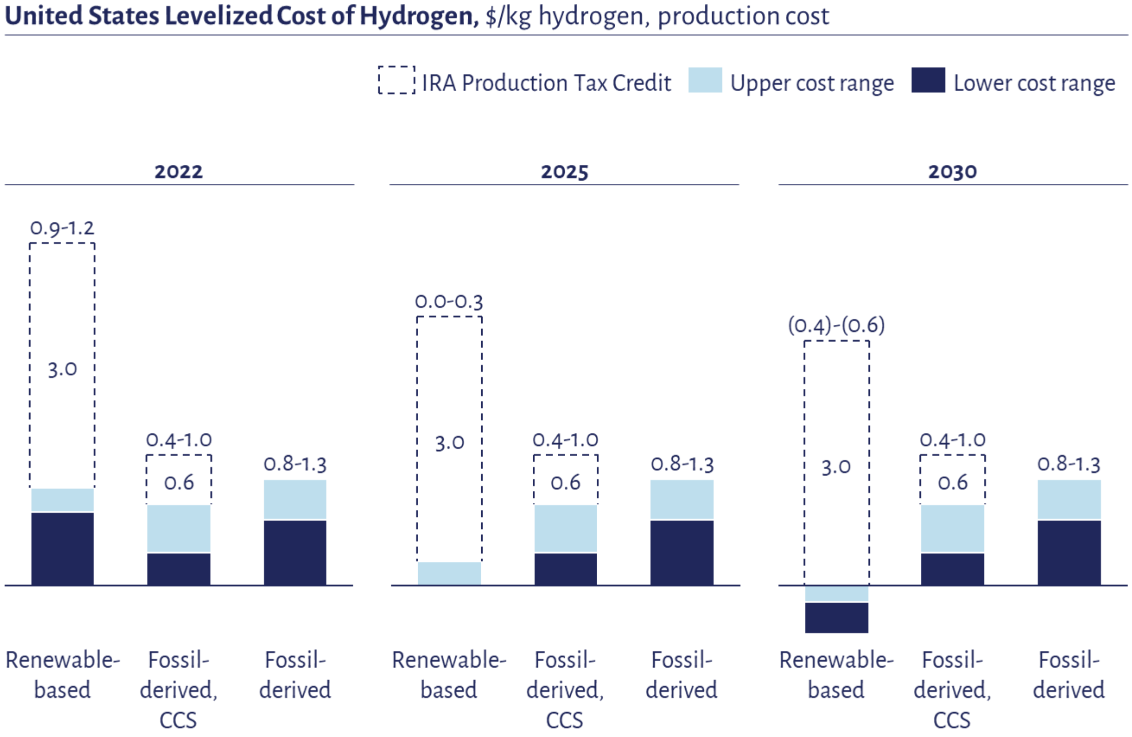
IRA subsidies production tax credit by carbon intensity, $/kg



Sources: Capgemini Research Institute.[25] *Europarl.*[26] *NRDC.*[27]

While the environmental benefits of renewable hydrogen are clear, its main disadvantage relates to **production costs**. Experts estimate that renewable hydrogen is currently 3 to 4 times more expensive than fossil-derived hydrogen. Even with expected efficiency gains, **fossil-derived hydrogen would still be around 50 percent cheaper than unsubsidized renewable hydrogen by 2030 in the United States** [Exhibit 5]. The **comparison in Europe looks different**, given the differences in availability of renewable energy and natural gas prices. By 2025, hydrogen produced in Portugal through co-located wind and solar may be 40-50 percent more expensive than fossil-derived hydrogen, but this heavily depends on the assumptions related to natural gas prices.[28] For every increase of EUR 15/MWh in natural gas, the price of fossil-derived hydrogen rises by about EUR 1/kg. Given fluctuations of more than EUR 100/MWh in 2022 in Europe[29], natural gas price uncertainty can significantly alter the cost-parity analysis.

Exhibit 5: United States Levelized Cost of Hydrogen



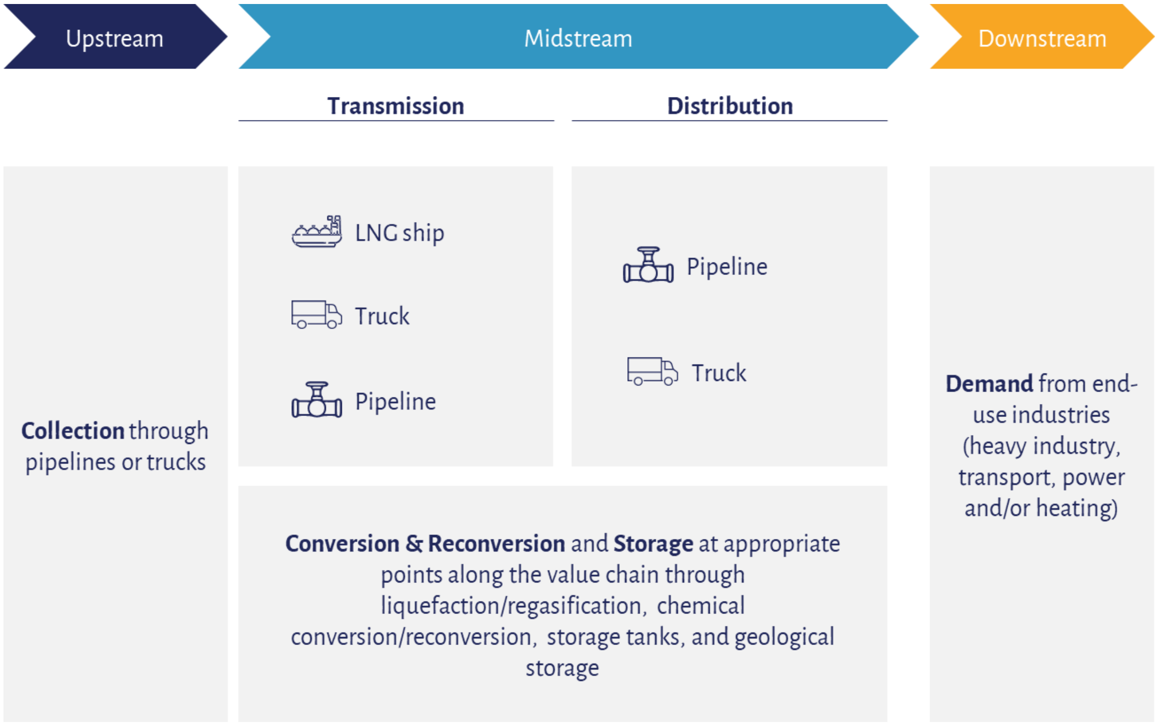
Source: Adapted from Boston Consulting Group[30]

Furthermore, questions remain in the United States and Europe regarding **how to determine the carbon intensity of hydrogen production**. In particular, there is no universal accounting standard for determining the emissions intensity of the electricity (or any other resource) used to produce hydrogen. In Europe, starting in January 2030, electrolysis-based hydrogen will count as "renewable" based on the carbon intensity purchased by the producer on an **hourly basis**.[31] On the other hand, in the United States, regulators and industry stakeholders are debating whether this **temporal matching** should occur on an hourly basis or an annual basis. Proponents of **hourly matching** point to the need to ensure that hydrogen production produces net emissions reduction, which is initially not likely with looser requirements. Other analysts, including many electrolyzer companies and industry associations, support **annual matching**, arguing that stricter standards will limit the growth of all parts of the value chain and thereby delay hydrogen's cost reductions. The Internal Revenue Service is expected to release guidance in August 2023 to clarify this question.[32] Other uncertainties include the definition of **additionality** (i.e., requirements that hydrogen production leads to additional renewable grid generation instead of cannibalizing renewable generation, which could activate marginal fossil fuel generators to support the rest of the grid load) and **geographic matching** (i.e., the degree to which low-carbon hydrogen production must be geographically linked to the renewable energy associated with its assigned carbon intensity).[33]

Midstream: Transporting Hydrogen

The volumetric energy density of hydrogen is low, making it challenging to store and transport. Therefore, it needs to be converted into hydrogen-based carriers at the midstream level before reaching end users.[34]

Exhibit 6: Hydrogen Distribution



Source: Adapted from IEA.[35]

Midstream components of the hydrogen value chain are projected to generate an estimated USD 11-14 billion in earnings by 2030 and can be broken down into two major categories: transmission and distribution [Exhibit 6].[36] **Transmission** comprises the equipment and processes involved in the compression, liquefaction, and reconversion of hydrogen and hydrogen products. **Distribution** entails the services and infrastructure involved in the storage and transportation of hydrogen.

At present, the transmission and distribution of pure hydrogen can be accomplished through the following technological **pathways and "vectors"**: as a gas through dedicated pipelines, as a high-pressure gas stored in tube trailers, as a cryogenic liquid carried in tankers, or as derivative products such as synthetic methane, synthetic liquid fuels, or ammonia.

While each vector has distinct competitive advantages and disadvantages depending on factors such as mode and distance, **technological and cost hurdles** remain prevalent for all midstream pathways.[37] Hydrogen pipelines, which carry around 88 percent of the energy content of their methane counterparts, require high capex for the initial buildout and high opex as compressors need to operate at three times the speed of natural gas due to the low molecular weight of hydrogen. The liquefaction of hydrogen is similarly capital and energy intensive; liquefier installation costs are higher than those of gas compression equipment, while the liquefaction process itself consumes more than 30 percent of the hydrogen's energy content.[38]

Given these challenges, sources of value for midstream components are primarily derived from **innovation** (i.e. technological advancements that allow efficiency gains or cost reductions) and **retrofitting**, (i.e. repurposing existing infrastructure for hydrogen use and potentially cutting expenses up to 60 percent).[39] The most efficient transmission and distribution strategies will require **a blend of established and developing technologies**, tailored to suit regional usage rates, travel distances, timeframes, and end-user needs.

Transition and geopolitical risks are the main challenges for midstream components. Transition risks arise from the fact that technological unlock (through liquefied hydrogen or ammonia) and capital inputs are required to facilitate the creation of a hydrogen transport infrastructure. Geopolitical risks result from the international cooperation and framework-building needed to create a common marketplace for cross-border hydrogen trade and transport.

The hydrogen infrastructure transition can **learn from relevant precedents in similar industries.** Namely, hydrogen development can be analogous with liquefied natural gas (LNG). Hydrogen and LNG large-scale and technically complex industries that involve the export of energy products as an industry feedstock to markets spanning across geographic areas, which requires a high level of market coordination. Nonetheless, hydrogen differs from LNG in that LNG was a direct alternative to traditional fossil fuels and did not require the extent of policy support for market or infrastructure development.[40] Issues such as liquefied hydrogen boil-off, embrittlement of pipeline metal, and blending difficulties create **cost, technological, and environmental challenges that are unique to hydrogen.**

In terms of ownership, potential commercial models for midstream assets include integrated merchant, segregated merchant, and integrated tolling. Integrated merchants own all export assets (electricity, hydrogen, and ammonia). Segregated merchants own the hydrogen and ammonia facilities and sell low-carbon ammonia, but purchase renewable electricity from third party generators. Integrated tolling companies own all the exports assets but provide a processing service to a third-party toller, who then conducts sales and pays a fixed fee for the service. [41]

In recent years, **a number of national and international policy initiatives have been proposed to address midstream needs**. Forecasts predict that five hydrogen supply and import corridors, which would connect areas with high demand to regions of abundant hydrogen reserves, could emerge by 2030.[42] In Europe, the Hydrogen Backbone Initiative involves 31 European gas infrastructure companies that planned a pan-European dedicated hydrogen transport infrastructure. The initiative can support the development of a 20.6 Mt low-carbon hydrogen market in Europe, which will employ a 53,000-km network of repurposed existing natural gas infrastructure by 2040. The proposed initiative requires an estimated total investment of EUR 80-143 billion, or an average of EUR 0.11-0.21 per kg H_2.[43] In the United States, the Regional Clean Hydrogen Hubs program (H_2Hubs) includes up to USD 8 billion to establish six to 10 regional clean hydrogen hubs across the nation. Funded through the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law, or BIL), the H_2Hubs are designed to be the central network drivers to connect producers, consumers, and local connective infrastructure across the hydrogen value chain.[44]

Downstream: Using Hydrogen

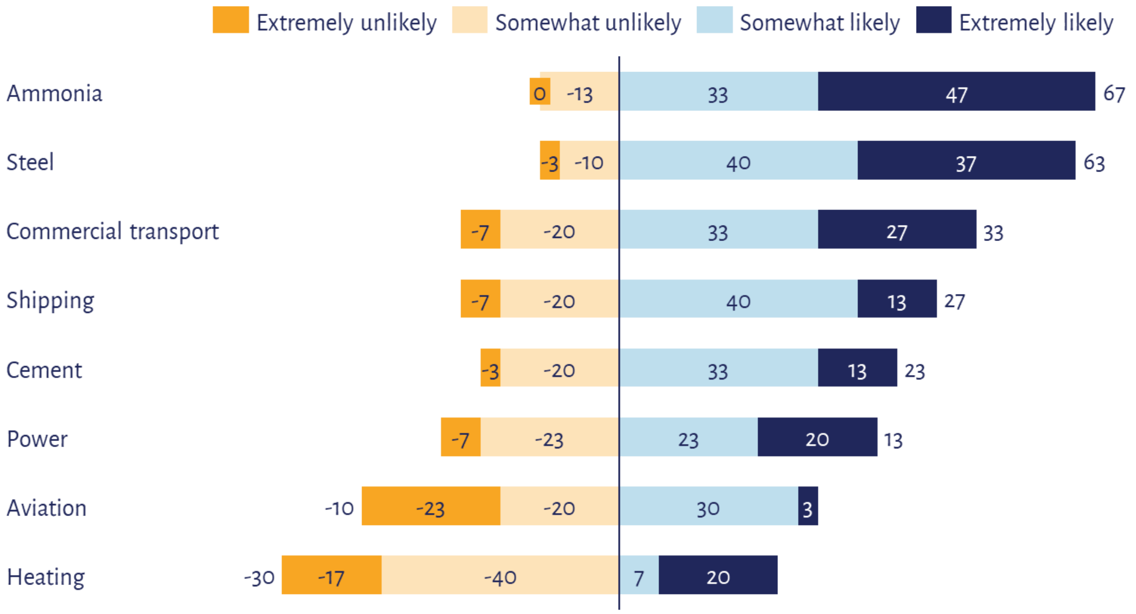
Hydrogen has several key properties that make it a versatile fuel source for a variety of end uses. It has a high gravimetric energy density, meaning that it contains a large amount of energy per unit of mass, making it an attractive option for transportation fuel and other mobile applications. Similarly, it can be converted and used in a range of modalities, including fuel cells, gas turbines, or as derivative products such as ammonia.

This report will focus on the most technically and commercially viable end uses for low-carbon hydrogen, which were selected through a comprehensive review of existing literature and a survey of industry experts. These end uses can be grouped into two main categories: heavy industry (ammonia, steel, and cement) and transportation (commercial transport, maritime shipping, and aviation).

Our survey results [Exhibit 7] indicate that ammonia, steel, and commercial transport are the top three end uses of low-carbon hydrogen in terms of most potential for technical and commercial viability by 2035. To examine and verify these findings, we conducted supplementary open-source research. The subsequent sections illustrate the results, evaluations, and discoveries of this study.

Exhibit 7: Technical and Commercial Viability of Low-Carbon Hydrogen by End Use

What is the likelihood that low-carbon hydrogen will be technically and commercially viable for end-use?, %



Source: Original industry survey.

Policy Environment

Policy is poised to play an increasingly important role in helping low-carbon hydrogen overcome current technological and cost barriers to reach economies of scale. This section takes a comparative approach to analyze recent policy developments in the European Union and the United States with a focus on their potential impacts on the hydrogen value chain.

United States

Hydrogen is steadily gaining policy momentum in the United States. The Biden Administration has identified the development and deployment of low-carbon hydrogen as key components of its plan to achieve net-zero emissions by 2050. To this end, the Biden Administration has pursued a number of initiatives through both the legislative and executive branches.

The Biden Administration's two landmark laws – the BIL and the IRA – both include provisions to support hydrogen through subsidies and tax benefits. The BIL, which was passed in late 2021, specifically allocates USD 9.5 billion in grant programs for hydrogen production and infrastructure.[45][46] Around USD 8 billion from the BIL will be disbursed through "regional hydrogen hubs" in cooperation with states, businesses, universities, and research institutions.[47] The IRA similarly offers robust tax credits to incentivize hydrogen production, including **up to USD 3/kg of production tax credit (PTC) based on the emissions of the hydrogen produced (see Value Chain section)**.[48] In addition, hydrogen producers can qualify for low-carbon hydrogen and renewable energy tax credits (a PTC of up to 2.6 cents/kWh) simultaneously.[49] At the same time, qualifying producers generating hydrogen via conventional methods with CCUS can take advantage of the 45Q tax credits, which provide up to USD 85/ton of CO_2 permanently stored.[50]

In the executive branch, the US Department of Energy (DOE) has launched several initiatives to support the development and deployment of hydrogen. The National Clean Hydrogen Strategy and Roadmap has served as the primary guiding document for the DOE's efforts. With the goal of reducing the cost of clean hydrogen (with emissions of less than 2 kg CO2/kg H2) by 80 percent to USD 1 per kg in a decade and deploying 5 to 10 GW of electrolyzers in the United States by 2030, the roadmap **identifies technology research and development, infrastructure development, market creation, and cross-cutting coordination as the four key pillars for the development of a clean hydrogen economy**.[51] Another key initiative is the H2@Scale program, which focuses on advancing technologies for low-cost, large-scale production of hydrogen from diverse domestic sources. H2@Scale also supports research into advanced storage technologies, such as solid-state hydrogen storage, and innovative applications of hydrogen, such as in fuel cells for trucks and other heavy-duty vehicles.

Similarly, the DOE's Hydrogen and Fuel Cell Technologies Office as well as its Energy Efficiency and Renewable Energy program have both provided funding for research into hydrogen storage technologies, advanced fuel cell systems, and other innovative hydrogen applications. The DOE has also engaged with the private sector and academia through the establishment of regional hydrogen innovation clusters and the issuance of Liftoff Reports, which establish a shared fact base and serve as a tool to foster ongoing public-private dialogue.[52]

In sum, the United States government has demonstrated its commitment to supporting the uptake of a low-carbon hydrogen economy through a range of initiatives. The BIL, IRA, as well as multiple DOE initiatives all provide significant support mechanisms to bring low-carbon hydrogen to technological maturity and cost parity with fossil-derived hydrogen within the next decade.

Europe

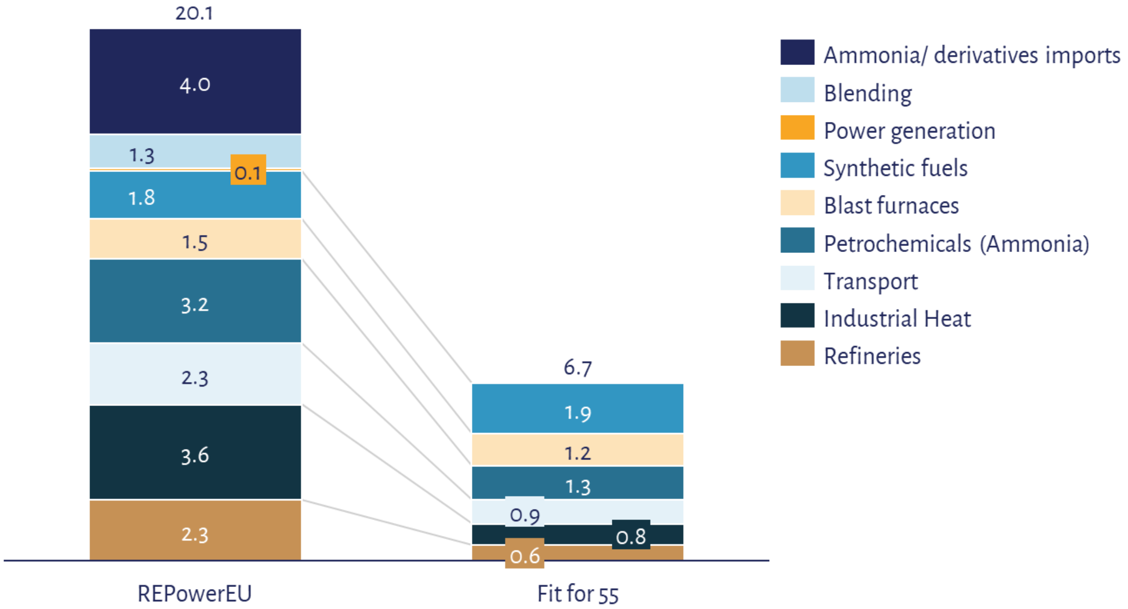
The EU Hydrogen Strategy, which was issued in July 2020, will guide the EU's uptake of renewable and low-carbon hydrogen. **The European Union aims to increase the share of hydrogen in energy consumption from less than 2 percent to 13-14 percent by 2050,** surpassing the IEA's goal of making hydrogen account for 10 percent of global energy consumption by 2050.[53,54] The Hydrogen Strategy lays out a three-phase plan focused on investment in hydrogen production and transportation infrastructure. For the production of renewable hydrogen, the European Union's stock of installed electrolyzers is expected to rise from 1 GW to at least 6 GW by 2024, and to 40 GW by 2030. [55]

Meanwhile, two milestone policy initiatives – the REPowerEU plan and the Green Deal Industrial plan – have accelerated the development of the EU hydrogen economy. The REPowerEU plan, issued in May 2022, boosts the renewable hydrogen target to 20 million tons by 2030 – half of which would be domestically produced, while the other half is expected to be imported.[56] The planned use of hydrogen in the industrial heat and transportation sector increased 4.5-fold and 2.5-fold, respectively, from the amount that was announced just a year prior [Exhibit 8].[57] **Critics have characterized REPowerEU goals as overly ambitious within the given timeframe and concerns have been raised about Europe's ability to generate enough demand for this amount of hydrogen by 2030.[58]** Meanwhile, other market projections suggest that the goal is still insufficient to meet the 1.5°C target by 2050, which would require 565 million tons of annual hydrogen production.[59] Along with these goals, the REPowerEU plan allocated EUR 41 billion to facilitate the transition to cleaner fuels, including another EUR 27 billion assigned to the deployment of key hydrogen infrastructure.[60,61]

The Green Deal Industrial Plan, released in early 2023, has served as the EU's response to the US IRA.[62] It earmarked EUR 3 billion for the European Hydrogen Bank (EHB) to establish the European Union's hydrogen market, an auction mechanism that provides subsidies of up to EUR 4/kg for the production of renewable hydrogen.[63,64,65] With the auction in place, producers would be able to produce hydrogen at a fixed price per kg for 10 years. The first auction would be launched in the fall of 2023, with EUR 800 million in funding backed by the EU Innovation Fund.[66] Aside from hydrogen production, the Green Deal Industrial Plan also vowed to provide full coverage of the Trans-European Transport Network with refueling options to strengthen the continent's "hydrogen backbone."

Exhibit 8: Hydrogen Use by Sector in 2030, REPowerEU and Fit for 55

Hydrogen use by sector in 2030, Mt H_2



Source: European Commission. [67,68]

In addition to the above EU plans, substantial financial support has been unlocked in the form of other public funding, loans, and state aid for renewable hydrogen production and innovation. Important Projects of Common European Interest (IPCEIs) program issued roughly EUR 10.6 billion in public funding for low-carbon hydrogen, including EUR 5.4 billion for the Hy2Tech initiative designed to support the use of hydrogen in industrial and transportation sectors.[69] An additional EUR 5.2 billion in funding was released through the IPCEI Hy2Use initiative, which also supports the construction of hydrogen infrastructure and the integration of hydrogen with the industrial sector.[70] **IPCEI's initial funding of EUR 10.6 billion is expected to crowd in another EUR 15.8 billion in private investment**.[71]

In addition, the EU Innovation Fund has announced EUR 1 billion in funding for innovation projects in low-carbon hydrogen production and hydrogen uptake in industry.[72] As of May 2023, there are currently 8 hydrogen projects under the Innovation Fund's portfolio, totaling EUR 402 million of the EU contribution.[73] The fund is financed by revenues from the auctioning allowances of the European Union's Emissions Trading System, which may amount to about EUR 10 billion. Through the InvestEU program, the European Investment Bank has provided a loan of EUR 315 million to a joint venture for the advancement of hydrogen-powered automotive propulsion technologies and the development of active safety systems.[74]

Russia's invasion of Ukraine has accelerated the European Union’s investment in hydrogen. For example, the Temporary Crisis and Transition Framework (TCTF) adopted in early March 2023 provides aid for member states to set up renewable energy investment schemes, which are projected to benefit hydrogen assets. **Within a month of the TCTF's launch, roughly EUR 10.6 billion of state aid was granted.** Meanwhile, another state aid amendment – the State Aid General Block Exemption Regulation – also facilitates hydrogen investment by streamlining administrative procedures for clean energy projects.[75]

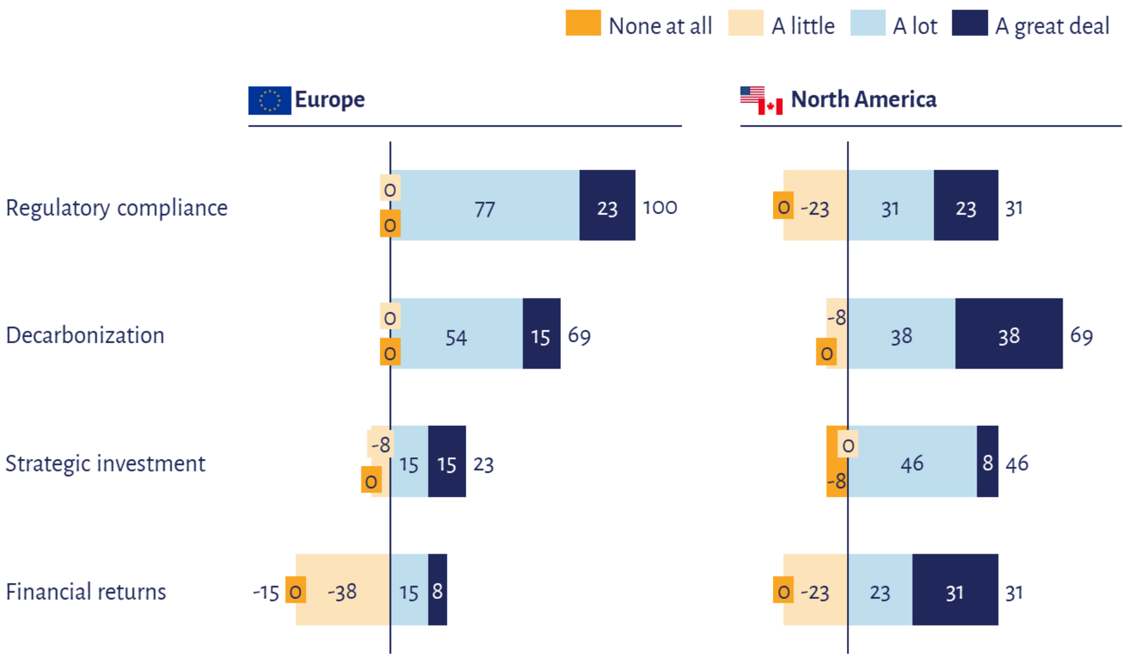
To summarize, the European Union places great importance on hydrogen and has established specific targets and financial incentives to support the entire hydrogen value chain. The urgency to adopt hydrogen is further driven by the energy crisis brought on by Russia's invasion of Ukraine, as well as the US IRA. In response, the European Union has invested resources into scaling the production of renewable hydrogen, as well as its integration with the industrial and transportation sector.

Regional Comparison: Europe vs. United States

Our survey finds that the regulatory compliance pressure for the adoption of low-carbon hydrogen is higher in Europe than in the United States [Exhibit 9]. A few factors can potentially explain this disparity. First, the hydrogen targets set by the European Union are more ambitious [Exhibit 10]. For example, the European Union aims to deploy 40 GW of renewable hydrogen electrolyzers by 2030, which is over four times higher than the US's target of 5-10 GW. Second, the United States is more lenient with its funding standards, offering tax credits for hydrogen with a higher carbon intensity (up to 4 kg CO_2/kg H_2).[76]

Exhibit 9: Expected Drivers of Low-Carbon Hydrogen Investment, Europe, and North America

To what extent will the below factors motivate future investment in low-carbon hydrogen?, %



Source: original industry survey. (The survey results are distributed based on the location of the survey respondent, i.e., Europe or North America.)

This provides higher potential upside for investors and is consistent with our survey findings that **financial returns are an incentive for low-carbon hydrogen adoption in North America, namely the United States** [Exhibit 10]. Third, the existing hydrogen-related policies in the United States have a strong emphasis on the cost reduction, with generous and seemingly unlimited subsidies to induce production. The European Union has also begun to offer similar incentives through the EHB and other programs, but these policy inventions are more recent than the US' BIL and IRA and therefore may be less integrated into decision making. Lastly, a comprehensive regulatory ecosystem that includes the EU Emissions Trading System (ETS) and the proposed Carbon Border Adjustment Mechanism (CBAM) puts additional compliance pressure on European stakeholders, who are exposed to regulatory risks in more categories than their American counterparts.

Exhibit 10: Hydrogen Policies, European Union, and United States

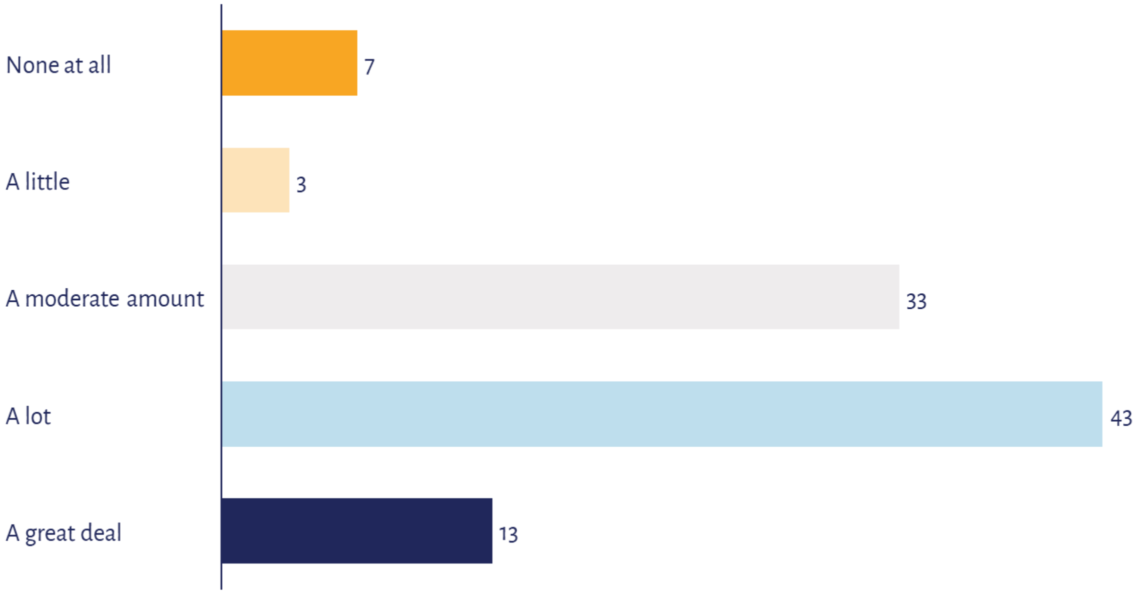
	Europe	**United States**
Goals and targets	• Cost of renewable hydrogen **below €1.8/kg** by 2030 • **20 MMT** low-carbon hydrogen annual consumption by 2030 • **40 GW** electrolyzer capacity by 2030	• Cost of low-carbon hydrogen to **$1/kg** by 2030 • **10 MMT** low-carbon hydrogen annual consumption by 2030 • **5-10 GW** electrolyzer capacity by 2030
Policy support programs	• **EU Green Deal Industrial Plan** – bidding up to €4/kg subsidy for low carbon hydrogen through €3B European Hydrogen Bank auction • **REPowerEU** – €27B for hydrogen infrastructure by 2030 and €41B for overall industry adaption of less fossil fuels • **Important Projects of Common European Interest** – €10.6B across Hy2Tech and Hy2Use • **EU Innovation Fund** – €1B in innovation projects in renewable hydrogen production and industry uptake	• **Inflation Reduction Act** – up to $3/kg production tax credit, 30% investment tax credit • **Bipartisan Infrastructure Law** – $9.5B in funding across H2Hubs, Clean Hydrogen Electrolysis Program and Clean Hydrogen Manufacturing and Recycling Initiatives

Source: Authors, based on Inflation Reduction Act.[77] *Bipartisan Infrastructure Law.*[78] *EU Hydrogen.*[79] *European Commission Press Corner.*[80]

Despite significant policy support offered by the United States and the European Union, the low-carbon hydrogen economy does not yet enjoy a complete regulatory environment that can facilitate its growth. Over half of the survey respondents (57 percent) still think more policy incentives are needed [Exhibit 11]. The market sentiment of uncertainty may be linked to the ongoing rollout of government funding and subsidies, as well as the fact that regulatory guidance is still being developed. Currently, roughly EUR 40 billion of targeted funding for hydrogen projects have been announced, but a cumulative investment of EUR 180-470 billion is needed to build up the European Union's envisioned hydrogen ecosystem by 2050.[81] The IEA also projects that USD 1.2 trillion in global hydrogen investment is required to achieve net-zero emissions by 2050 and urges major economies to take decisive policy actions to enable the maturation of the hydrogen value chain.[82]

Exhibit 11: Additional Policies Needed for Low-Carbon Hydrogen Investment

How much are additional policies needed to enable investment in low-carbon hydrogen?, %



Source: Original industry survey.

Heavy Industry

Low-carbon hydrogen has strong potential to decarbonize industrial processes. **Combined, heavy industry makes up nearly 40 percent of global CO_2 emissions**, due to the fuel demanded to generate high-temperature heat for kilns and furnaces.[83] As such, decarbonizing industry will be a challenging step in the transition to a low-carbon economy.

This section will focus on ammonia, steel, and cement production. These specific end uses were identified based on their high carbon abatement potential and the existing technologies that support potential use of low-carbon hydrogen in production.

Current Uses of Ammonia

At a Glance:

- As an existing consumer of hydrogen, the ammonia industry has high and immediate potential to transition from its carbon-intensive hydrogen feedstocks to low-carbon alternatives.
- Ammonia producers will need to take advantage of existing government incentives to overcome high upfront costs of building electrolyzers or carbon capture systems.

Market Overview

As it is used today, ammonia is **an essential building block of the food system and a key component of a range of chemical products** such as plastics, explosives, and textiles. Specifically, ammonia is a critical precursor for all mineral nitrogen fertilizers, which accounts for 70 percent of ammonia demand.[84] As reflected in other sections of this report, potential expansion of the ammonia market into the transport and power sectors[85] may also create additional upside for low-carbon ammonia production. **While we recognize this potential for growth, this section will focus on the decarbonization pathways of ammonia production for its current market applications.**

Europe and the United States both produce ammonia for domestic consumption, primarily in the agricultural sector. In 2022, the United States produced 13 million metric tons of ammonia at 35 plants, mostly in states with cheap and accessible natural gas supplies, including Louisiana, Oklahoma, and Texas.[86] In 2021, the top European producers – Germany, Netherlands, Poland, and Ukraine – combined to produce around 8 million metric tons.[87] The ammonia industry is highly capital intensive and consists of a limited number of large companies. In the United States and Europe, major industry players include BASF, CF Industries, Dyno Nobel, Koch Fertilizer, Nutrien, and Yara.[88,89]

Europe relies more heavily on imported ammonia than the United States, a condition that has been exacerbated by the supply chain impacts of Russia's 2022 invasion of Ukraine. In the United States, imports constitute around 10 percent of domestic consumption and are almost entirely from Canada and Trinidad and Tobago.[90] On the other hand, the European Union imported an average of 295,000 tons of ammonia per year between 2019 and 2021, with the majority coming from Russia, Algeria, and Trinidad and Tobago.[91] Since the invasion of Ukraine, high volatility in natural gas prices have dented Europe's domestic ammonia production, with large producers such as CF Industries, Yara, and others reducing or pausing production in response to high volatility in natural gas prices.[92] Some EU plants have even closed due to high fuel prices.[93] To replace ammonia imports from Russia, Europe has increased imports from the Middle East[94] and the United States.[95]

Ammonia production currently accounts for 2 percent of total global final energy use, 1.3 percent of global CO_2 emissions from the energy system, and 5 percent of total industrial sector CO_2 emissions.[96] **Since ammonia producers already consume hydrogen as a feedstock, integrating low-carbon hydrogen into existing value chains presents a strong and immediate market opportunity**.

Technology Pathways

Steam Methane Reforming and Auto-thermal Reforming

Making ammonia involves 1) isolating hydrogen and 2) combining hydrogen with nitrogen from the air, which is known as the Haber-Bosch process.[97] In addition to hydrogen and nitrogen inputs, process energy is needed to generate heat and pressure. **In Europe and the United States, most hydrogen is extracted from natural gas through SMR or auto-thermal reforming (ATR).**

The hydrogen produced through SMR or ATR undergoes methanation to remove any leftover carbon compounds and is combined with atmospheric nitrogen under pressure to create ammonia. SMR is more common than ATR and is preferred for newly built plants today because it is slightly more energy efficient on a net basis.[98]

There are two main ways to decarbonize ammonia production: replacing conventional methods with electrolysis or using conventional methods combined with carbon capture. These pathways are exposed to different risks, such as fuel costs, infrastructure demands, and technology risks. In this section, we outline the key factors that the ammonia industry may consider when pursuing low-carbon hydrogen technologies.

Electrolysis-based Ammonia

Electrolysis-based ammonia involves splitting water to produce hydrogen and oxygen as a by-product. All parts of this process can be electrified, and therefore can reduce indirect CO_2 emissions to negligible levels.

However, electrolysis-based ammonia production can lead to indirect CO_2 emissions based on the carbon intensity of the electricity source. In fact, some scenarios see CO_2 emissions from the ammonia industry increasing due to adoption of electrolytic hydrogen outpacing grid decarbonization.[99] Ammonia producers may avoid this timing mismatch through variable renewable energy electrolysis,[100] but this process faces challenges such as lower capacity factors and hydrogen storage costs. Upstream investments in renewable electricity are necessary before grid-based electrolytic ammonia can be considered a low-carbon production method.

Conventional Ammonia with Carbon Capture and Storage

Emissions from reforming-based ammonia production can be reduced through capturing direct CO_2 emissions from natural gas. **In fact, conventional ammonia production already involves removing CO_2.** There are several different methods that have reached technological maturity today, ranging from physical to chemical absorption of CO_2. Ammonia plants regularly isolate CO_2 as part of the production process and use it onsite for urea synthesis.[101] Capturing the rest of the feedstock CO_2 would require additional processing equipment to prepare it for transport and storage and would need no additional technological innovations. However, to capture the CO_2 emissions that result from fuel combustion would entail an additional capture unit and is seldom implemented today.[102] This extra component is estimated to incur between twice and four times the cost of capturing feedstock CO_2.

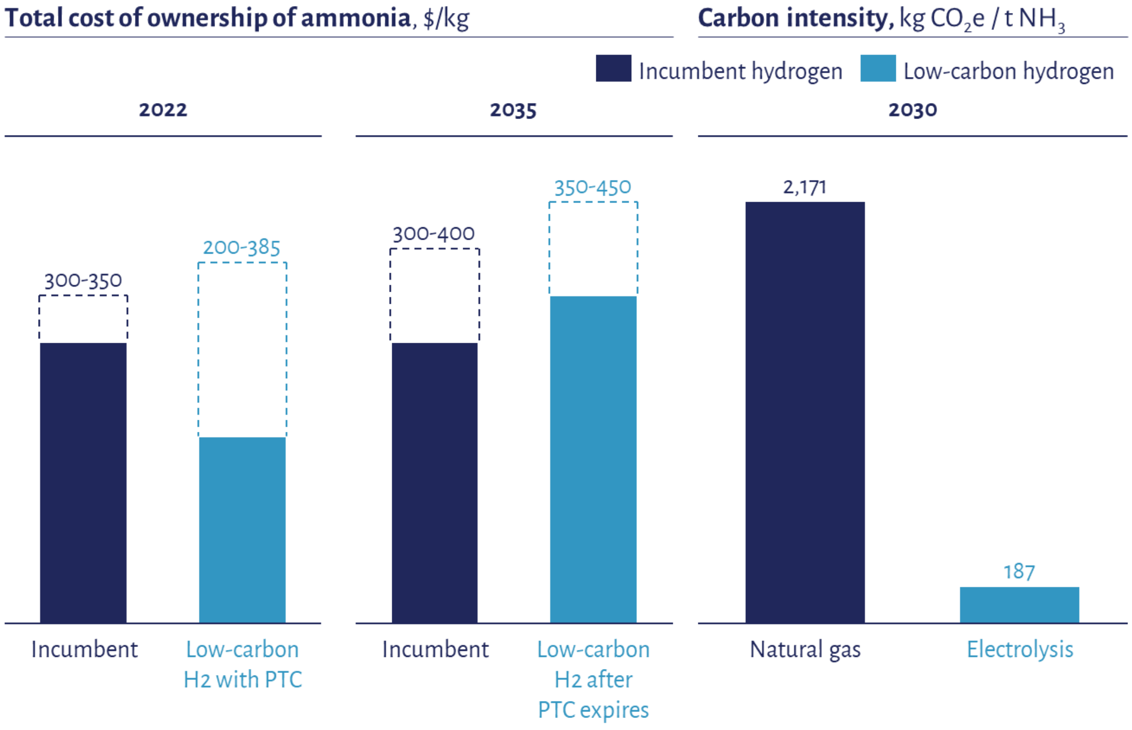
Low-carbon hydrogen enjoys several **advantages** that may enable transition investments:

- **High technology readiness.** The ammonia industry is actively pursuing low-carbon hydrogen pathways via electrolysis and CCUS-based methods. In the United States, 4.4 million metric tons per year of new low-carbon ammonia projects had been announced by the end of 2022, making up 23 percent of overall low-carbon hydrogen project commitments in the United States.[103] Although electrolysis only accounts for 0.2 percent of global ammonia production today,[104] many ammonia plants in the United States and Europe have added electrolyzers to supplement existing fuel sources, such as Fertiberia's plant in Puertollano, Spain;[105] Yara's plant in Porsgrunn, Norway;[106] and CF Industries' plant in Donaldsonville, Louisiana.[107] Meanwhile, ammonia producers also already employ CO_2 capture at many plants in the United States and Europe[108,109] and have planned major investments to expand capacity in the near future.[110,111]

- **Established markets with hydrogen experience.** The ammonia industry has always used hydrogen. In comparison to other end use sectors, hydrogen is an intrinsic component of the ammonia supply chain, rather than just one option among many possible feedstocks or fuel sources. The industry can change the source of its hydrogen feedstock through plant retrofits while incurring relatively little technology risk. Also, for the majority of ammonia plants that produce hydrogen onsite in the United States,[112] there is a limited need to build additional midstream infrastructure to reach new fuel sources.

- **Government incentives and policy signals.** The ammonia industry enjoys favorable policy frameworks for decarbonization. US ammonia producers with co-located reforming-based hydrogen production equipment may find IRA PTC and 45Q tax credits as attractive mechanisms for recovering CCUS retrofit costs, although breakeven points would be sensitive to natural gas prices.[113] In addition, some electrolysis-based ammonia projects are already cost competitive when compared to conventional production, with total cost of ownership (TCO) with IRA subsidies ranging between USD 200 and USD 385 per metric ton [Exhibit 12]. Since the passage of the IRA in August 2022, the ammonia industry has rapidly expanded the project pipeline for both electrolytic[114,115] and CCUS-equipped production.[116] Meanwhile, the European Union has set ambitious and binding targets for industrial uses of hydrogen, including ammonia. A recent provisional agreement requires European industry to source 42 percent of hydrogen from "renewable" sources by 2030 and 60 percent by 2035.[117] Even if Europe falls short of these commitments, the EU ammonia industry will pursue decarbonization of its hydrogen feedstocks to comply with these regulatory requirements. This process may occur in parallel with rising imports of low-carbon ammonia, including from the United States, as major ammonia companies may choose to invest in import and distribution infrastructure rather than reopen production facilities that have closed due to price volatility in EU natural gas markets.[118,119] Also, the European Union's Carbon Border Adjustment Mechanism (CBAM) will increase the price of carbon-intensive imported ammonia and therefore should foster the decarbonization of the domestic market.[120]

Exhibit 12: TCO of Low-Carbon Ammonia



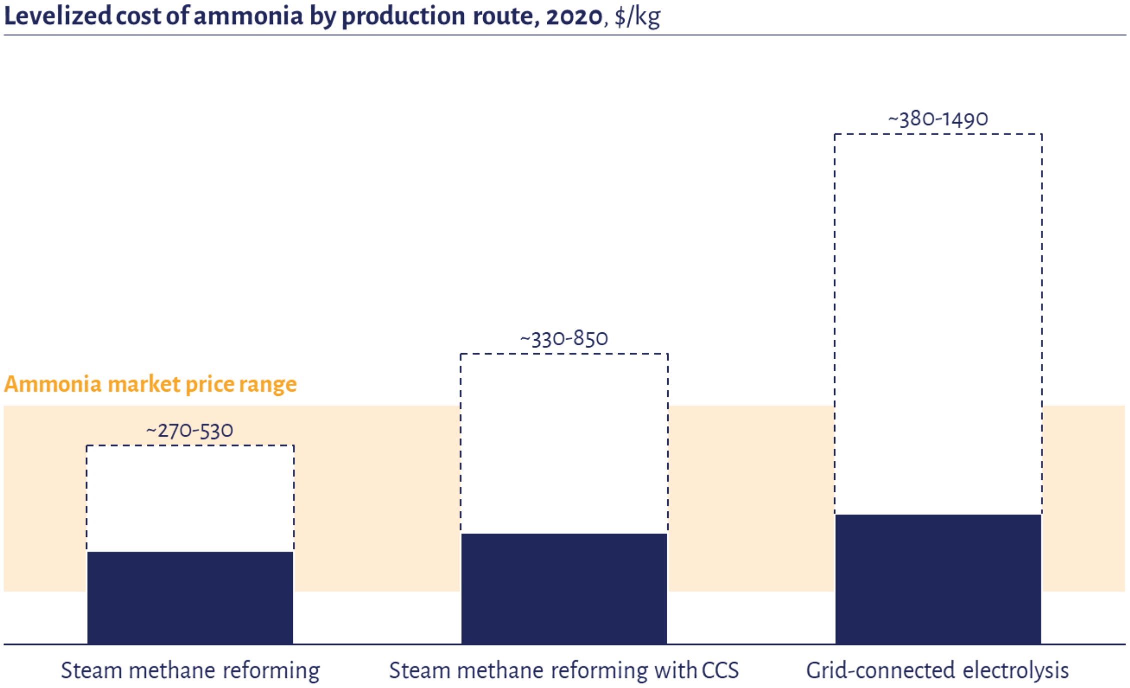
Source: Department of Energy.[121]

At the same time, there are a number of **inhibiting factors** that may slow the adoption of low-carbon hydrogen in the ammonia industry, including:

- **Financial expenditure.** Ammonia producers will need reliable access to capital to fund expensive retrofits and facility upgrades. Even relatively cheap carbon capture retrofits would incur a 10 to 25 percent increase in lifetime costs from increased capex and opex for the capture equipment, higher energy consumption, and CO_2 transport and storage [Exhibit 13]. CCUS retrofits could cost hundreds of millions of dollars or more for an average ammonia plant, with the sum reaching the billions for new-build electrolytic ammonia plants.[122]

- **High cost of electricity.** As with other applications of electrolytic hydrogen, local electricity costs determine the cost of electrolytic ammonia. While electrolyzer costs are expected to fall with scale, uncertainty remains about the pace of this development.
- **Lack of reliable feedstocks.** Ammonia producers without integrated on-site hydrogen generation will demand a stable supply of hydrogen. Investments in distribution and storage infrastructure will be necessary to encourage confidence, reduce uncertainty, and spur ammonia companies to decarbonize facilities that lack co-located hydrogen supply.

Exhibit 13: Levelized Cost of Ammonia (Conventional and Low-Carbon)



Source: IEA.[123]

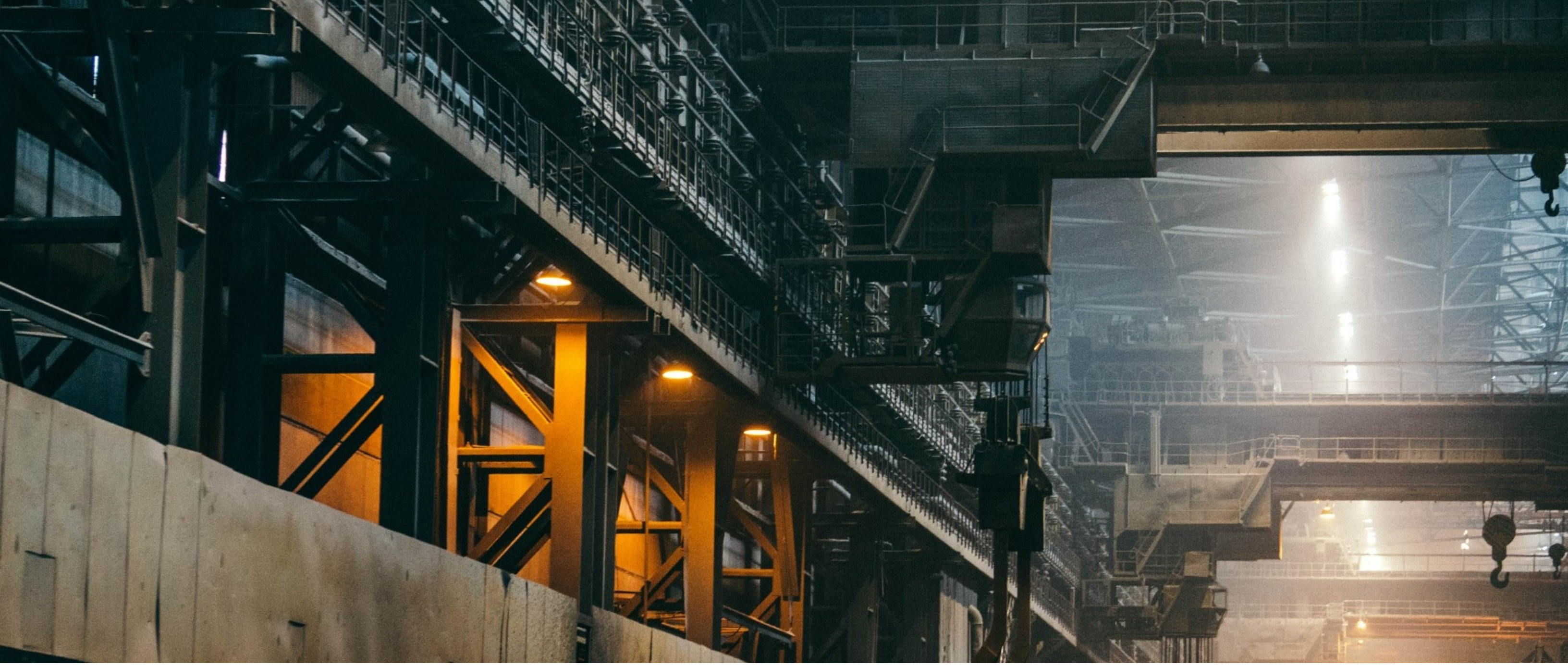
Potential of Low-Carbon Hydrogen in Ammonia Production

The ammonia industry has a high potential to adopt low-carbon hydrogen in large-scale commercial production. Our stakeholder survey suggests that ammonia is the most technically and commercially viable end use for low-carbon hydrogen in the United States and Europe through 2035 [Exhibit 7]. Even under its business-as-usual scenario, DOE predicts that low-carbon hydrogen demand will be at least "partially realized" in the US ammonia industry by 2030.[124]

As the ammonia market rapidly evolves, there are several **factors to monitor** that may influence the potential for market adoption of low-carbon hydrogen fuel sources:

- **Developing regulatory treatment.** In the United States, delays and uncertainties in the IRA rulemaking process may stymie investment in the short run. For those considering large capital investments, it will be crucial to gain reliable information on how to qualify for ITCs and PTCs for low-carbon hydrogen in order to recoup capital expenditure. In Europe, regulators have so far moved slowly to elaborate on strategic plans to decarbonize the industrial sector. While policy signals are helpful, regulatory clarity will be needed to accelerate full-scale commercialization of these technology pathways.

- **Ammonia market expansion.** If low-carbon ammonia evolves into a key fuel source and energy storage medium, the market dynamics will impact the costs and risks associated with decarbonization investments in the sector. For example, growth in international ammonia trade would drive production in exporting countries and require significant infrastructure investments in importing countries.



Steel

At a Glance:

- Over two-thirds of all existing emissions-intensive blast furnaces will require reinvestment in the next 10 years, presenting a significant opportunity for hydrogen-based steel production.
- Yet the uncertain availability of low-cost hydrogen and renewable energy could prevent this technology from gaining dominance. In regions where there is access to both, there is potential for hydrogen-based production to outcompete traditional steelmaking processes by 2035.

Market Overview

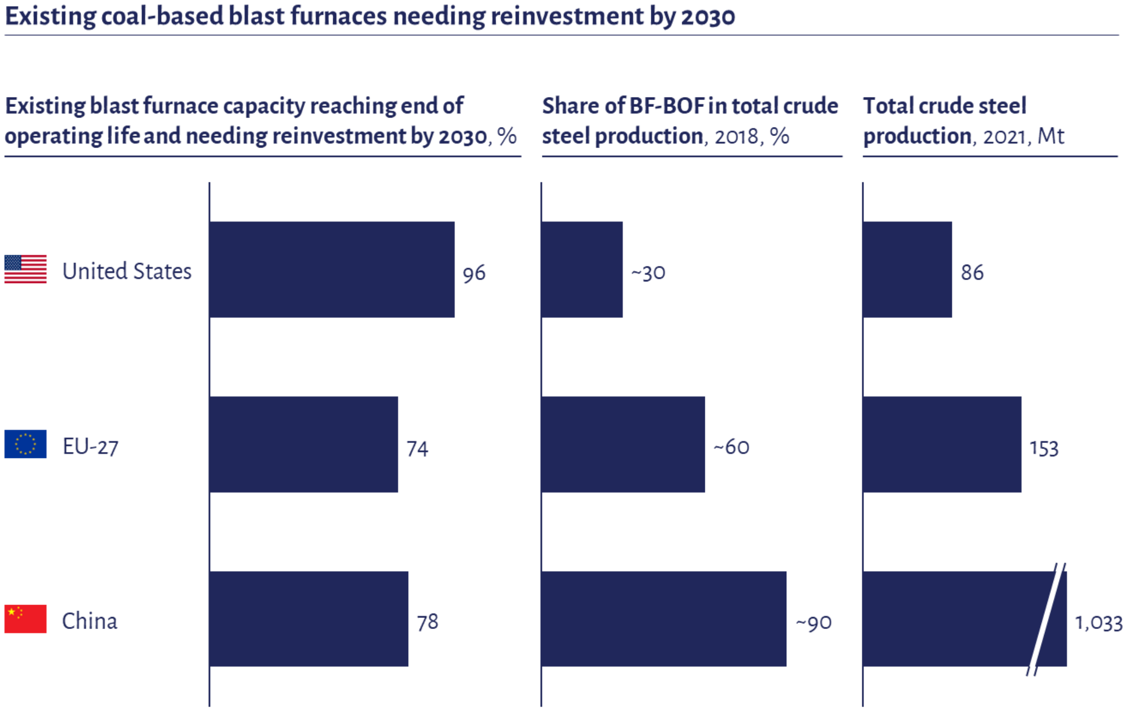
Steel is one of the most critical engineering and construction materials for the global economy, and plays an important role in the transportation, furniture, and packaging industries.[125] Steel is also a crucial component for the development of renewable energy infrastructure needed for the energy transition.[126] In 2022, the **global market for steel was valued at USD 1.27 trillion,[127] but this is expected to continue growing**, particularly in emerging markets, with projections suggesting a roughly 6 percent increase in demand by 2030.[128]

More than half of today's steel is produced in China. The largest steel producers worldwide include Baowu Group (China), Ansteel Group (China), and Shagang Group (China), ArcelorMittal (Luxembourg), and Nippon Steel (Japan), which **together produce nearly 75 percent of the global output**.[129] Any changes to the steelmaking process at scale is largely dependent on the investment decisions of these companies.

The steel industry is highly carbon-intensive, accounting for roughly 8 percent of global CO_2 emissions. **Producing one metric ton of steel emits nearly 1.8 metric tons of CO_2.**[130] Given the carbon intensity of the industry, steelmakers have faced pressure from regulators, customers, and investors to decarbonize in order to meet net-zero targets. Fourteen percent of steel companies' value is estimated to be at risk if they do not decrease their environmental impact.[131]

Given this backdrop of evolving expectations and risk, the next five years represent an **important investment window** for steelmaking. It is estimated that **74 percent of emissions-intensive steel plants in the EU and 96 percent in the United States** (together representing 1090 Mt of production) **will require reinvestment by 2030** [Exhibit 14]. Given the long lifetime of steel plants, decisions made during this period can either accelerate progress towards 2050 net-zero targets or cause us to fall behind.[132]

Exhibit 14: Existing Coal-based Blast Furnaces Needing Reinvestment by 2030



Source: Climate Bonds Initiative[133]

Technology Pathways

Fossil Fuels

In traditional steelmaking, fossil fuels serve two roles. First, fossil fuels – primarily coal, but also oil and natural gas – are used as a fuel source for high-temperature furnaces. The second application for fossil fuels is as a reducing agent to extract iron from ore so it can then be converted into steel.

The most common process for steelmaking uses an integrated blast furnace to produce iron paired with a basic oxygen furnace to convert iron into steel (BF-BOF). This process uses furnaces powered by fossil fuels and coal – specifically coke – as a reducing agent. **Roughly 69 percent of current steelmaking plants use this emissions-intensive BF-BOF process**.[134]

Another common approach for steelmaking is the use of an electric arc furnace (EAF), which offers two modes of production. First, EAFs can process steel scrap to produce recycled steel. Alternatively, they can produce steel using direct reduced iron (DRI) – the output of direct reduction, which uses natural gas or coal to remove oxygen from iron ore as an alternative to the BF approach.[135] Since EAFs are powered using electricity, they are considered to be slightly more environmentally friendly. Estimates suggest that EAFs emit roughly 0.7 tons of CO_2 per ton of crude steel, compared to 2.3 tons of CO_2 per ton of crude steel for BOFs.[136] However, EAF production still has further potential for carbon abatement through the use of renewable electricity for high-heat processes and the decarbonization of the DRI process.[137]

The strongest tailwinds for traditional steelmaking are the **low fuel costs and the long useful life of steel facilities** (roughly 40 years).[138] However, **growing volatility in oil and natural gas markets** risk raising the costs associated with this steelmaking method over the long-run. Additionally, investors locking in fixed investments in carbon-intensive production pathways should consider exposure to taxation and regulation in the future and the risk of stranded assets.

Renewable Electric Arc Furnace

As noted above, one potential solution to decarbonize steel production is to use renewable energy to power EAFs. This approach has the potential to produce zero-carbon steel because the furnaces are powered without the use of fossil fuels.

The **primary challenges with the renewable EAF** approach are the availability of low-cost inputs and limited market share:

- **Input reliability**. Access to consistent, low-cost renewable electricity is required to make this approach cost competitive.[139] Additionally, the limited availability of quality scrap steel creates a significant bottleneck for the EAF approach.[140]
- **Market share**. EAF only represents 31 percent of global steel production, so massive capital investments are needed to build out additional EAF infrastructure and increase market share.[141] Further, scrap-based production accounts for only 20 percent of current EAF production, so further decarbonization of the DRI process is still needed for the industry to reach net zero.[142]

Carbon Capture, Utilization, and Storage

Another low-carbon alternative for steel production is the use of CCUS. This approach allows steel producers using the BF-BOF and traditional DRI processes, but the resulting CO_2 is captured and stored underground. In theory, sequestration could reduce the CO_2 emissions from the coke feedstock by nearly 85 percent.[143] Additionally, retrofitting with CCUS requires less upfront capital investment as it does not meaningfully change the way the furnaces themselves operate.[144]

However, CCUS also has considerable disadvantages, including the technological maturity of CCUS and a lack of policy support:

- **Technological maturity**. The most significant drawback of this option is that CCUS projects are still in the pilot stage at steel plants.[145] More research and investment is needed to bring this solution to market at scale.[146]
- **Abatement potential.** Even if commercial viability is demonstrated, research suggests that the theoretical carbon abatement estimates are overstated. As much as 90 percent of the stated emissions reduction targets for CCUS projects have been unachievable in practice. Further, to date, a majority of captured carbon has been used in enhanced oil recovery, whereby carbon is reinjected into oil fields to extract more fossil fuels – only serving to increase global emissions.[147]
- **Safety**. There are also concerns related to the long-term storage and disposal of the sequestered carbon. If not properly contained in underground reservoirs, the sequestered carbon could leak back into the atmosphere or into water supplies.[148]
- **Policy**. Given the significant safety and efficacy concerns, there is mixed policy support for CCUS solutions overall, particularly in Europe. Additionally, many argue that CCUS is a greenwashing tool that enables continued reliance on fossil fuels. As such, it is unclear if CCUS will receive the same regulatory support that other low-carbon solutions – like hydrogen – have received to make it a cost-competitive option.

Hydrogen

Low-carbon hydrogen can be used to replace fossil fuels in the steelmaking process. In the near-term, hydrogen can be blended into existing DRI units that already use natural gas to reduce the emissions intensity of those operations. It can also be blended into existing blast furnaces at a maximum rate of 30 percent.[149] Both of these options are technically viable now and require minimal modifications to existing steel plants, which can serve as a catalyst for uptake of hydrogen in the steel industry.

There is also testing underway for full hydrogen-based DRI production, referred to as H_2-DRI. The hydrogen-based DRI can then be paired with a renewables-powered EAF to produce low- or zero-carbon steel,[150] or it can be compressed into hot-briquetted iron and used in BOFs to achieve partial decarbonization of the high-emitting production process.[151] It is expected that this technology will mature to a commercial scale by 2030.[152] The combination of these approaches provides a **strong pathway for the production of steel with reduced or even zero emissions**, depending on the carbon intensity of the EAF and BOF processes and the hydrogen itself.

The **largest barriers** to the H_2-DRI approach are the upfront capital and input costs:

- **Capital costs**. Building new DRI plants will require significant upfront capital costs and higher operating expenses, which could increase unit production costs by as much as 30 percent.[153]
- **Cost of hydrogen.** Another challenge is the availability of low-cost hydrogen, as discussed in greater detail in the value chain section of this report. To compete with traditional steelmaking

and natural gas-based DRI (paired with CCUS), the IEA estimates that low-carbon electricity prices need to range from USD 5-25/MWh, which translates into a low-carbon hydrogen cost of USD 0.7-2.0/kg H_2.[154] These prices may only be realistic in regions where there is substantial access to low-cost renewables, like in parts of Europe or the United States. Yet, if these conditions are met, reports suggest that H_2-DRI steel production could become a cost competitive option between 2030 and 2040.[155]

- **Supply chain bottlenecks**. The H_2-DRI approach also requires a higher-quality iron ore for processing. Reserves of high-grade iron ore are available in the United States, Europe and the Middle East, but there is a limited amount currently being produced in these regions. Alternatively, converting lower-grade iron ore requires additional refining, leading to increased energy inputs and higher embedded costs.[156] This could create a bottleneck for the adoption of hydrogen-based production and cause ripple effects in the mining industry.[157]

Potential of Low-Carbon Hydrogen in Steel Production

Given the long useful life of steel plants, the upcoming reinvestment decisions in steel production capacity will dictate future profitability for steelmakers and determine progress against our 2050 net-zero ambitions. Balancing both of these objectives, **H_2-DRI steel production in conjunction with renewable EAF represents a strong pathway to decarbonizing the steel industry.**

This optimism was reflected by the respondents of our original survey [Exhibit 7] – over 60 percent of experts surveyed said that low-carbon hydrogen would “somewhat” or “extremely likely” be commercially viable for use in the steel industry within the 2035 timeframe. This was the second highest ranking end use behind ammonia.

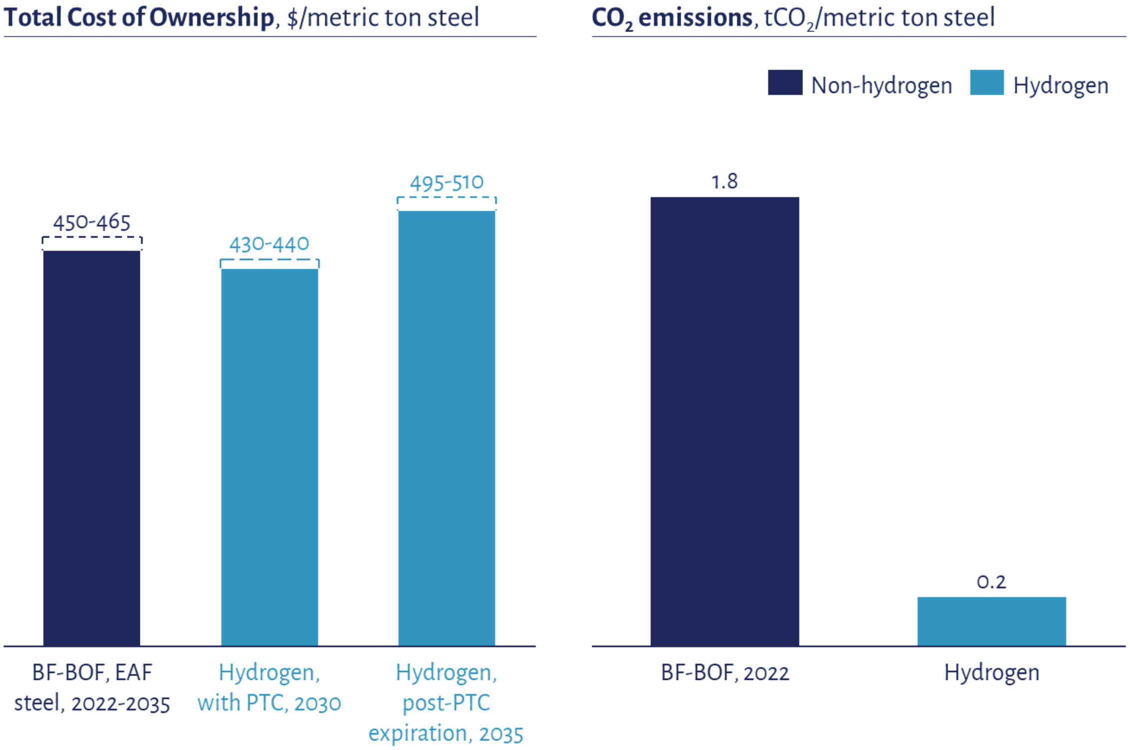
Looking ahead, the following factors will be critical to determining if, and where, H_2-DRI steel production will grow in market share:

- **Input reliability.** The availability of low-cost low-carbon hydrogen and access to renewable energy sources will be critical factors in determining whether H_2-DRI becomes a cost competitive, saleable option within this important investment window.

- **Evolution of policy support**. Recent regulations in the United States and Europe provide hope that hydrogen-based steel production could become cost competitive. In the United States, the IRA’s PTC could allow hydrogen-based steel production to undercut traditional steelmaking approaches while achieving significant carbon abatement [Exhibit 15].[158] In addition, the European Union plans to roll out CBAM in 2026, which could boost demand for United States low-carbon steel production.[159]

- **Market concentration**. While hydrogen-based steel production could become cost competitive in the United States and Europe within the 2035 timeframe, limitations arise due to the United States’ and Europe’s relatively small market share in steel production. China is the overwhelming global leader in steel production, so any investment decisions it makes will likely have the greatest impact on decarbonization of the sector.[160]

Exhibit 15: TCO and CO_2 Emissions of Steel



Source: Department of Energy[161] *McKinsey & Company*[162] *(The non-hydrogen TCO range is based on BF-BOF and EAF steel. The hydrogen TCO is based on new build H2-DRI.)*

Cement

At a Glance:

- Although the relevant technologies are still maturing, hydrogen could play a role in reducing cement's carbon intensity by serving as an alternative fuel source for high-heat processes.
- Since the conversion of limestone into cement releases significant process emissions, no fuel switching method – including to hydrogen – can fully decarbonize cement production. At most, low-carbon hydrogen would serve as one of several methods, including carbon capture and alternative materials, to decarbonize the cement industry.

Market Overview

Portland cement[163] is a ubiquitous construction material and a foundational component of modern industrial economies. It is a primary component of concrete, mortar, stucco, and grout, and is therefore a cornerstone of the construction industry.

Cement production entails heating limestone ($CaCO_3$) at a high temperature to produce clinker, the principal binder in Portland cement products. This chemical reaction releases significant volumes of CO_2 process emissions.[164] In addition, heating limestone, clay, and other raw materials in a kiln – known as pyroprocessing – requires substantial fuel inputs. The combustion of these fuels – typically coal or natural gas – emits additional CO_2. In short, **cement production emits CO_2 through both direct process emissions and indirect (i.e., fuel) emissions.** While different countries depend on different energy mixes for pyroprocessing, fuel emissions account for only around 35 to 40 percent of total cement industry CO_2 emissions, with the remainder due to the calcination chemical process.[165,166]

The United States and Europe account for only a small fraction of global cement production, which totaled 4.1 billion metric tons in 2022. In the same year, the United States produced 95 million metric tons of cement, nearly half of which was made in Texas, Missouri, California, and Florida.[167] Meanwhile, the European cement industry produced 171.5 million metric tons in 2020.[168] Large cement producers in the United States and Europe include Cemex, Holcim, HeidelbergCement, and Lafarge.

The United States imports around 15 to 20 percent of the cement it consumes, mostly from Canada, Turkey, and Greece. Due in part to rising carbon prices, Europe has become more dependent on cement imports, which rose 160 percent between 2016 and 2020.[169] The European Union's CBAM, which will be fully implemented by 2026, intends to levelize the costs faced by EU producers and foreign cement exporters to reduce this import dependence.[170]

Cement production accounts for one-quarter of total global industrial emissions and emits the most CO_2 per revenue dollar of any industrial sub-sector.[171] Given the scale of these emissions, innovators are developing a variety of different decarbonization methods. Some of these technologies aim to reduce chemical process emissions, while others mitigate fuel combustion emissions. Given the range of options for decarbonization, only about half of our survey respondents were optimistic about low-carbon hydrogen's role in the cement industry, reflecting concerns about its market viability and competitiveness [Exhibit 7].

Technology Pathways

Fossil Fuels

In the United States, cement production primarily relies on natural gas and coal for fuel, with the gravimetric energy mix fluctuating significantly from year to year. In 2015, coal made up 46 percent of cement's final energy consumption and natural gas accounted for 11 percent. However, in the following year, the proportions nearly flipped, with natural gas accounting for 46 percent and coal only 15 percent.[172] In 2018, coal returned to accounting for 44 percent of fuel sources.[173] In addition to improving the energy efficiency of the various steps of the production process,[174] the cement industry is also pursuing the following options.

Biomass and Alternative Fuels

Some cement kilns can be powered by biomass and alternative fuels, which can refer to a variety of industrial and municipal waste.[175]

One **advantage** of biomass and alternative fuels is their **established market role.** In Europe, the domestic cement industry has accelerated adoption of alternative fuels, with the source making up 46 percent of the energy mix in 2017, including 16 percent from biomass.[176] Cembureau, the European cement industry association, has set a goal of consuming 30 percent biomass fuel by 2030.[177]

At the same time, the **drawbacks** of biomass and alternative fuels include **technological barriers and negative externalities.** Current technology only allows for these fuels to be added to existing kilns up to a certain blend percentage. Compared to coal or natural gas, these fuels can also have a higher water content and lower heating value, so technological development would be necessary to deploy alternative fuels at scale. Also, there are significant public health and safety concerns associated with combusting some alternative fuels, such as waste plastics, that must be considered due to their potential impact on human and natural environments.[178] Finally, without adequate sourcing requirements and monitoring, increased use of biofuels can lead to deforestation and other environmental harms.[179]

Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are typically added to cement or concrete to reduce cost or adjust physical properties of the product. SCMs can be made from a range of different substances, but are often by-products of industrial processes, such as coal combustion, steelmaking, and other metallurgy.[180]

The principal **advantage** of SCMs is its **emissions reduction potential.** Since adding SCMs effectively reduces the proportion of clinker needed to make cement, they can mitigate the carbon intensity of the resulting cement and concrete.

However, the **risks** associated with SCMs relate to **supply and performance concerns.** The cost and market availability of SCMs can vary regionally based on proximity to industrial hubs.[181] Even natural SCMs, such as ground limestone and pozzolans,[182] still trigger concerns about the durability of the resulting cement, which is a priority issue for a risk-averse industry and its regulators. Some industry players are even exploring replacing Portland cement altogether,[183] but the technical maturity of these alternative binding materials remains relatively low, and there is high uncertainty about performance under various conditions.

Carbon Capture, Utilization, and Storage

Many industry[184] and third-party analysts[185] see CCUS as a promising method of cement decarbonization. There are several CCUS options for cement production that can sharply reduce both process and fuel-based emissions.[186]

The key **advantage** of CCUS is its **high abatement potential** [Exhibit 16]**.** Fuel switching and material innovations can each only reduce one source of the industry's overall emissions; CCUS can alleviate both.

In addition to the safety, efficacy and policy concerns mentioned in the steel section, the **disadvantages** of CCUS for cement include **high cost and additional energy demand.** CCUS technologies are still maturing and demand high capital and operational expenditures. Depending on the location and the type of CCUS method employed, production costs could increase by 65 to 95 percent compared to an unabated baseline.[187] The need for additional energy inputs to power the capture units could also threaten the net abatement potential of the equipment, depending on the energy source. Robust policy support would be needed to incentivize CCUS for cement applications and bring down its relative cost.[188]

Hydrogen

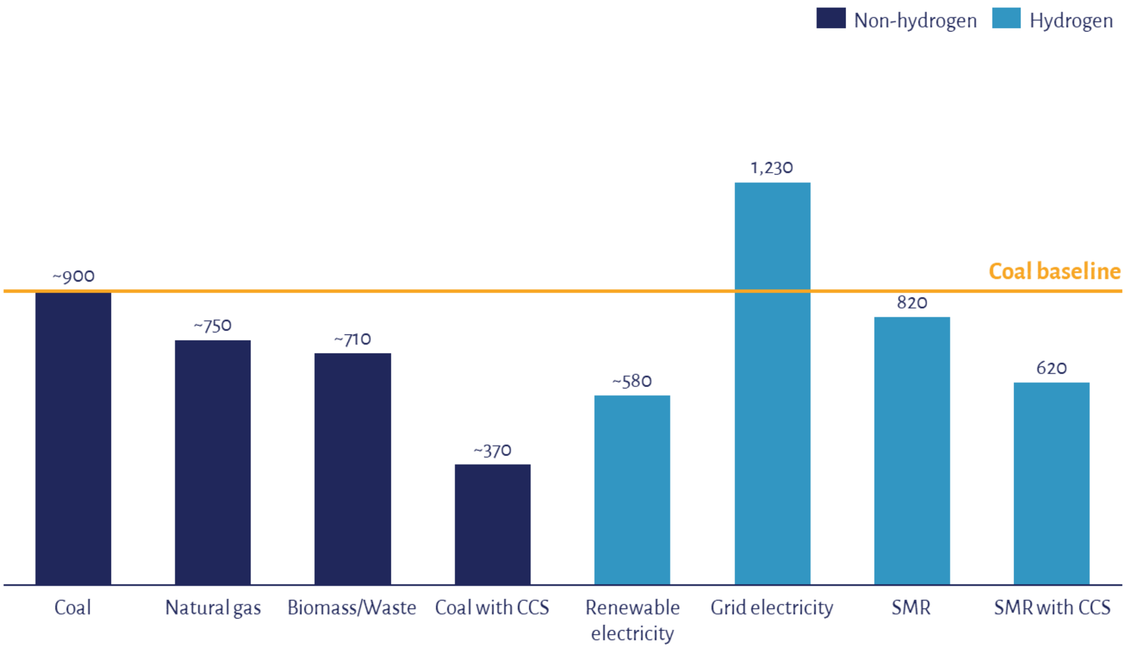
Low-carbon hydrogen can substitute for fossil fuels in cement kilns to lower CO_2 emissions.

One key **advantage** of hydrogen is its **blendability.** Cement plants can add low-percentage hydrogen fuel blends without substantial changes to the kiln design.[189] Many cement companies have already taken steps to integrate hydrogen into their fuel supply. In 2021, a UK subsidiary of HeidelbergCement ran a successful operating trial powered entirely by an alternative fuel mix that included 39 percent hydrogen.[190] After running successful trials at its Alicante plant in Spain in 2019,[191] Cemex retrofitted all its European plants to take hydrogen fuel in 2021. However, it is unclear how much hydrogen Cemex plants currently use, even though they are equipped to accept it.[192]

The principal **challenges** for hydrogen include its **technical profile and non-carbon environmental impacts**. Pure hydrogen flame has a lower heat transfer rate than natural gas; this heat profile demands updating the kiln design.[193] Also, hydrogen gas combustion can lead to acidification from nitrous and sulfur oxides, creating safety and environmental concerns.

Exhibit 16: CO_2 Intensity of Cement

Carbon intensity of cement based on fuel source, kgCO_2e / MT clinker



Source: Sandalow et al.[194]

Potential of Low-Carbon Hydrogen in Cement Production

Hydrogen is one of many options to limit the CO_2 emissions of the cement industry, but it cannot achieve full decarbonization alone as it does not address the chemical process of clinker production. Many cement producers therefore have instead focused on improving energy efficiency and incorporating alternative fuels to pursue emissions reduction goals, especially in Europe.[195] Low-blend hydrogen can reduce emissions with limited capital expenditure and in regions without CCUS options, but **technological and environmental challenges remain that limit greater penetration of hydrogen as a fuel source in cement production.**

Factors to consider that could impact the role of hydrogen in cement production include:

- **Technological development.** The success or failure of current hydrogen-fueled cement pilots and demonstrations will determine whether it becomes a trusted technology in the sector. Innovations to overcome technical limitations could also impact the market uptake of hydrogen.
- **Evolution of policy support.** The United States and Europe may facilitate cement decarbonization through different policy frameworks; the cement industry will need to respond accordingly. For example, the European Union's CBAM and its regulatory treatment of CCUS may influence how cement companies select among a range of abatement options.

International markets. Since most cement production occurs outside of the United States and Europe, the decarbonization strategies of producers in China, India, and other developing economies could affect costs and influence trade-offs for producers in the United States and Europe.

Transportation

Low-carbon hydrogen is one of the pathways to decarbonize the transportation industry, a fundamental component of the economy. In the United States, the overall demand for transportation accounted for 8.4 percent of GDP in 2021 and for USD 235 billion in private investments.[196] At the same time, transportation is a significant contributor to GHG emissions. Transportation makes up nearly 25 percent of GHG emissions in Europe[197] and one-third in the United States.[198]

The focus of this section will be on commercial transport, maritime shipping, and aviation. These sectors were identified because of their high carbon abatement potential and the existing technologies that support potential use of low-carbon hydrogen in fueling transportation on land, over sea, and in air.

Commercial Transport

At a Glance:

- Diesel trucks are leading the market given their affordability, but their emission profile will lead the market to alternative powertrains.
- Hydrogen fuel cell electric vehicles (FCEVs) can replace diesel trucks in the long-haul segment if their technology proves cost-competitive and infrastructure is built.
- Battery electric vehicles (BEVs) are unlikely to be suitable for long-haul trucking given their cost, battery size and charging time, but may dominate the urban and regional transport market.

Market Overview

Global commercial vehicles sales amounted to about 14.2 million units in 2021.[199] North America is by far the largest market, accounting for more than half of the world's demand, while demand in Europe accounts for about 10 percent of global demand.[200] The largest commercial vehicle producers by revenue are Daimler, Volkswagen and Volvo, with USD 45 billion, and USD 34 billion and USD 22 billion in revenue, respectively.[201] The demand for heavy commercial vehicles is forecasted to grow by 50 percent in the next three decades.[202] Given the **industry's current heavy dependence on fossil fuels**, a major challenge will be to decouple this demand growth from growth in GHG emissions. This challenge is even **more important for medium and heavy-duty vehicles (MDVs and HDVs)**: they make up about a quarter of transportation emissions,[203] but comprise less than 5 percent of the total fleet.[204] Reaching the Paris Agreement goals will require a drastic shift towards alternative powertrain technologies in transportation,[205] as most new trucks sold will need to be zero-emissions vehicles by 2040.[206]

Technology Pathways

Decarbonizing the commercial transport industry will require moving away from the incumbent technology, the internal combustion engine (ICE) vehicle. ICE commercial vehicles currently use around 17 million barrels of oil per day globally (almost 18 percent of total global oil demand).[207] **Two major technologies have the potential to replace the incumbent ICE vehicle**: BEVs and FCEVs.[208] Both technologies still currently face barriers to adoption, including cost, use case, and infrastructure considerations. While ICE vehicles have the largest market share today, this market share may be challenged in the future, notably around policy and fuel price uncertainty. In this section, we highlight the most important factors impacting the technological evolution of the commercial transport industry for MDVs and HDVs. In Europe, MDVs are considered vehicles with a gross weight of 3.5-16 tons, whereas in the United States, they have a gross weight between 6.5-15 tons. HDVs exceed 16 tons in Europe, and 15 tons in the United States.[209,210] More specifically, we focus on **commercial vehicles for regional and long-haul use** because these are considered to have the greatest potential for hydrogen.[211]

Diesel Internal Combustion Engines

ICE vehicles are the most common type of powertrain in the HDV market. In Europe, they made up 99.5 percent of the new MDV and HDV sales in 2021.[212] Of these, 96 percent were diesel vehicles.[213] Diesel ICE vehicles are preferred due to their tank-to-wheel energy efficiency and diesel's energy density characteristics compared to the current alternative on the market, gasoline trucks. Specifically, diesel engines have higher compression values, which makes them more efficient than other engines, and it is 10 to 15 percent more energy dense than gasoline fuel, which is used more frequently in personal vehicles.[214]

Diesel ICE vehicles have numerous advantages, mostly related to cost and reliability, which make them the current market leader.

- **Upfront cost and TCO.** ICE vehicles have a significantly lower upfront cost than current technology alternatives. ICE vehicle trucks may cost around USD 110,000,[215] while BEVs may cost between USD 300,000[216] and USD 500,000, and FCEV around USD 250,000.[217] This results in a lower TCO for ICE, although ICE vehicles are forecasted to lose their TCO advantage by 2030 for long-haul vehicles and even sooner, by 2023, for vehicles with ranges of 100 to 250 miles.[218]

- **Maintenance and brand familiarity.** Diesel ICE vehicles benefit from a lock-in effect with transport companies. Companies prefer consistency in truck manufacturers to ensure that maintenance staff can quickly resolve any issues, as truck outages are expensive, transport industry margins are thin, and competition is fierce. Given this dependence on reliability, truck companies are reluctant to change manufacturers, let alone powertrain technologies.[219]

- **Range.** The range depends on the truck, but varies from 1,000 to 2,000 miles per tank,[220] which exceeds the average distance traveled of 650 miles per day for a long-haul truck today.[221]

- **Fueling speed and infrastructure.** ICE vehicles can refuel 300 gallons of fuel in 10 to 15 minutes,[222] minimizing the limitations on the truck's operation. In addition, fueling infrastructure is highly prevalent throughout Europe and the United States.[223]

Diesel ICE vehicles also have important disadvantages which will likely lead to their decline in the years to come, notably around policy and environmental concerns.

- **Emissions and pollutants.** Diesel engines release CO_x, NO_x, particulate matter, SO_x, and organic compounds. CO_2 emissions depend on factors such as the load and vehicle type, but range between 29 and 119 g/km-ton. Trucks also emit 7 g/mile of NO_X, which exceeds gasoline car NO_X emissions by a factor of 10.[224]

- **Policy.** As a result of emissions, ICE vehicles have been impacted by unfavorable policy. The European Parliament approved emission reduction targets of 65 percent by 2035 and 90 percent by 2040 for HDVs.[225] In California, the Advanced Clean Trucks rule requires half of HDVs sold to be fully electric by 2035, and many states are expected to follow California's lead in putting stricter regulations in place.[226] California will also ban new diesel truck sales by 2036 and to require conversion of existing trucks to zero emissions by 2042.[227] Federally, the Biden Administration is proposing rules that a quarter of HDVs sold will be all-electric by 2032.[228]

- **Fuel price uncertainty.** Even though ICE vehicles benefit from a lower TCO, their TCO is extremely sensitive to fluctuations in fuel prices, given that fuel prices account for 49 percent of the TCO of a heavy-duty truck (compared to 33 percent for BEVs)[229]. For instance, when the retail price of diesel in the United States went up from USD 2.64/gallon in January 2021 to peak at USD 5.81/gallon in June 2022 (increase of 120 percent),[230] the TCO of driving a diesel truck went up by 60 percent.

Battery Electric Vehicles

In the last few years, BEVs have seen a considerable increase in sales in the passenger vehicle market, accounting for 17 percent of sales in Europe and 4.5 percent in the United States in 2021.[231] This market uptake has supported cost reductions and technology improvements in battery production, which may spill over to commercial vehicles.[232] BEVs only made up 0.2 percent of global commercial vehicle sales in 2021,[233] but the number of available BEV models is growing exponentially, albeit mostly in the urban and regional range segment.[234]

BEVs have advantages that may support its market uptake in the transition towards zero-emission vehicles.

- **TCO parity within reach.** BEVs may reach cost parity with ICE vehicles between 2025 and 2030, depending on the distance and powertrain.[235,236] Maintenance for BEVs is 20 to 30 percent cheaper than for ICE vehicles due to the simplicity of the powertrain. In addition, due to superior well-to-wheel efficiency (64 to 86 percent)[237], the cost-per-mile is also lower than ICE.[238] Finally, the higher upfront cost of the vehicle and the battery pack are forecasted to decline by 60 to 70 percent in the 2020s (from USD 250/kWh to USD 80-100/kWh)[239], even though the cost of battery packs rose for the first time in 2022 due to lithium price spikes.[240]

- **Zero (tailpipe) emissions and reduced pollution.** BEVs have zero pipeline emissions,[241] meaning that there are no CO_2 emissions from the use of BEVs on the road and local air pollution is reduced.[242] However, the total emissions per vehicle lifetime depend on a range of factors, such as the source of electricity on the grid when charging the vehicle, and the minerals used to produce the battery pack.[243] BEVs bought today would result in a 63 percent reduction of lifecycle GHG emissions compared to ICE vehicles, based on the projected 2021-2040 grid mix in Europe. If BEVs are powered by all renewable energy, the reduction potential increases to 92 percent.[244]

- **Availability of technology**. BEV trucks can benefit from improvements in battery technology that have occurred in the last decade.[245] While the current number of BEV truck models is low (less than 10), it is expected that a broad range will become available in the next few years.[246]

- **Policy**. In addition to rules around new truck sales, BEVs are benefiting from subsidies supporting its further uptake as well. The IRA includes a battery PTC of USD 45/kWh,[247] or between 20 and 30 percent of today's battery cost. In addition, the IRA features a 30 percent tax credit (up to USD 40,000) for commercial vehicles.[248] European companies can benefit under the same Commercial Clean Vehicle Credit scheme,[249] and most European countries still offer a range of EV subsidies.[250]

However, **BEV trucks also have disadvantages** that may prevent their uptake, mostly related to infrastructure requirements and operational characteristics:

- **Limited range.** The range of a BEV truck increases with the size of its battery pack. However, costs also increase proportionally to the battery pack size.[251] For instance, adding 100km of range could cost about USD 45,000 in 2023 and USD 12,000 to USD 15,000 by 2030.[252] As such, most BEV truck models have been designed with a range of less than 450 km,[253] even though Tesla claims its semi-truck will have an 800-km range.[254]

- **Charging infrastructure investment requirements.** Transport companies may hesitate to adopt BEVs if insufficient charging infrastructure is available. Significant upgrades are required, both in terms of quantity and power of the charging infrastructure. Charging infrastructure with power exceeding 750 kW would reduce charging times, but this technology is still under development and could cost north of EUR 200,000 per charging point in Europe.[255] Adding this charging infrastructure would also require significant local grid upgrades, requiring approval processes which have recently taken up to five years.[256]

- **Refueling speed.** Depending on the use case, vehicle type and battery size, BEVs may require between 3 and 20 hours to fully recharge. Slow refuels combined with range limitations may limit the potential of BEVs for long-distance trips.[257]

- **Payload restrictions.** Given the weight of the battery pack, BEV trucks may have payload restrictions, meaning that trucks can load less cargo per trip.[258] If BEVs with an 800-km range existed today, their battery pack would weigh about 8 tons, which is substantial given the average payload for long haul transport is 25 tons.[259] Even considering extensive improvements in energy consumption and battery density, the battery pack would still weigh 4.5 tons by 2030.[260]

Fuel Cell Electric Vehicles

FCEVs and BEVs both run on electric motors. However, FCEVs rely on hydrogen fuel cells instead of batteries to power this motor. Fuel cells convert chemical energy stored in hydrogen into electricity. Fuel cells only emit water and heat, and given there is no combustion to generate electricity, FCEVs produce no tailpipe pollution.[261]

FCEV have a range of benefits that could make them cost-competitive and attractive for long-haul trips in the next decade:

- **Lower TCO by 2035 for certain use cases.** FCEVs can achieve TCO superiority versus BEVs and ICEs by 2035, especially in the use of trucks over longer distances.[262] However, two factors make this forecast uncertain: costs of low-carbon hydrogen need to decrease substantially (see section on Upstream), and costs of fuel cells need to decrease as well.[263] Fuel cell stack costs (currently around USD 250/kW) may need to decrease between 45 and 60 percent for FCEVs to be financially competitive.[264] This fuel cell cost improvement is within reach, as the DOE's cost curves demonstrate that for every doubling in production, stack costs could decline by 22 percent.[265] However, given that fuel cells have limited and uncertain mass-market applications beyond the transportation sector, most of the volume uptake would need to come from MDVs and HDVs.[266]

- **Low emissions.** FCEVs can yield considerable lifecycle GHG emissions savings compared to ICE vehicles, depending on the source of hydrogen. Renewable-based hydrogen would result in 89 percent emissions savings compared to ICE, while conventional hydrogen would merely reduce emissions by 15 percent.[267]

- **Lighter than batteries.** Hydrogen has higher gravimetric energy density than batteries, making FCEVs easier to design for long distances.[268] Given its high gravimetric energy, the impact on the payload of a truck is much lower for FCEVs than BEVs (10 to 15 percent added to the average weight of a FCEV compared to 30 percent for BEVs),[269] which improves its economics. In fact, 100 kg of hydrogen may fuel a FCEV for a range of 1,200km.[270] That said, hydrogen has a low volumetric density, so the size of the hydrogen tank may limit the volume of cargo transported,[271] but the overall impact on truck economics is smaller than the payload restrictions for BEVs.[272]

- **Faster refueling**. FCEVs can refuel in similar timeframes to ICE vehicles, minimizing the limitations on the truck's operations. Refueling for 10 to 15 minutes could give enough fuel to drive for 200 to 300 miles.[273]

- **Policy.** FCEVs benefit from the same carrots and sticks that BEVs benefit from in Europe and the United States. In addition, the IRA has significant policy support for hydrogen of up to USD 3/kg (see Policy section), which would result in considerable support for FCEVs, and could accelerate TCO parity with ICE vehicles by 2 to 3 years.[274] Furthermore, in March 2023, EU states provisionally agreed to support the deployment of hydrogen refueling infrastructure, building stations in every major city and every 200 km along major routes by 2031.[275,276]

FCEVs also have a range of drawbacks given their early stage of development in the trucking industry, which may hamper adoption in the years to come:

- **Unproven technology.** As of this report's publication, there are fewer than five models available and fewer than 10 models are expected to be on the market by 2024.[277] The limited range of options are one signpost that the technology is not at a mature stage of development.[278] In a risk-averse transport industry, the lack of trust in new powertrains may hamper FCEV adoption. Indeed, in one survey, 23 percent of respondents indicated that reliability and quality issues are pain points for introducing FCEVs.[279]

- **High upfront costs.** FCEVs can cost up to USD 250,000,[280,281] almost double that of an ICE vehicle. This creates reluctance for uptake and will require new financing models to support adoption.[282] That said, transport companies are accustomed to accessing debt to finance their operations.[283]

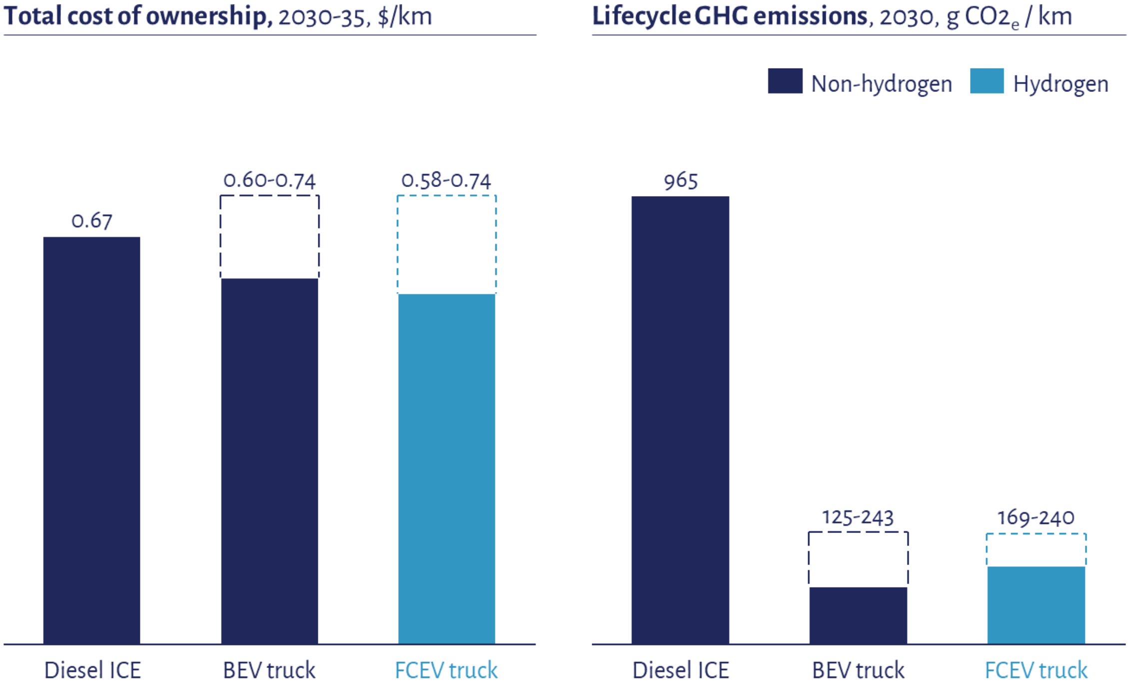
- **Largely nonexistent infrastructure.** There are very limited FCEV refueling stations, apart from in California and a handful of countries in Europe. Substantial infrastructure investment will need to precede commitments of trucking companies to buy FCEVs. Given that refueling stations tend to be expensive (USD 1 to USD 1.5 million), and a minimum of 55 percent utilization may be needed to reach break-even,[284] policy support may be required. Due to its economics, hydrogen refueling stations will likely be more concentrated in high-traffic areas such as highways. As such, one station would serve around 200 trucks, and reduce refueling costs to USD 0.03/kWh.[285]

Potential of Low-Carbon Hydrogen in Commercial Transport

In the commercial transportation industry's transition away from fossil fuels, BEV trucks have gotten a head start, leaning on their progress in the passenger vehicle market and the resulting cost improvements in battery packs. As such, cost parity with ICE vehicles is well within reach [Exhibit 17]. While **BEVs** are likely to be the most dominant technology for regional transport, **their battery pack may prohibit them from reaching scale in the long-haul vehicle market.** Long-haul trucking requires ranges north of 600 km, and battery packs supporting those ranges are too expensive and too heavy to be economical – even when considering technology improvements by 2030. In addition, much more investment in charging infrastructure is required to support the uptake of truck BEVs.

On the other hand, **FCEVs allow for further range, faster recharging, and less weight.** These conditions may make FCEVs an optimal fit for long-haul trucking, but given the early stage of the FCEV, **further fuel cell optimization is required to convince prospective customers.** However, if these technological improvements materialize, FCEVs are forecasted to reach cost parity as well [Exhibit 17], and may capture up to 15 percent of market share in the long-haul segment by 2035,[286] while decarbonizing the trucking industry. In addition, like BEVs, FCEVs require a massive rollout of refueling infrastructure, likely with substantial policy support.

Exhibit 17: TCO and Lifecycle GHG Emissions of Trucks



Source: Authors, based on Department of Energy,[287] Goldman Sachs,[288] McKinsey & Company,[289] ICCT[290]

A few elements to monitor when gauging the potential of FCEVs and BEVs in the MDV and HDV market include:

- **Cost improvement of batteries** (including density and cost per kWh) **and fuel cells** (cost per kW)
- **Evolution of policy support in the United States and Europe**. Support for FCEVs and BEVs in on both regions is substantial, but it will be crucial to see how these result in material actions supporting the further adoption of both technologies (e.g., in refueling infrastructure)
- **Model development.** Given the limited scale of models currently available in the market, vehicle manufacturers will need to place their bets in future model development. While some have committed to BEVs only, others are focusing more on FCEVs, and yet others are hedging between both alternatives.

Maritime Transport

At a Glance:

- ICEs powered by heavy fuel oil (HFO) still dominate the maritime industry, but increasing regulatory pressure is facilitating the shift towards other fuel alternatives.
- LNG-fueled vessels provide a short-term decarbonization solution given high market readiness and zero sulfur emissions but fall short of achieving long-term targets.
- Ammonia is a promising hydrogen-based solution due to its mature production and transportation infrastructure, but its short-term adoption is hindered by high investment cost of the bunkering infrastructure and vessel engines, as well as other technological limitations.

Market Overview

The maritime industry plays a significant role in international trade, delivering over 80 percent of global goods.[291] Based on its current trajectory, there will be an expected average annual increase of 1.3 percent in shipping volume from now until 2050.[292] The maritime industry currently accounts for 2 to 3 percent of global GHG emissions, totaling 1 million tons per year.[293] The forecasted surge in shipping activity is projected to increase GHG emissions. **If no further actions are taken, shipping emissions are expected to rise from approximately 90 percent of 2008 levels in 2018 to as much as 130 percent of 2008 levels by 2050.**[294] The International Maritime Organization (IMO) has set out the decarbonization strategy to reduce CO_2 emissions by at least 50 percent below 2008 levels by 2050. The **IMO's target entails a cumulative investment of around USD 1-1.4 trillion between 2030 and 2050.**[295] However, this goal would still fall short of the pathway outlined in the Paris Agreement.[296]

Major international maritime corporations such as Mediterranean Shipping Company (18.2 percent market share) have committed to reach net zero by 2050.[297] Danish shipping giant Maersk (15.8 percent) vowed to achieve net zero by 2040, a decade ahead of schedule.[298] **However, today's maritime industry still relies heavily on carbon-dense bunker fuel, and the use of low-carbon fuels is virtually non-existent**.[299] The industry will therefore have to rapidly innovate and transition from its current fuel sources to meet its decarbonization goals.

Technology Pathways

Fossil fuels, constituting over 99 percent of the total energy supply, have historically dominated international shipping.[300] Faced with increasing pressure to decarbonize, market players are seeking cost-competitive alternatives, as well as investing in dual-fuel vessels that could run on fossil fuels or other low-carbon alternatives. As of March 2022, nearly 40 percent of the orders for ships consisted of vessels that are capable of operating on multiple fuels.[301]

The type of fuel used for ships of different sizes tends to be determined by the physical properties and cost characteristics of different technological pathways [Exhibit 18]. Of the 200 zero-emission vessel pilot projects in the pipeline, roughly 40 of them are powered by ammonia. Ammonia has been mostly utilized on larger vessels. Meanwhile, hydrogen fuel cells, hydrogen combustion engines, and battery propulsion have mostly been limited to smaller ships.[302]

Heavy Fuel Oil

HFO remains the dominant fuel in the international shipping industry, accounting for 79 percent of maritime fuel consumption in 2018.[303] It is estimated that the global maritime industry consumes 105 billion gallons of fuel annually, and this figure is projected to double by 2030 as maritime trade expands.[304]

HFO has multiple upsides, primarily due to its cost advantages and developed bunkering infrastructure.

- **Cost.** HFO is roughly 30 percent cheaper than other oil alternatives as it is the residual fuels incurred from the oil distillation process.[305] The price of high sulfur fuel oil (HSFO) is around USD 400-650/mt; in contrast, very low sulfur fuel oil (VLSFO), which is in compliance with current IMO's sulfur emission requirement, costs USD 550-900/mt.
- **High volumetric energy density.** Energy density and storage volume are important factors that impact the range and bunkering frequency of maritime vessels.[306] The gravimetric energy density of heavy fuel residuals and distillates is approximately 40 MJ/kg, which is lower than LNG's 50 MJ/kg.[307] However, it has a much higher volumetric energy density, allowing it to use only one third the space needed to store the same amount of LNG. [308]

The major disadvantages of HFO are its high pollution and increasing compliance concerns.

- **Sulfur and nitrogen pollutants.** The impurities present in HFOs result in a high sulfur composition, which converts into sulfur dioxide (SO_2) after combustion and is a major contributor to acid rain. Shipping activities account for 9 percent of sulfur oxide (SO_x) and 18 percent of nitrogen oxide (NO_x) emissions.[309] Besides air pollution, potential HFO leakage poses serious risks to the marine environment.[310]

- **Regulatory requirements**. The need to comply with existing and potential regulations is pressuring major industry players to decarbonize. In 2020, the IMO set a cap to control SO_2 emissions, mandating all ships to use marine fuel with a sulfur content of 0.5 percent or less.[311] To comply with the new regulations, some ship owners are transitioning to VLSFO, which has a price premium over HSFO of more than USD 100/mt.

Liquefied Natural Gas

The use of LNG in ships has been rising steadily, representing almost 10 percent of the global fleet in service or on order, with an additional 3 percent easily converted to use LNG. [312] As an alternative to conventional fuels, LNG may reduce SO_x and NO_x in the near term, complying with IMO's sulfur requirements. However, its GHG emissions limit its capacity to achieve long-term maritime decarbonization goals.

LNG-fueled vessels have multiple advantages, including relatively low emissions compared to HFO and existing high market adoption in other sectors.

- **Market availability.** LNG has established infrastructure and market position, which creates an opportunity for it to replace HFO. It is easily accessible on major trade routes, with more than 100 bunkering solutions in operation worldwide. [313]
- **Reduced emissions.** LNG-fueled vessels produce 23 percent less GHG emissions and nearly eliminate SO_x particulate matter emissions.[314] After accounting for methane leakage, the real GHG emission reduction potential of LNG is projected to be between 8 to 20 percent compared to HFO.[315]

At the same time, **LNG-fueled vessels also feature significant disadvantages** including methane leakage, storage issues and market fluctuations.

- **Potential methane leakage.** There has been an 87 percent increase in methane emissions between 2012 and 2018, driven by an increase in LNG consumption and a transition to dual-fuel machinery. [316] Compared to zero-emission alternatives such as hydrogen and ammonia, LNG-fueled vessels are still not an ideal long-term solution in terms of environmental impacts.
- **Low volumetric energy density.** LNG storage on ships remains a challenge due to its lower volumetric energy density compared to conventional fuel oil, necessitating larger tanks to achieve the same operational range. Additional space is also required for tank insulation and gas handling systems.[317]
- **Price volatility**. The primary difference between the cost of LNG and traditional HFO arises from significant regional price variation of the LNG. The price volatility also partially stems from various geopolitical shocks, such as the LNG price spike in Europe that resulted from the Russian-Ukraine war.

Hydrogen and Ammonia

Hydrogen is most efficiently used in fuel cells, with an efficiency of around 50 to 60 percent. It can also be used in adapted combustion engines, but with lower efficiency of 40 to 50 percent.[318] Blending hydrogen and ammonia with other fuels is also being explored as a way to improve combustion and emission properties. For Ammonia, it could either be used as the feedstock for hydrogen fuel cells after decomposing into nitrogen and hydrogen or be used for direct combustion. The IEA estimates that ammonia will account for 45 percent of energy demand in shipping to achieve net-zero emissions by 2050.[319]

Hydrogen and ammonia have several **advantages** for maritime use.

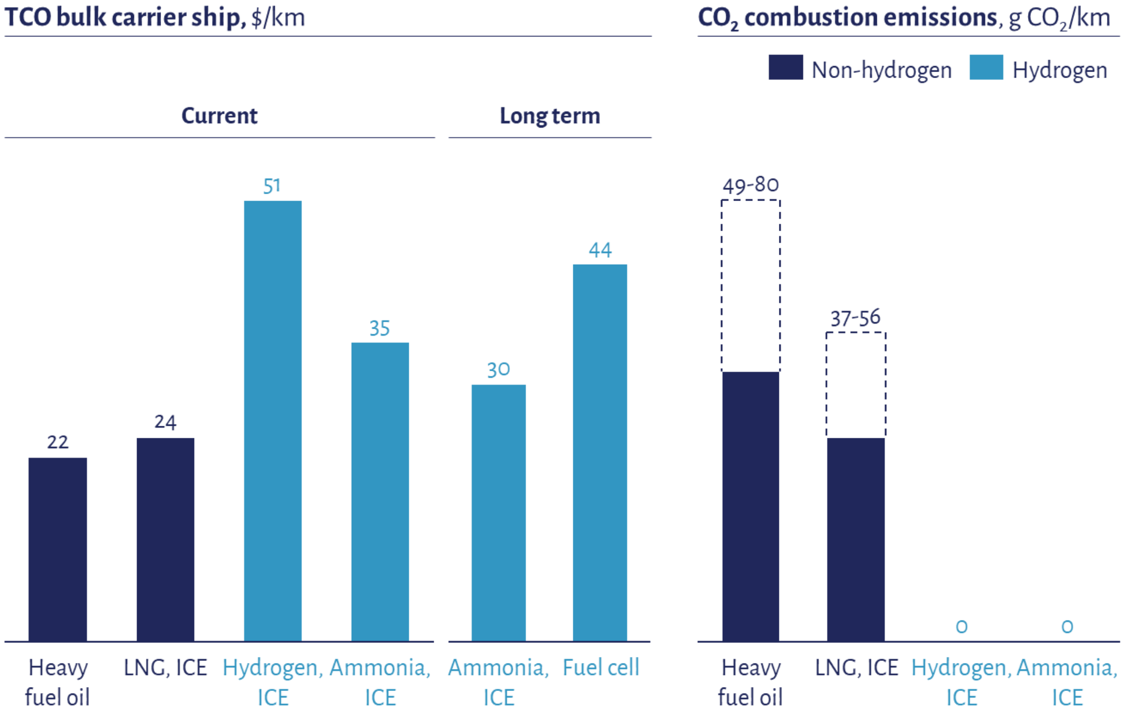
- **Low emissions**. Hydrogen fuel cells produce zero direct GHG emissions during operation.[320] The major carbon footprint for hydrogen stems from upstream hydrogen and ammonia production, depending on the energy source. That said, for direct use of ammonia, incomplete combustion could potentially increase the emissions of N_2O and NO_x.[321]
- **Established international market and logistical infrastructure**. Since ammonia is a widely traded commodity, there is already established infrastructure for the production, transportation, and storage for ammonia, including at 130 ports globally.[322,323] Moreover, retrofitting of certain LNG terminals could also be a viable means to expand necessary infrastructure for ammonia.[324] For example, some German LNG terminal projects have recently been built with future flexibility to switch to ammonia.[325] The cost of repurposing LNG pipelines for hydrogen is expected to be only 10 to 35 percent as much as constructing new pipelines.[326]

At the same time, the adoption of hydrogen and ammonia in the maritime sector also has drawbacks related to **challenges in fuel storage and high capex.**

- **High TCO**. Hydrogen- and ammonia-based maritime solutions currently have a higher TCO because of the high production costs (see Value Chain section), expensive fuel cells, and the lack of bunkering infrastructure.[327,328] As an illustrative example, Equinor and Air Liquide recently abandoned a liquefied hydrogen shipping project after failing to attract customers for two years, mainly due to higher production costs compared to marine diesel.[329] Due to low production volumes, marine fuel cells cost more than USD 1000/kW.[330] Other onboard expenses such as reforming, evaporator, gearbox, and electrical systems may also need to be factored in. [Exhibit 18][331]
- **Low volumetric energy density**. To produce the same energy output as one cubic meter of LNG, liquid hydrogen fuel tanks would need to be at least three times larger than those used to store LNG. The ammonia-to-LNG tank size ratio is approximately two to one.[332] Compared to conventional marine fuel oil, ammonia-fuelled vessels would require 1.6 to 2.3 times more storage volume.[333]
- **Safety concerns.** Exposure to high concentrations of ammonia in the air can cause serious health issues such as blindness and lung damage.[334] On a ship, ammonia leakage can be a serious hazard to onboard personnel, even as the pungent odor of the gas makes it easy to detect. The maritime industry could learn from existing management techniques for ammonia

in other applications. However, these techniques require modification to adapt to conditions where site evacuation may be infeasible.

Exhibit 18: TCO and CO_2 Emissions of Bulk Carrier Ships



Source: IEA, IRENA[335,336]

Potential of Low-Carbon Hydrogen for Maritime Transport

Hydrogen and ammonia have great decarbonization potential, but market uptake in the short term is hindered by high TCO and storage inefficiency. Ammonia could serve as a hydrogen carrier to overcome hydrogen's low volumetric density, but several technological hurdles and safety issues need to be addressed. Ammonia has established infrastructure for production, transportation, and storage due to its use as a fertilizer, but the lack of bunkering infrastructure becomes a major obstacle that would require significant policy support. **Over the next decade, using ammonia-fuel blends in ICE may be the most practical method for introducing hydrogen-based maritime solutions**. While not the most efficient GHG reduction option, initial adoption of ammonia could speed up infrastructure development and prepare for its use in other technology paths, such as fuel cells, in the future.

A number of potential developments are worth monitoring that may affect the future adoption of low-carbon hydrogen in the maritime industry. They include:

- **Technology breakthroughs.** Innovation that reduces costs of fuel cells and modification of ammonia combustion engines will drive market adoption.
- **Evolution of policy support.** Policies that include specific provisions to bridge the infrastructure and operational costs for low-carbon hydrogen and ammonia technologies could have the potential to significantly disrupt the outlook for the sector.
- **Regulatory developments**. The alignment of IMO's decarbonization goal with the Paris Agreement is anticipated to accelerate the adoption of hydrogen and ammonia.

Aviation

At a Glance:

- Aviation is a highly concentrated, emissions-intensive industry with pronounced path dependency on fossil fuels.
- Hydrogen can be used through different modalities including combustion, fuel cell, and as feedstock for synthetic fuels. Hydrogen-powered aviation, however, is associated with high capex and opex, significant technological hurdles,and a lack of infrastructure. At present, there are no clear existing targeted policies that can substantively address these obstacles.
- As a result, hydrogen as a feedstock for drop-in synthetic fuels currently represents the most viable opportunity given concrete policy support and reasonable transition costs, though this is not the pathway with the highest emissions reduction potential.

Market Overview

Aviation is a high-emission and hard-to-abate industry. Aided by a strong recovery from the COVID-19 pandemic, the global aviation market generated about USD 782 billion in revenue in 2022.[337] By 2035, the industry is expected to grow by 4.3 percent annually.[338] **Europe and the United States remain highly influential in the aviation market.**[339] North America and Europe are expected to account for more than 53.5 percent of the global aerospace services market by 2041, while Airbus (EU) and Boeing (US) alone manufacture about 65 percent of the global airline fleet. In fact, the 10 largest aircraft manufacturers by revenue are all either European or American.[340]

Aviation emissions increased by 34 percent over the past five years, while growing population and consumption habits will further increase demand by 3 to 5 percent per year through 2050.[341] The aviation industry currently faces two main decarbonization challenges. First, **activity growth is outpacing fuel efficiency improvements**. While new aircraft are up to 20 percent more fuel efficient, passenger volume has grown at double the pace of fuel efficiency improvements. Air passenger traffic is expected to more than double by 2050 under current trends.[342] Even if efficiency improvements accelerate to 2 percent per year in accordance with targets set by the International Civil Aviation Organization, aviation emissions will still double to 1.5-2 gigatons of CO_2 by 2050. Second, **the sector faces technological bottlenecks and cost hurdles** due to fundamental characteristics of aircraft design and operational costs. Unlike road or maritime transport, for which decarbonization technologies are at a more mature stage of development, significant R&D in aircraft engineering is generally needed to enable further efficiency improvements and fuel switching. As a result, **paying for the transition will be tricky**; ticket prices may increase by 10 to 20 percent in the next decades to offset decarbonization costs.[343]

Decarbonizing the aviation industry will require low-carbon propulsion technologies, new fuels to complement improvements in incumbent aviation fuel systems, and other efficiency measures. After discussing the fossil fuel incumbent, this section will focus on three promising alternatives: electric aircraft, sustainable aviation fuels (SAF), and hydrogen.

Technology Pathways

Incumbent Fossil Fuels

Oil dominates the aviation fuel supply mix, but multiple forecasts predict that in order to meet net-zero goals, its share needs to fall to 25 percent by 2050.[344] Two main types of fossil fuel-derived products are used in aviation: kerosene-based jet fuel, usually used in turbine engines, and gasoline-based AVGAS, usually used for propeller aircraft and small piston-engines.

As the incumbent, kerosene- and gasoline-based aviation fuels benefit from path dependency.

- **Competitive upfront cost and TCO.** Most non-fossil fuel engines and airframe designs are still in early stages of R&D estimated to be more than a decade away from commercial viability and cost parity. As a result, kerosene- and gasoline-based aircraft continue to enjoy commanding cost advantages.
- **Mature existing infrastructure allows for operating efficiency.** The existing global refueling network, which includes fueling stations, ground transportation of fuel, and logistics operations, enables conventional aircraft to operate beyond typical single-refuel ranges (>10,000 kilometers for large long-range aircraft). Combined with the fact that kerosene has the highest refueling rate of all existing technological pathways at about 900 liters per minute, fossil fuel incumbents enjoy high operating efficiency that reduces cost.[345]

Despite these advantages, conventional aviation fuels also face significant **challenges.**

- The **environmental impacts** of conventional aviation fuels are substantial. Along with NO_x, water vapor, and soot, aircraft combustion engines emit 3.15 kilograms of CO_2 for each kilogram of kerosene burnt in flight, which remains in the upper atmosphere for 50 to 100 years.
- Conventional aviation fuels are **highly susceptible to risks including resource depletion, supply security, and market volatility**. Fuel cost is in particular one of the most variable costs, representing between 15 to 20 percent of total airline expenses.[346] As a result, airline bottom

lines are consistently beholden to fuel prices, which are often determined by geopolitical uncertainties.

- Path dependency can be a double-edged sword. **As climate change accelerates, existing risks will likely compound** and increase the cost of incumbent fuels. Due to the high upfront costs of fuel switching and infrastructure retrofit, the risk of stranded assets will be especially high if operators do not prepare for a transition until costs reach unsustainable levels.

Sustainable Aviation Fuels (Non-hydrogen)

SAF produced from renewable sources such as biomass (i.e., plant and animal materials) or waste (i.e., solid or gaseous waste) have similar physical and chemical characteristics as conventional jet fuel but with lower life-cycle GHG emissions.

At present, SAFs are considered a leading solution for aviation decarbonization, with 4.5 million gallons per year produced in the United States.[347]

- With similar physical and chemical properties, SAF can be a **"drop-in" replacement** for conventional jet fuel and the two can be safely mixed without the need for airframe and engine redesign. Similarly, existing support infrastructure such as ground transport and maintenance can be used to transport SAF almost seamlessly.
- SAFs enjoy **concrete policy support**. In the United States, the IRA makes SAF quantifiable for the blender's tax credit and PTC up to USD 1.75/gallon for" very low lifecycle" GHG fuels through 2027.[348,349] The "SAF Grand Challenge," a multi-agency initiative, includes R&D investments and supply chain support for SAF.[350] The federal Renewable Fuels Standard and California's Low Carbon Fuel Standard also allow jet fuel producers to participate in lifecycle GHG reduction programs with compliance credits for SAFs. In Europe, the proposed ReFuelEU Aviation regulation, which is currently under development, will set blending mandates for SAFs if adopted.[351]

SAFs, however, are not a silver bullet for aviation decarbonization, due to the following **disadvantages.**

- The production risks, costs, and benefits of SAFs will remain tied to their renewable energy or biomass feedstock, which can **muddy their true emissions abatement.** Similarly, shocks affecting renewable energy and biomass production will affect SAFs.
- On the supply side, **technological hurdles** still exist for some SAF technologies (i.e., alcohol-to-jet and feedstock gasification) that are still in early demonstration stages. Similarly, biomass feedstocks suffer from limited availability and slow rates of adoption , which may make it **more difficult to quickly scale production** .[352]
- On the demand side, SAF is on average **three to five times more expensive** than conventional jet fuel without subsidies and other policy incentives. Numerous industry players have made preliminary commitments to adopt SAFs (i.e., Delta Airlines committed to replacing 10 percent of jet fuel with SAF by 2030, the United Postal Service plans to use SAFs for 30 percent of aircraft by 2035), but future demand will still hinge on **uncertain improvements in cost competitiveness.[353]**.

Battery Electric

Similar to electric automobiles, battery electric aircraft use stored electricity to power electric motors in place of ICE.

Battery electric aircraft enjoy a number of **potential advantages**.

- Electric aircraft can unambiguously reduce aviation emissions, as they produce **no direct emissions** and negligible in-flight climate impacts.
- Electric aircraft are also projected to have much **lower operational and maintenance costs** than conventional aircraft**.** In 2022, a conventional two-seat aircraft was almost fourfold more expensive to operate than its electric counterpart.[354]
- Electricity provides the possibility for grid connection, which could create further **efficiency gains** from grid optimization.

However, significant technological **challenges** must be weighed against these advantages.

- **Battery energy density and weight severely restrict the range and size** of aircraft. At present, the volumetric energy density of fossil jet fuel is about 20 times higher (9,700 Wh/L) than advanced commercial lithium batteries, which are also 50 times heavier than equivalent aviation fuel.[355] These physical characteristics will likely restrict electric aircraft to short-range flights (< 3,000 kilometers) only.
- Switching to electricity will expose the aviation industry to the risks associated with the **production and transmission of renewable energy as well as the sourcing of key materials** for battery production (i.e., rare earth elements). Costs will remain high if these risks are not adequately mitigated.
- During the transition to an electricity-powered aviation ecosystem, fundamental operational changes and the expansive build-out of support infrastructure, such as transmission and storage, will incur **significant capex.**

Hydrogen

Hydrogen is a versatile option for the decarbonization of aviation. Hydrogen-enabled aviation can follow three distinct pathways, each with advantages and outstanding challenges:

- **Direct use (or, turbine)**, in which hydrogen is consumed via combustion in jet engines. This solution is projected to reduce emissions by 50 to 75 percent compared to incumbent fuel sources. Since hydrogen requires four times more volume than conventional jet fuel to supply the same amount of energy, and turbine-powered aircraft need a completely new airframe design, this solution presents a host of technological and financial challenges, namely high capex, opex, and infrastructure costs.
- **Fuel cell,** in which hydrogen is stored in fuel cells that can be used to power electric motors. This solution is projected to reduce emissions by 75 to 90 percent. Similar to turbine-powered aircrafts, fuel cell adoption would require new airframe designs, while heavy fuel cells can limit

range and performance. Similar challenges related to high capex, opex, and infrastructure costs are associated with this solution.

- **Power-to-liquid (PtL)**, in which hydrogen is used as feedstock for SAF. For this pathway, electricity is used to produce hydrogen and capture carbon, before combining the two into a synthetic fuel. With renewable feedstock, PtL is projected to reduce emissions by 30 to 60 percent. While the technology is still not at scale, it is a drop-in replacement that requires minimal equipment and infrastructure investment.

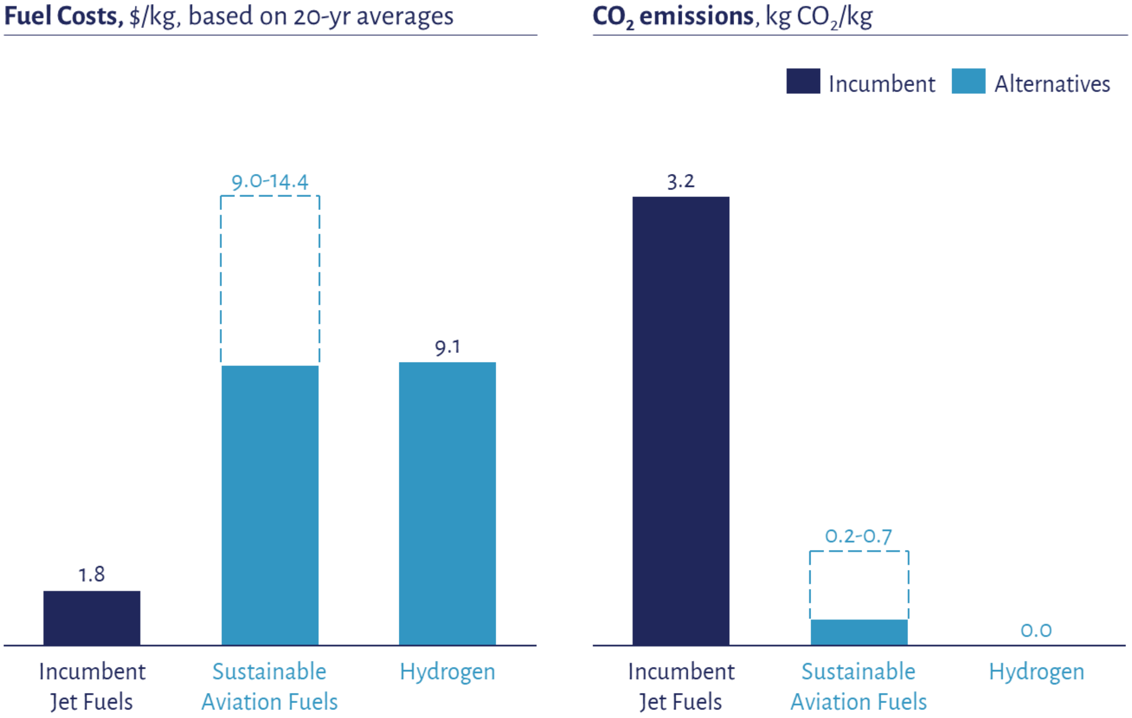
Survey respondents ranked aviation second-to-last place on the list of end uses with the highest technical and commercial viability by 2035 [Exhibit 7], reflecting concerns about the significant technological and infrastructure hurdles facing the sector discussed in this section. At the current pace of technological advancements, large aircraft fueled by hydrogen will likely not be commercially viable within the next 15 years; fleet penetration will take even more time.[356] An uncertain timeline can result in a crucial mismatch with aircraft development cycles, which occur about every 15 to 20 years.

However, a number of major aircraft manufacturers and airlines have shown strong interest in hydrogen. Airbus is currently the leader in large hydrogen-powered aircraft; its ZEROe program is aimed at developing large hydrogen-combustion jet turbine aircraft for commercial operation by 2035.[357] Rolls-Royce is designing smaller hydrogen aircraft through retrofits and tank-swapping. Additionally, Air Liquide and other European entities are in talks to retrofit airports with the infrastructure designed for hydrogen aircraft.[358,359]

Potential of Low-Carbon Hydrogen in Aviation

Aviation is a highly concentrated and emissions-intensive industry dominated by a small number of large companies. Aside from policy and decarbonization objectives, fuel price volatility is a major structural incentive for the industry to decouple from fossil fuels. In aviation, hydrogen can be used through different modalities including combustion, fuel cell, and as feedstock for synthetic fuels. Hydrogen-powered aviation, however, is associated with high capex, opex, and infrastructure costs. At present, there are no clear existing targeted policies that can substantively address these obstacles. As a result, **hydrogen as a feedstock for drop-in synthetic fuels currently represents the most viable opportunity given concrete policy support and reasonable transition costs, though this is not the pathway with the highest emission reduction potential [Exhibit 19]**.

Exhibit 19: Cost and CO_2 Emissions of Aviation Fuels



Source: US Energy Information Administration, [360] *Department of Energy,* [361] *McKinsey & Company,* [362] *Rhodium Group,* [363] *EESI* [364]

A number of potential developments may change current adoption calculus and affect the future role of hydrogen in the aviation industry. They include:

- **Technological breakthroughs.** Revolutionary advancements in airframe, battery, and related infrastructure design can offset the reliability, range, and cost limitations currently associated with hydrogen aircraft.
- **Input costs.** The availability of low-cost low-carbon hydrogen and access to renewable energy sources will be critical factors in determining whether hydrogen overcomes the cost advantage of incumbent fossil fuels.
- **Evolution of policy support.** Landmark policies with specific provisions designed to materially improve parity in ownership, infrastructure, and operational costs for hydrogen technologies can disrupt the sector outlook.

Key Conclusions

Low-carbon hydrogen has promising potential for emissions abatement in both the heavy industry and transportation sectors. However, based on the results of our comprehensive research, expert interviews, and an original survey, **additional action is needed to create an enabling environment** that fosters sustained investment in the low-carbon hydrogen sector and supports long-term decarbonization goals.

Key conclusions related to the commercialization pathways of low-carbon hydrogen by 2035 are as follows:

1. **Low-carbon hydrogen has the greatest potential to make significant decarbonization contributions at commercial scale in the ammonia and steel industries by 2035.** The ammonia industry is already a significant consumer of hydrogen, providing a clear runway for the transition to using low-carbon hydrogen within the 2035 timeframe. The steel industry, on the other hand, is facing a major reinvestment period for production assets over the next 10 years, and hydrogen DRI (paired with renewable EAF) has strong potential to significantly reduce carbon emissions in the industry. For both industries, the adoption of low-carbon hydrogen will largely depend on the availability of low-cost hydrogen inputs.

2. **Challenges related to high capex, low margins, competing technology pathways, and lack of adequate upstream and midstream infrastructure persist across nearly all of the potential end uses examined.** Many industries can avoid the steepest upfront costs by blending low-carbon hydrogen into their existing fuel supply, enjoying flexibility and scalability as the cost of low-carbon hydrogen falls. However, some sectors – especially steel, commercial transport, and aviation – face significant financial hurdles to reinvest or retrofit their productive assets and associated infrastructure to integrate with hydrogen. Across all end-uses, low margins make near-term investment decisions challenging given uncertainties related to future availability of upstream and midstream infrastructure, and as a result, the cost competitiveness of low-carbon hydrogen.

3. **Low-carbon hydrogen is unlikely to serve as a decarbonization "silver bullet" in any of the industries explored**. Given the complexity of the decarbonization challenge, there is rarely one single solution for each industry, and many sectors are hedging their bets by investing in different technology pathways. For example, in the transportation sector, hydrogen is a promising alternative for long-range shipping and commercial transport, but electrification may be a stronger alternative for short distances. For industrial processes, industry players will likely continue to pursue CCUS projects in tandem to hydrogen investment – particularly in the cement industry where hydrogen has limited decarbonization potential.

4. **Recent policies in the European Union and United States help facilitate the adoption of low-carbon hydrogen, but existing policies alone are not sufficient.** Additional policy support is needed to overcome market uncertainty, regulatory hurdles, and collective action problems. Given regional differences, policymaking may take divergent paths in the European Union and

United States due to variation in policy frameworks, social acceptance, industrial priorities, and resource availability. Therefore, global policymakers and other stakeholders must collaborate to develop coherent and effective policy frameworks that support the transition to low-carbon hydrogen and address the specific needs and challenges of each region.

5. **Investors must stay aware of changing definitions and industry standards around low-carbon hydrogen.** For example, the debate around additionality and temporal/geographical matching in the United States has tremendous implications for the regulatory treatment of various hydrogen production processes and the development of the low-carbon hydrogen market. Moving forward, investors will have to adjust their strategies to account for different standards and practices between jurisdictions.

List of Exhibits

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