Policy strategies to grow decarbonized hydrogen demand

Sector-specific recommendations

World Business Council *for Sustainable Development*

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Foreword

Executive *summary*

Executive Summary

Hydrogen is gaining momentum as a pivotal solution to achieve society's net-zero emissions goals by 2050, particularly in applications where low-carbon electricity alone is expected to fall short of meeting energy needs. Although 41 countries worldwide have energy **strategies**[1] with targets for decarbonized[2] hydrogen production, only a few include comprehensive policy packages to stimulate hydrogen demand. Consequently, companies hesitate to invest in decarbonized hydrogen due to its higher costs than conventional hydrogen and the lack of visibility on or existence of support mechanisms.

Despite recent and ongoing technological advancements, without supporting mechanisms, clean hydrogen will remain more expensive than conventional fossil-based hydrogen in the early stages of market development. Therefore, **it is urgent to develop policies tailored explicitly to end-use sectors to make clean hydrogen more attractive to corporate off-takers, establish price visibility, and instill confidence in investors and project developers.**

To effectively drive demand for decarbonized hydrogen, it is crucial to implement policies that support new hydrogen applications, the transition to decarbonized hydrogen in industrial sectors that currently use carbon-intensive hydrogen, and the development of market-wide enablers, such as carbon pricing mecha nisms. Together, these measures, for which this report provides detailed examples, will bolster the use of hydrogen in industrial sectors and foster global trade in the hydrogen economy.

Governments must effectively implement relevant policy instruments[3] in a timely manner considering the maturity of markets and technological solutions. The implementation of policy strategies should follow a timeline that first enables production cost reductions, then stimulates demand and increases the cost of carbon and, finally, bans conventional hydrogen without incurring a heavy cost burden to the switch.

Proposed timeline for the implementation of policies fostering hydrogen demand

Up to 2025 – In the next 2-3 years

→ **National energy strategies and industrial roadmaps** include clean hydrogen, with quantified production targets providing visibility to the market for the coming decades.

→ **Direct financial support** increases to facilitate the adoption of decarbonized hydrogen solutions – building production assets, infrastructure and manufacturing capacity – across the value chain through **loans, grants and tax credits.**

→ Market enablers develop further. Such enablers include **certification** to facilitate global trading – especially to distinguish the source of production and carbon intensity of hydrogen and its derivatives – and **standards** to handle crucial dimensions of deployment, such as health and safety, public security, distribution and environmental protection, correctly.

Period 2025-2030 – During this decade

→ **Market-based mechanisms** (MBMs), such as contracts for difference (CfD) and carbon contracts for difference (CCfD), progressively replace direct financial support, incorporating environmental costs into market dynamics and providing a more efficient allocation of public funding.

→ The introduction of **mandates and quotas** for decarbonized hydrogen solutions creates specific conditions to stimulate market adoption (performance indicators, standards, and preferential market conditions).

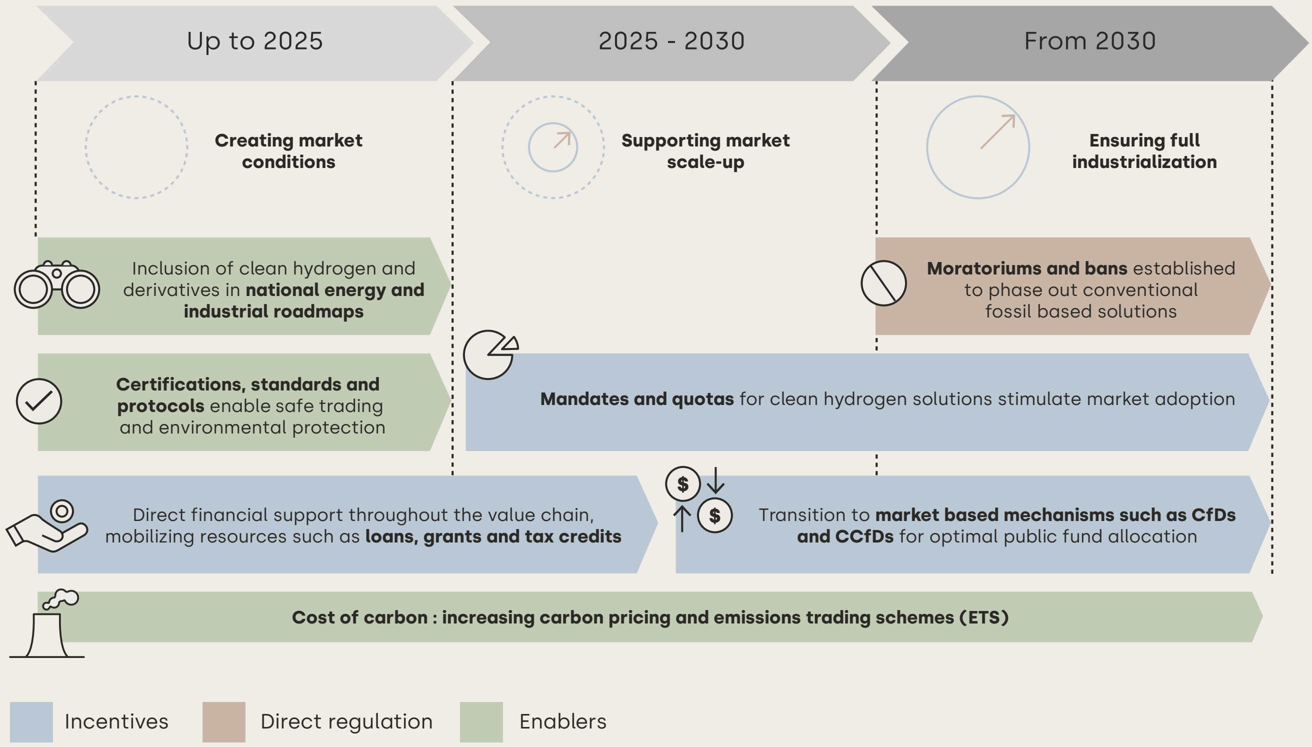
From 2030 – In the longer term

→ The creation of **moratoriums and bans** starts the **phasing out of conventional fossil-based solutions** (through moratoriums, bans, in addition to the implementation of costs of carbon) and replacement of unabated fossil-based feedstocks, to fully open the market to decarbonized hydrogen solutions and help the market ramp up to become cost competitive.

Throughout the period

→ Steadily **rising costs of carbon** and the existence of **emissions trading schemes (ETS)** support the policy strategies mentioned in the previous phases. The objective is to discourage fossil-based solutions and provide incentives for the uptake of low-carbon hydrogen solutions completed by selling carbon credits.

Figure 1: Timeline for policy instrument implementation



There are four end-use sectors for which hydrogen is a key decarbonization lever - **heavy-duty road transport, green steel production, clean ammonia production** and **oil refining.** As each sector has unique transition requirements, we offer specific recommendations for the implementation of policy packages in the following areas:

Heavy-duty road transport

→ Achieving cost parity between hydrogen-fueled and diesel-fueled trucks by 2030 requires a pragmatic combination of policy measures. Some countries have implemented effective solutions, including **incentive taxation regimes, carbon taxes, differentiated road tolling, and mandates for refueling infrastructures.** Adopting these measures at a larger scale now would then lead to minimal policy support requirements for the sector starting from 2030, as fuel-cell vehicle costs decrease, hydrogen refueling prices become more competitive, and the cost of long-haul diesel trucks increases due to higher carbon prices.

Green steel production*

→ The green steel industry has high operational expenditures (OpEx), which account for over 90% of total production costs, including feedstock and energy costs. **Market-based mechanisms** that reduce OpEx or bridge the entire cost gap, such as CfDs or CCfDs, hold significant promise for this sector. Additionally, recognizing the lower-carbon composition of fossil-free steel products is crucial in this highly competitive and globalized market. **Carbon accountability mechanisms** like the forthcoming[4] Carbon Border Adjustment Mechanism (CBAM) in Europe ensure harmonized policies which are essential. However, different end-use markets for green steel, such as construction, automotive and white goods, may require differentiated policy support, such as **quotas** in sectors capable of absorbing and/or passing on the green (cost) premium to customers.

*Green steel refers to steel manufactured without the use of fossil fuels

Ammonia:

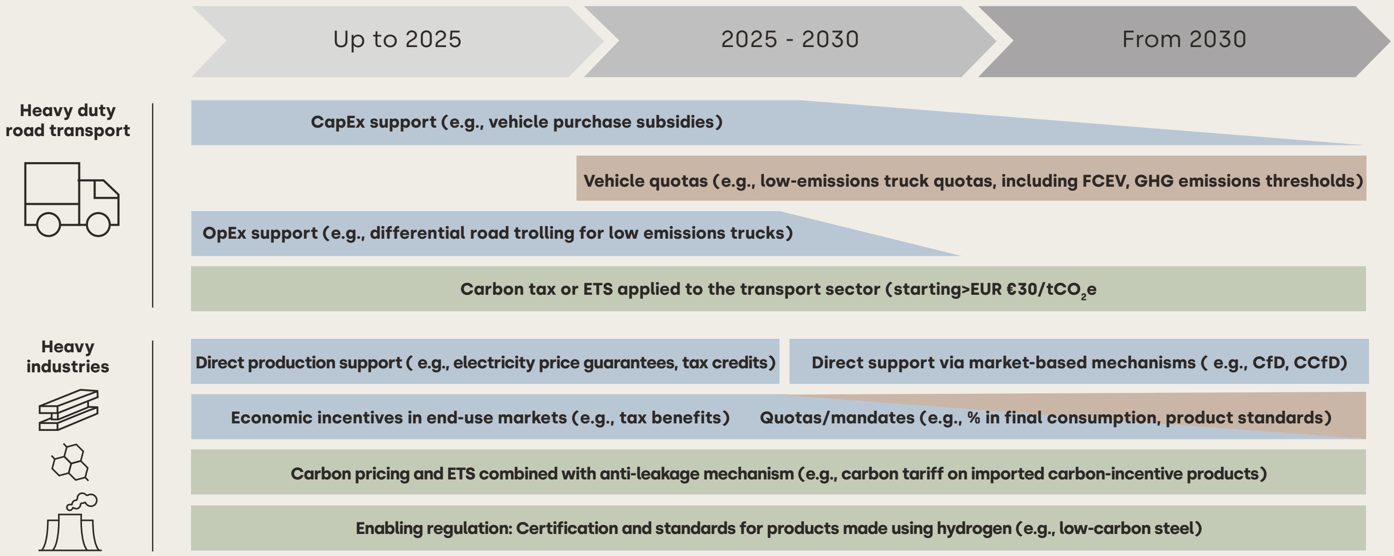
→ Like the steel sector, the ammonia industry requires substantial OpEx support to adopt decarbonized hydrogen. Policies incentivizing the uptake of green ammonia for two major, although very different applications are crucial: fertilizer production (linked to the food industry) and maritime transport (using ammonia to power ships). Legislative measures to promote low-carbon ammonia should primarily encompass mechanisms to drive up carbon prices **(carbon markets, emissions trading systems),** making low-carbon ammonia and its derivative products more competitive **(carbon accountability mechanisms),** alongside policies aiming to accelerate the adoption of clean hydrogen **(mandates, quotas).**

Refineries:

→ Replacing conventional hydrogen with clean hydrogen in the refining sector poses financial and technological challenges due to the technical complexities of refineries. Policies designed to help refineries reduce their carbon emissions could encourage them to produce or purchase decarbonized hydrogen. Refineries would also be encouraged to use decarbonized hydrogen to reduce pollution and explore cleaner fuel options. These policies should target refineries facilities. Governments can stimulate this transition by defining **clear targets (quotas, mandates) for using decarbonized hydrogen** in refineries, accompanied by economic **(CapEx and OpEx support) and fiscal incentives (reduced carbon tax)** to promote clean hydrogen production, such as exempting electrolyzers from grid fees, taxes and levies.

Figure 2 summarizes the primary measures identified for each of the four sectors examined in our analysis.

Figure 2: Primary measures for each of the four sectors



FCEV = fuel cell electric vehicle | GHG = greenhouse gas | ETS = emissions trading schemes | CfD = contracts for difference | CCfd = carbon contracts for difference

The climate crisis calls for rapid policy actions. Countries are unlikely to meet climate goals by depending on market forces alone to drive the adoption of clean hydrogen as prices fall. Clean hydrogen requires political support and it needs it now.

With the findings of this report, we seek to empower policymakers with the necessary knowledge to drive hydrogen demand and support the transition to a more sustainable and cost-effective hydrogen economy. The industry urgently needs supportive sector-specific and cross-sector mechanisms – up and down the value chain – to provide offtakers with certainty about the availability and affordability of clean hydrogen. With support to break down obstacles and barriers to its deployment at a large scale, clean hydrogen has the potential to emerge as a viable decarbonization option for the four industries covered in this document over the next decade.

Note

There is currently no universally agreed-upon standard definition of low-carbon hydrogen. Whenever we use the terms "clean" and "decarbonized" hydrogen in this document, we mean hydrogen with an intensity below 3 kg CO_2/kg H_2 using a full life cycle analysis, which aligns with various other definitions. When we mention "hydrogen" without any specification, it refers to "decarbonized" hydrogen, not any type of hydrogen.

Introduction

01.

01. Introduction

The uptake of decarbonized hydrogen is not on track with net-zero scenarios

Hydrogen and its derivatives are among the energy solutions that will help the world achieve climate **targets**[5] by 2050. Their greatest potential lies in their ability to decarbonize hard-to-abate sectors (i.e., iron and steel, cement, road freight, chemicals, shipping and aviation), which require a substantial amount of energy to run their operations and can currently not be decarbonized in an effective manner with low-carbon electricity.

Despite the widespread recognition that hydrogen plays an important role in limiting the global temperature rise to 1.5°C above pre-industrial levels, evidence so far shows that the world is falling short of the hydrogen-related targets set to this end. For instance, in its updated Net-Zero Emissions Scenario, the International Energy Agency (IEA) estimates that decarbonized hydrogen use grows by 6% annually until the end of this decade. This implies reaching more than 150 million metric tons of hydrogen (MtH_2) use by 2030, with 40% coming from new applications. Yet, in 2022,[7] less than 1% (or 0.07 MtH_2) of production came from decarbonized hydrogen projects, significantly below the volume projected by market development trajectories. Announced projects today total 20 Mt of low-emission hydrogen production, and 38 Mt if early-stage projects are included. Concerningly, the IEA notes that only 4% of announced projects have reached final investment decision or are under **construction.**[6]

While suggesting that the number of planned hydrogen projects is and will be rising year after year, this data also highlights the need to accelerate progress in the hydrogen sector to meet the ambitious targets for a 1.5°C scenario and maximize its potential. Several barriers hinder the achievement of this goal:

→ High decarbonized hydrogen production costs, mainly due to high electricity and electrolyzer costs, the latter not having yet reached their cost reduction potential and optimal efficiency;

→ Carbon-intensive production remains more cost-effective than producing decarbonized hydrogen due to the absence of carbon-related costs;[7]

→ Infrastructure challenges requiring substantial investments in large-scale hydrogen storage tanks, transportation and distribution assets;

→ Insufficient renewable electrification capacity leading to the inability to also reach decarbonized hydrogen production targets;

→ A lack of incentives for end-use sectors, including transportation, industry and power generation, to invest or purchase decarbonized hydrogen.

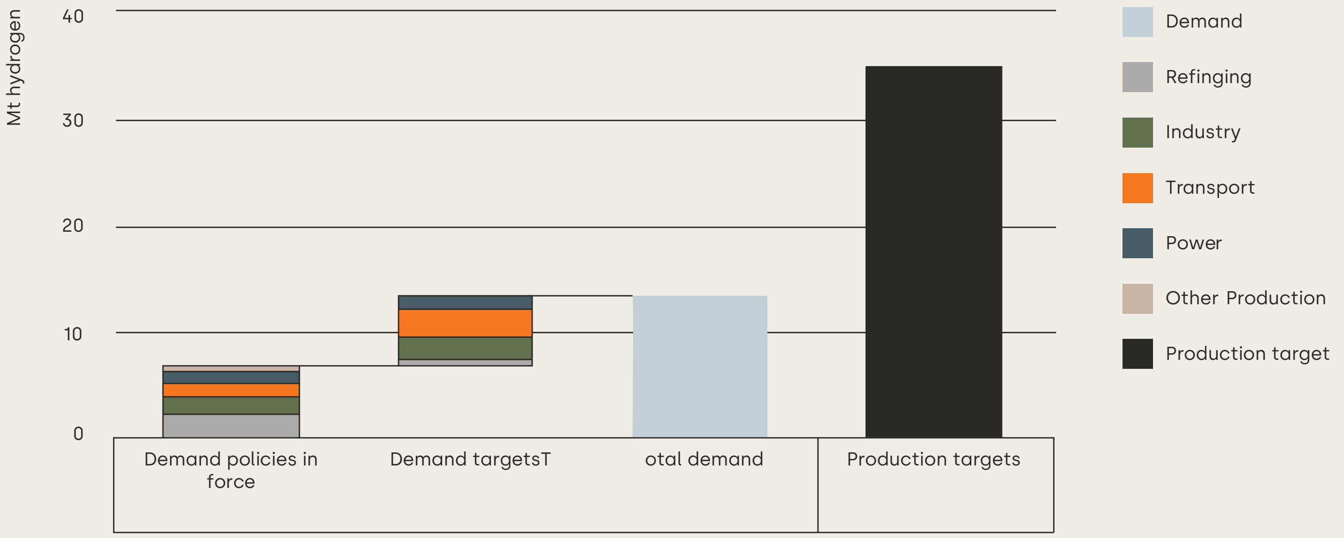
→ Significant challenges to transform industries (operations and infrastructure) to use hydrogen (instead of fossil fuel feedstocks);

→ Public and industry concerns about its safety, mainly because of its inflammability.

Large-scale adoption of hydrogen requires policy support

Hydrogen uptake at scale faces a dilemma. Without sufficient consumer demand, the deployment of hydrogen projects and infrastructure remains limited. In turn, this lack of scale further inhibits demand, creating a cycle of constraints. Despite expectations that hydrogen demand will grow in applications such as refining, industry and transport to account for over half of final hydrogen demand by 2050,[11] this projected growth will not be enough to achieve the goals outlined by the IEA in its Net-Zero Emissions scenario: there is gap between what governments have pledged via policies and what is required to meet net-zero emissions (see Figure 3).

Figure 3 : Potential demand for low-emission hydrogen created by implemented policies and government targets vs production targets set by governments, 2030[8]



Four changes need to happen to align hydrogen demand with production targets established by governments and the IEA's Net-Zero Emissions scenario:

- Lowering the cost of clean hydrogen to enhance its competitiveness for customers;
- Supporting the operational and infrastructure changes required in industrial uses;
- Developing market conditions enabling producers to secure investments and reduce their risks, ultimately facilitating the expansion of production and cost reductions;
- Accelerating the decarbonization of hard-to-abate sectors to meet climate goals.

It is essential to collectively make stronger efforts for these changes happen. As is often the case in nascent markets, policy and regulatory support is necessary to stimulate the market to the point of promoting the transition at the required pace and scale. A total of 41 governments have now adopted hydrogen strategies, whose countries account for nearly 80% of global energy-related CO_2 **emissions.**[9] Most of them have identified explicit targets for low-emission hydrogen production and only a few address hydrogen end-uses.

While a higher supply of decarbonized hydrogen is advantageous for its potential as a clean and versatile fuel, the barriers listed above could decouple the growth in supply from the corresponding increase in demand, whereas it is necessary for them to grow in tandem. Therefore, addressing these factors with targeted policies is indispensable in achieving a balanced and sustainable hydrogen economy.

In this publication, we make policy recommendations, specifically on scaling up hydrogen demand in end-use sectors.

Policymakers can implement numerous instruments to spur the adoption of hydrogen in end-use sectors. These instruments fall into the following categories:

- **Direct financial support** to reduce the upfront cost of producing or purchasing clean hydrogen – subsidies, investment tax credits, loan guarantees, feed-in tariffs;
- **Market-based mechanisms** to leverage market dynamics such as contracts for difference (CfDs) and carbon contracts for difference (CCfDs) provide long-term visibility to end-users and optimised public funds allocation;
- **Policy instruments putting a cost on carbon** to incorporate the environmental costs such as carbon taxes and emissions trading systems, and enable fair competition in the case of anti-leakage mechanisms;
- **Regulatory instruments** to facilitate trades and support market creation – standards, certification, tradable systems.
- **Quotas and targets** to impose decarbonized hydrogen adoption in industrial applications – purchase obligations, emissions targets, use of decarbonized hydrogen (%) in the industry.

Focus: Explanation of different policies to scale up the demand for clean hydrogen

Incentives for products made using clean hydrogen in end-use sectors

Increasing the demand for low-carbon hydrogen-based products will stimulate the entire upstream hydrogen value chain. Among the policy instruments mentioned above, several could specifically stimulate demand for green end products:

- Identifying customer options and issuing incentives such as tax credits to encourage them to buy items with the lowest carbon footprint.
- Endorsing the development of low-carbon product standards that require a gradual and long-term reduction of the average CO_2 intensity resulting from producing essential materials/products (e.g., steel, chemicals, fertilizers) across the economy and allows regulated entities to trade compliance credits. Adopting these rules at lower stringencies will provide an early market signal, enabling industries to plan and adapt as higher thresholds come into effect over time.
- Promoting the progressive adjustment of building codes to encourage using low-carbon materials.
- Encouraging voluntary market initiatives applicable to hydrogen end-users as the demand for voluntary carbon credits steadily increases and credit trading focuses on shifting from reducing emissions to eliminating them.
- Creating public procurement guidelines (e.g., for low-carbon steel) to help early market creation. For example, governments may amend public procurement contracts to mandate contractors use a steadily increasing amount of 'low-carbon intensity steel' for public buildings or infrastructure projects. Such changes might help kickstart demand rapidly.

Contracts for difference (CfD) and carbon contracts for difference (CCfD) in competitive bidding

CfD and CCfD[10] are policy instruments to boost clean hydrogen applications in various industries. Clean hydrogen or low-carbon material producers (e.g., steel or chemicals) could receive support via auctions based on the volumes produced. Auctions would reward cost-efficiency for minimizing the costs to the public and maximizing the leverage of private capital. Along with a carbon price, a CCfD could support long-term investment decisions, such as increasing the amount of 'low-carbon intensity steel' for public buildings or infrastructure projects.

Anti-leakage mechanisms to ensure the creation of an international playing field

Carbon leakage prevention requires regulations to ensure the harmonization of the cost of carbon in domestic and international markets. Countries that have provided free allowances to trade-exposed industries are now considering carbon border adjustment mechanisms for that aim.

Well-phased clean hydrogen mandates to stimulate demand

Mandates are efficient instruments to stimulate demand if aligned with the ability of the actors to transition to low-carbon solutions, particularly in hard-to-abate industries (e.g., refining, chemicals). Policymakers can progressively design clean hydrogen mandates so that industrials can use the new supply of clean hydrogen without changing their entire operating processes in a short period. The government needs to ensure that these measures support, not hinder, the existing policies or standards aimed at reducing emissions in industries. If a carbon pricing mechanism exists, policymakers might adjust the emissions reduction threshold for consistency with the mandates.

Scaling hydrogen demand requires policies across the value chain and market-wide regulation

Increasing demand volumes in specific sectors requires the establishment of a comprehensive approach that includes both demand-side and supply-side incentives. This fosters increased production capacities and reduces the cost of clean hydrogen solutions. In turn, this will make hydrogen more attractive to industrial users and ultimately stimulate greater demand.

In the following sections, we categorize policies as follows:

- **Demand** refers to policy instruments supporting the use of hydrogen in end-use sectors;
- **Supply** refers to policies that focus on reducing hydrogen production costs and supporting investments in hydrogen facilities (production, storage, distribution, transport);
- **Market-wide** refers to key enablers that help the development of global market mechanisms.

Table 1 provides a non-exhaustive list of measures that policymakers can consider to alleviate some of the major hurdles in the hydrogen market.

Table 1: Key policy measures to scale up the hydrogen market

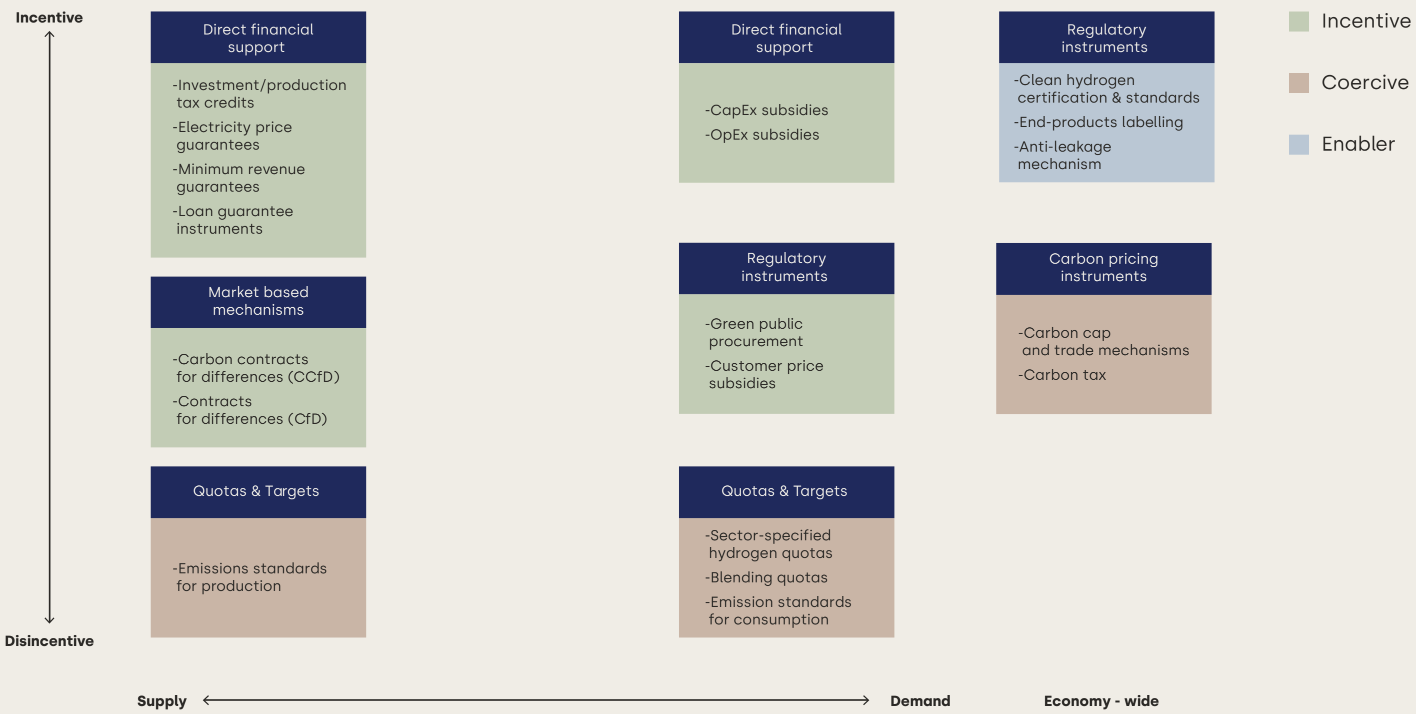
Policy category	Main barriers	Key policy measures	Targeted impact
Demand	High price of low-carbon hydrogen	Financial support: capital expenditure (CapEx) and operating expenditure (OpEx) support	Reduce clean hydrogen prices
	Lack of demand for clean hydrogen-based product	Regulatory instruments: green public procurement, phasing-out of fossil-fuels subsidies Financial incentives: customer price subsidies	Create and increase clean hydrogen demand Reduce clean hydrogen prices
	Carbon taxation in highly competitive and globalized markets leading to carbon leakage	Financial support: capital expenditure (CapEx) and operating expenditure (OpEx) support Anti-leakage mechanisms	Integrate the environmental costs Ensure fair competition of globalized markets
	Hydrogen demand uncertainty	Quotas: sector-specific quotas for hydrogen and its derivatives, blending quotas Targets: emissions standards for consumption	Foster market creation Promote clean hydrogen in industrial applications

Supply	High electricity/gas prices in hydrogen production	Financial support: tax credit (exemptions from electricity taxes, renewables production tax credits)	Reduce clean hydrogen production costs, increase clean hydrogen attractiveness and demand Support renewable electricity development
	Market willingness to pay the current premium for decarbonized hydrogen	Guaranteed revenues: minimum revenue guarantees, feed-in premiums, feed-in tariffs	Improve the business case for producers and increase supply volumes
	High investment risk for hydrogen production	Derisking instruments: loan/price guarantee instruments, CfD and CCfD	Secured hydrogen business models leading to more FIDs
Market-wide	Unfit market design	Efficient operating rules	Provide transparency to the hydrogen economy
	Unclear or no decarbonization strategies, no embedded carbon cost	Market-based incentives: carbon taxes	Promote the production and use of clean hydrogen
	Lack of standardization (design, safety) and transparency about the externalities of hydrogen	Regulatory instruments: low-carbon hydrogen certification and standards, product labeling	Provide transparency and harmonization to the hydrogen economy

To create markets and support global trade, incentives, disincentives, capital and operational expenditure support, along with essential components like certification schemes and standards, are essential. The optimal combination of policy measures, including demand-side, supply-side and market-wide instruments, will differ from country to country based on market design, policy objectives and fiscal arrangements.

Figure 4 summarizes the different policy instruments that we refer to in the rest of the document. It maps out their influence at various value chain stages and highlights the degree of support these measures provide in driving the hydrogen economy transformation.

Figure 4 : Mapping of hydrogen policy instruments across the value chain



Example: California Low Carbon Fuel Standard – Incentive and coercive sides of the policy

The California Low Carbon Fuel Standard (LCFS) is an innovative trading mechanism that aims to reduce pollution from the transport sector in the state. The policy relies on a threshold limiting the transport emissions to 3,500 tons CO2 each year. This mechanism rewards, in the form of credits, companies that produce low-carbon fuels like hydrogen. Other companies can buy these credits if they pollute too much. But, if a company doesn't align with the policy, a penalty applies. The LCFS is a good way to spur the use of cleaner fuels and reduce pollution from cars and trucks in California.

Policies help bridge the cost gap in four specific hard-to-abate sectors

In this document, we examine the policies that can drive the adoption of decarbonized hydrogen and demonstrate the crucial role of policy support in bridging the financial gap between conventional and clean hydrogen solutions.

Policy actions and market incentives can turn a new energy source into a major player in the global energy scene. Take liquefied natural gas (LNG) as an example. It had similar challenges 50 years ago as hydrogen does today, like high costs and low demand. But governments and international groups supported LNG by making long-term contracts, offering financial help, and creating rules to help it grow. **Through thorough economic analysis, we show how the implementation of the right policies can profoundly impact the hydrogen uptake to become a major global energy source.**

To comprehensively explore the potential of policy support, we have divided this document into four sections, each dedicated to one of the selected end-use sectors: heavy-duty mobility, steel production, ammonia and refining. We have chosen these sectors due to their heavy reliance on fossil fuels: these hard-to-abate sectors account for about 30% of global emissions (10 $GtCO_2$ eq per year).[11] It makes their decarbonization crucial in achieving net-zero emissions targets by 2050.

Each section focuses on the respective sector's specific challenges and outlines the policy levers recommended to address them, the timeline for their implementation and an economic analysis of the differences in cost. The document also provides examples from around the world to illustrate the positive outcomes an effective combination of policy measures can bring to this sector. The report ends with a concluding chapter that summarizes the key takeaways, identifies the immediate actions needed, and outlines WBCSD's role in supporting the policy recommendations.

Heavy-duty *road transport*

02.

02. Heavy-duty *road transport*

The global transition of heavy-duty fleets is still in its early stages.

In 2020, global sales of heavy-duty trucks reached approximately 1.7 million vehicles.[12] The dominant markets for these trucks were China, the USA and Europe. The vast majority of sales took place in China, which now accounts for over 95% of fuel-cell trucks globally, driven largely by a more than fivefold increase in heavy-duty fuel-cell trucks from the end of 2021 to June **2023**.[13]

While heavy-duty road transport enables long distance shipping with high payloads, it also contributes to air and noise pollution. As efforts to mitigate the environmental impacts of conventional trucks grow, the rapid development of zero-emissions vehicles is gaining momentum. Net-zero emissions scenarios show they need to capture around 30% of sales of the combined European, American and Chinese markets by 2030 to meet **targets**.[14] Within this timeframe, forecasts indicate fuel-cell vehicles will make up 5% to 10% of total heavy truck sales, with the European market holding the largest share.

The deployment of hydrogen fuel-cell vehicles is a promising solution due to their similarities to diesel trucks, such as high payload capacity, long-range autonomy and fast refueling. Beyond these similarities, fuel-cell vehicles have a clear advantage as they meet requirements for zero emissions as their sole byproduct is water vapor.

Currently, over 90% of the available medium-duty and heavy-duty trucks models are battery electric. It is estimated that 20 models of fuel cell heavy-duty trucks will be available by **2024**.[15]

The limited progress in the market stems from the significantly higher costs of operating fuel-cell vehicles:

- Fuel-cell technology is still in the early stages of commercialization and entails substantial research and development expenses. The production and integration of fuel cells, hydrogen storage systems and associated components require specialized manufacturing processes and materials. The absence of economies of scale in manufacturing leads to higher unit costs. Moreover, fuel-cells rely on expensive materials like platinum or other catalysts that are crucial to the electrochemical reactions that generate electricity. Their scarcity and high costs contribute to fuel-cell system expenses.
- Secondly, fuel-cell trucks require hydrogen fuel infrastructure, which is presently limited and costly to develop. The expenses associated with establishing hydrogen production, storage and distribution facilities further add to the overall financial burden of adopting fuel-cell technology. Specialized maintenance and service facilities are also essential to supporting fuel-cell trucks, requiring trained technicians, diagnostic tools and spare parts, which increases operational and maintenance costs.
- Lastly, the market for fuel-cell trucks remains relatively niche compared to traditional diesel trucks. With fewer manufacturers and limited competition, there is less downward pressure on prices. However, scenarios show prices will decrease over time as more manufacturers enter the market and competition intensifies.

Supportive policies by market development phase

Policy support is important to overcoming initial barriers because it can promote technological advancements and stimulate market demand for fuel-cell trucks, driving costs down and enhancing the economic viability of fleet operators. A successful transition to low-emissions vehicles requires comprehensive support through targeted policies in both the hydrogen and transport sectors, recognizing the financial constraints transport and logistics companies face.

In the transport sector, policies should focus on:

- Discouraging the use of diesel trucks by implementing measures such as emissions standards, carbon pricing and restrictions in urban areas to incentivize the adoption of low-emissions alternatives;
- Providing financial support in the form of incentives or subsidies for purchasing and operating hydrogen vehicles during the early stages of market creation and deployment, reducing the upfront costs for fleet operators;
- Supporting the conversion of production lines and supply chains to ensure an adequate production capacity of heavy-duty hydrogen vehicles, enabling economies of scale and cost reductions;
- Supporting the development of refueling infrastructure to solve the chicken-and-egg problem in the deployment of hydrogen vehicles.

In the hydrogen sector, policies should concentrate on:

- Standardizing cross-border certification of hydrogen to facilitate trade flows and optimize international cooperation, fostering a harmonized market and reducing regulatory barriers;
- Developing guidelines and standards for safely handling and transporting hydrogen, including considerations for tunnels and bridges, to ensure safety and build public confidence in the technology.

By implementing proper policies, hydrogen fuel-cell trucks can become competitive with diesel trucks by 2030

Governments should apply effective policy measures consistently over time and cover various aspects of the value chain, addressing supply and demand. This comprehensive approach is necessary to transition to hydrogen fuel-cell trucks in the next decade successfully. The combination of policy measures will also vary depending on the specific market deployment phases in the heavy-duty road transport sector.

Start-up phase

By 2025, the hydrogen-electric heavy vehicle sector will be in its start-up phase, primarily focusing on research, development and initial deployment. During this phase, often referred to as the pilot phase, projects initiate the deployment of the first operational vehicles.

- In these early stages of market deployment, the support for hydrogen-fueled trucks should aim to bridge the CapEx gap between diesel and fuel-cell trucks. This is achievable through direct subsidies and tax incentives. However, there are opportunities to implement direct OpEx support, such as differential road tolling costs or subsidizing refueling stations to reduce hydrogen prices, as OpEx constitutes the largest portion of these vehicles' total cost of ownership (TCO).
- The development of the vehicle offer is supported by the establishment of groups of refueling stations, which create the first ecosystems for hydrogen mobility, bringing together users, service stations and maintenance centers. CapEx funding for hydrogen fueling stations and can enable projects to start.

Industrial scale-up

The period between 2025 and 2030 marks a crucial phase characterized by the accelerated production of heavy-duty hydrogen vehicles. During this phase, the focus shifts to establishing dedicated, automated production lines and increasing production volumes. These efforts aim to achieve cost reductions for trucks through economies of scale. Similarly, fuel-cell and hydrogen tank technologies undergo economic upscaling, reducing costs for these vital truck equipment components. These advances reduce the TCO significantly.

In addition to the measures implemented during the start-up phase, other strategies come into play. Governments progressively implement sales quotas for zero-emissions vehicles and introduce CO2 emissions thresholds to incentivize manufacturers to expand their portfolios and prioritize the production of low-emissions vehicles. These policies encourage manufacturers to enhance their commitment to sustainable transportation solutions. If they do not meet quotas, governments can create incentives to do so, such as subsidies, tax benefits, grants, a gradual phase-in approach, and combine them with punitive actions like penalties and stricter enforcements. The aim would be strike a balance between promoting the adoption of fuel-cell vehicles and ensuring a realistic and achievable transition for the industry.

Full industrialization

By the end of the decade, scenarios expect the full industrialization of hydrogen-electric trucks. Starting in 2030, projections show implementing carbon taxes and enforcing more stringent emissions standards will cause a rise in diesel fuel prices. Consequently, forecasts show low-carbon heavy-duty trucks will become more economically competitive compared to their diesel counterparts by **2035**.[16]

Support for CapEx and significant OpEx will still be necessary by 2030. But the anticipated decrease in vehicle production costs and the decline in hydrogen refueling prices indicate that full industrialization will only require moderate support.

Expectations are for technological advancements and economies of scale to contribute to cost reductions in producing hydrogen-electric trucks, making them more financially viable without extensive financial assistance.

Focus: hydrogen refueling infrastructure

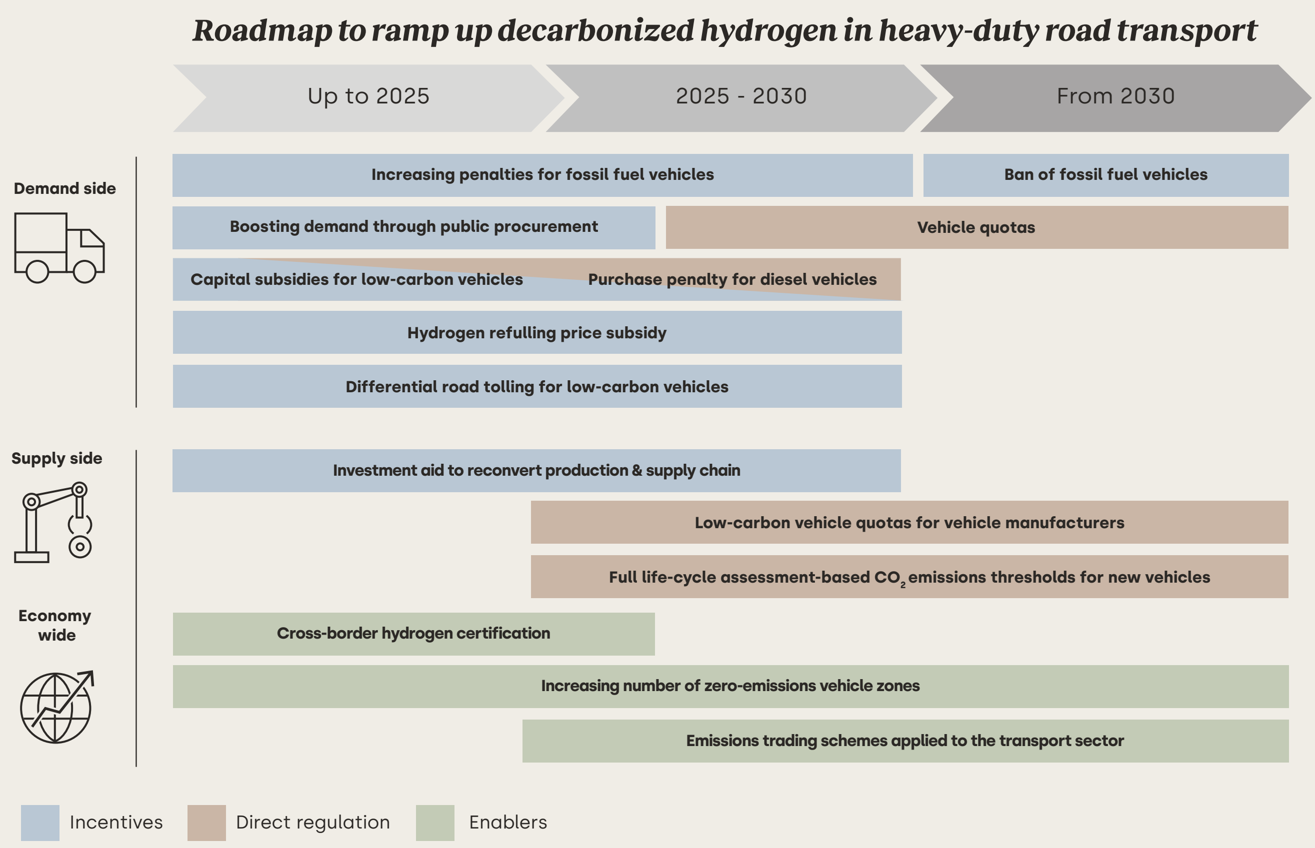
In the early stage, the vehicle offer develops through the establishment of groups of refueling stations, creating the first ecosystems for hydrogen mobility, bringing together users, service stations and maintenance centers. It requires CapEX funding for hydrogen refueling stations to enable the projects to be launched.

In the industrial phase, the infrastructure follows the demand growth for trucks with policies supporting the deployment of long-distance networks of refueling stations. A fully integrated policy framework with credits scheme is required to incentivize the build of these stations and overcome the underuse in the early years. OpEx support in the form of electricity cost waiver is also very important due to the significant amount of electricity needed to run the station with the compressor. The framework can be completed with incentives (mandates) to deploy further the networks. For instance, the new European regulation for the deployment of alternative fuels infrastructure (AFIR) sets mandatory targets for hydrogen refueling infrastructure for the road sector. The regulation seeks to develop a sufficient refueling infrastructure across the EU to facilitate refueling for consumers. It takes the form of the TEN-T core network which will deploy a station in all urban nodes and every 200 kms.

In the longer term, the refueling infrastructure should be sufficiently dense network to allow viable hydrogen vehicles business models, but only if the appropriate coordination and policy measures have been introduction early in this decade.

Figure 5 shows the policy roadmap supporting the transition to low-carbon hydrogen in heavy-duty road transport.

Figure 5: Policy roadmap supporting the transition to low-carbon hydrogen in heavy-duty road transport



Note

The policy roadmap presented in this section is neither an exhaustive list nor a complete package that requires implementation to transition successfully. The precise mix of policies will vary from country to country depending on existing policy targets and fiscal arrangements.

In Figure 6, fuel-cell vehicle owners represent the demand side and vehicle manufacturers the supply side. We discuss policies to support clean fuel supply in the chapter on refineries.

Lowering the TCO to accelerate market creation

Heavy-duty fuel-cell vehicle development acceleration ties closely to achieving an acceptable TCO for end-users. As of 2022, the TCO for fuel-cell trucks remained comparatively high, twice as expensive as diesel models.[17] This economic disparity primarily stems from higher vehicle CapEx and fuel prices. Estimates anticipate a decrease in the cost of fuel-cell trucks and the halving of the price of hydrogen. In contrast, projections show the cost of diesel trucks will rise due to carbon taxes and the implementation of new emissions **standards**.[18]

For instance, consider a fuel-cell truck driving 80,000 km/year. The annual fuel expenses for this vehicle, with a hydrogen consumption of 6 kgH_2/100 km, would amount to EUR €43,000/year.

In contrast, an equivalent diesel model consuming 25 l/100 km with a diesel price of EUR €1.40/l incurs €28,000/year in fuel costs. Notably, the refueling cost, which constitutes approximately half of the TCO, currently stands at twice the expected level of EUR €5/kgH_2 projected over the next decade.[19]

This section examines the impact of various policy measures on the TCO of fuel-cell trucks. Figure 7 illustrates the anticipated TCO ranges for fuel-cell and diesel trucks – the range represents values between rigid (lower bound) and articulated (upper bound) trucks – across the three deployment phases of the market. The **analysis**[20] assumes constant market development supported by incentive policy frameworks and excludes OpEx factors such as driver costs and insurance.

Figure 6:TCO differences between fuel-cell and diesel trucks in Europe over three main market development phases

Figure 7 and Figure 8 demonstrate the substantial impact of a significant CapEx subsidy in driving the initial deployment phase of heavy-duty road transport.

This form of support plays a crucial role in stimulating the adoption of fuel-cell trucks. However, as the industry progresses, estimates anticipate that the reliance on CapEx subsidies will decrease by up to 80% by the decade's end.

Figure 7: Policy support enabling the closing of the economic gap for fuel-cell articulated vehicles in the deployment phase (2025)

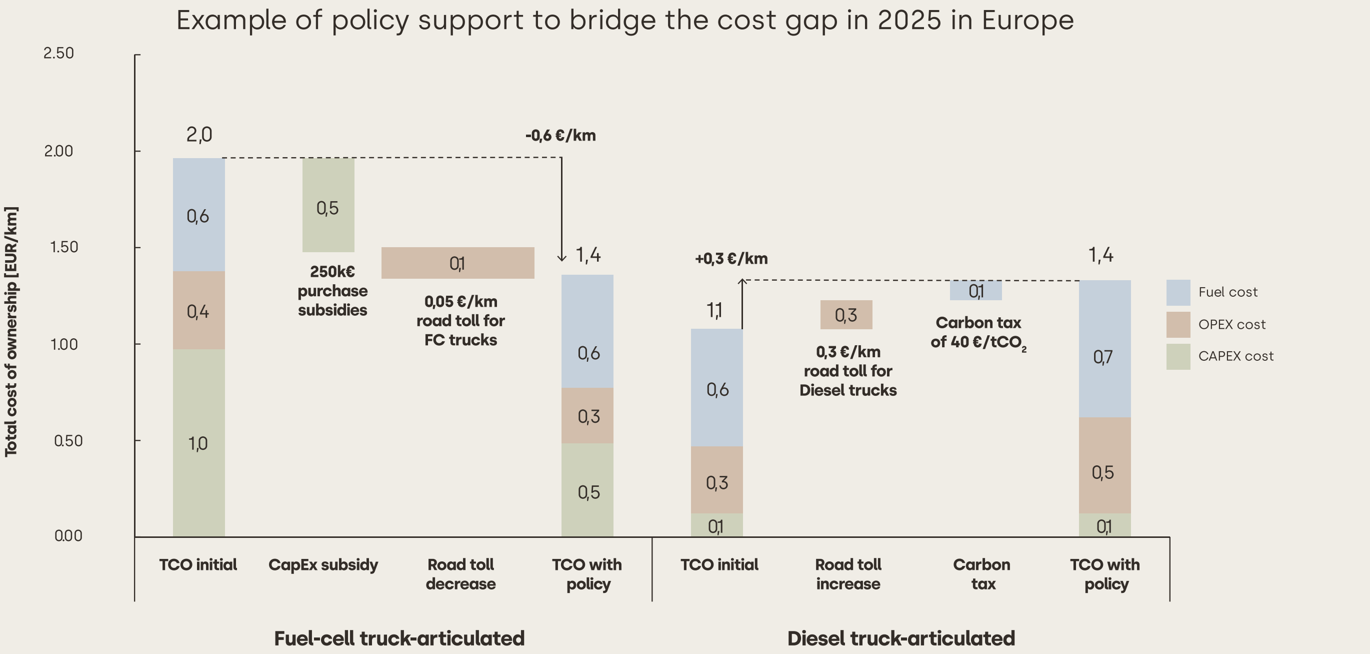
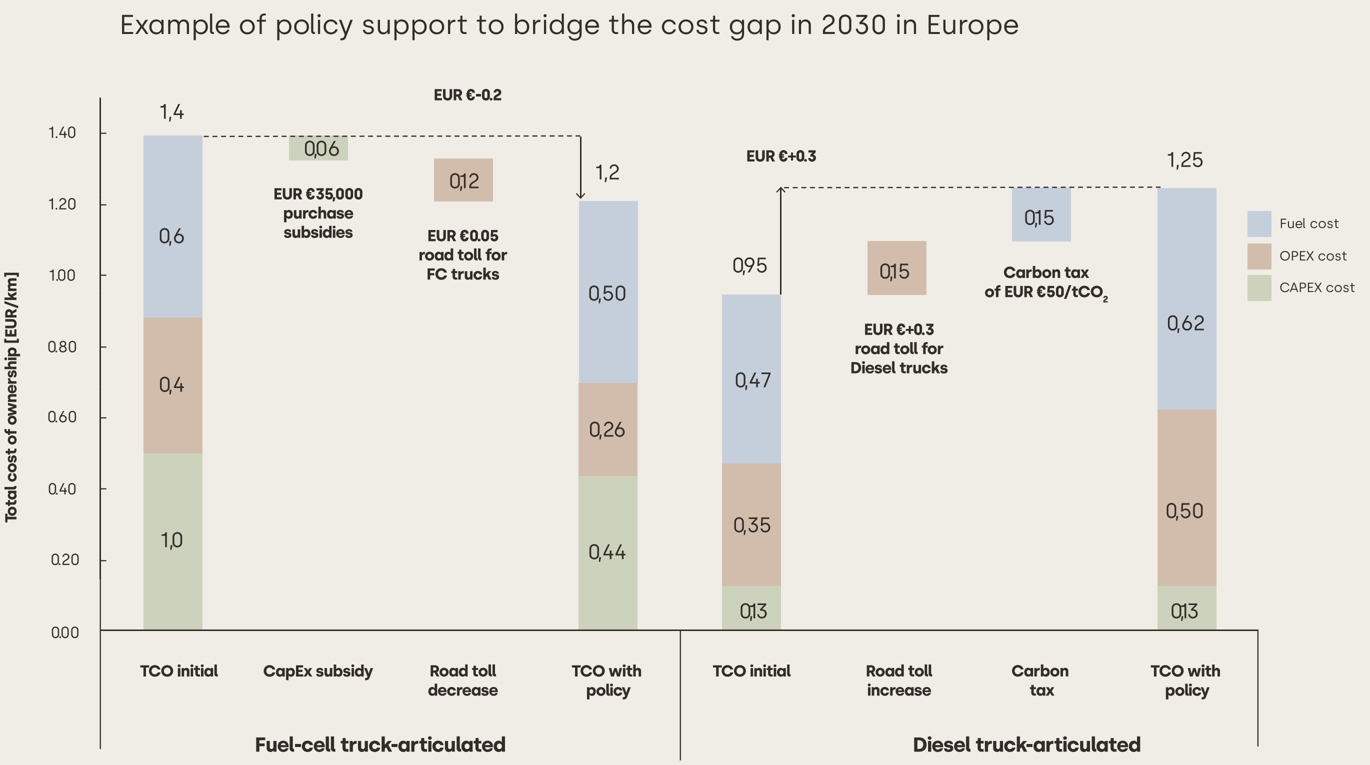


Figure 8: Policy support enabling the closing of the economic gap for fuel-cell articulated vehicles in the industrial scale-up phase (2030)



In conclusion, to facilitate the development of the hydrogen fuel-cell truck market in the near- and mid-term, it is crucial to implement targeted policy actions aimed at cost reductions throughout the value chain.

The following instruments must be considered:

- CapEx subsidies: Implement subsidies to assist in purchasing hydrogen fuel-cell trucks, encouraging their adoption by fleet operators and reducing the upfront costs associated with these vehicles.
- OpEx support: Introduce differential road tolls granting lower tolls or exemptions to hydrogen fuel-cell trucks, incentivizing their use, and providing financial relief to operators.
- Cost of carbon: Establish a carbon-related measures where carbon markets do not exist, starting at a minimum of EUR €30/ton, which increases gradually over time to reach the same level as trading schemes. This mechanism internalizes the environmental costs associated with carbon emissions, creating an economic incentive for adopting low-carbon alternatives like fuel-cell trucks.

With the industry's scaling, the need for ongoing CapEx support should decrease. As the production of fuel-cell trucks and hydrogen refueling infrastructure expands, economies of scale will drive down costs, reducing the requirement for ongoing financial assistance.

By carefully implementing these policy measures, the industry can foster the growth and adoption of hydrogen fuel-cell trucks. The initial phase aims to overcome cost barriers and incentivize early adoption. In contrast, the subsequent full industrialization phase capitalizes on scaling effects and reduced costs, making fuel-cell trucks more economically viable without extensive ongoing support.

Steel *production*

03.

03. Steel *production*

Currently, 70% of global steel production relies on a combination of blast furnace (BF) and basic oxygen furnace (BOF) **processes.**[21] These conventional methods use iron ore as a feedstock and reduce it with carbon to create steel. The process requires coal or coke as a feedstock to generate high temperatures in the blast furnace, resulting in significant CO_2 emissions. The steel industry accounts for around 8% of total energy sector emissions (10% if indirection emissions from electricity generation are included), or around 2.8 Gt of CO_2 emissions per **year.**[22] Additionally, a significant portion of coal-fired blast furnaces will reach the end of their operating lifetime by 2030, resulting in the need for substantial **reinvestment.**[23]

With the growth foreseen in steel demand, emissions from steel production will grow. Emerging economies alone, in fact, will require an additional capacity of at least 150 million tons of steel each year to transition to a net-zero future and support industries like the construction industry, infrastructure development, renewable energy and the automotive sector. Expanding renewable energy generation will require over 74 million tons of **steel.**[24]

Increasing demand for steel and the need to modernize steelmaking facilities present unprecedented opportunities to adopt low-carbon steelmaking technologies. The future higher costs of conventional steelmaking processes due to carbon taxes (especially in Europe with the expected decline of CO_2-free **allowances**),[25] the potential for new revenue streams through green steel premiums[26] and the imperative to decarbonize the industry to meet net-zero targets reinforce the business case for these low-carbon steelmaking technologies.

Steel producers have three pathways to decarbonize their production:

- Recycling scrap steel in an electric arc furnace (EAF), although this method is limited to less than 25% of new steel **demand**;[27]
- Coupling conventional fossil-based production with carbon capture and storage (CCS);
- Using low-carbon hydrogen for direct reduced iron[28] (DRI) production or electrolytic steelmaking processes.

Current global steel production amounts to 2 billion tons per year, with around 28% produced by EAF and the rest by fossil-fueled blast **furnaces**.[29] Only a few companies have committed to achieving net-zero emissions by 2030 by transitioning their steel production to green alternatives using hydrogen-based DRI, EAF or CCS technologies. The higher cost of green steel using hydrogen-based DRI remains a significant barrier preventing widespread adoption.

Low-carbon steel is 20% to 40% more expensive than steel produced from fossil fuels. The substantial upfront investment required to replace blast furnaces with DRI plants (representing 10% to 20% of green steel's levelized production cost) and the high operational expenditures influence this cost gap, with energy procurement accounting for a significant portion (30% to 40%) of the steel production cost, including the supply of clean hydrogen.

Supportive policies across the steelmaking value chain

A successful transition to low-carbon steel calls for comprehensive support along the value chain. It encompasses specific policies targeting steelmakers and end-use markets, such as buildings, automotive and white goods.

Steel production

To facilitate the transition to low-carbon steelmaking, producers need supportive measures on the supply side that help offset the higher costs associated with producing low-carbon steel. The main challenge is converting existing processes to hydrogen-based direct reduced iron (H_2-DRI) plants. Several measures can help overcome this obstacle:

- OpEx-oriented compensation schemes to provide long-term support for operations, easing the financial burden associated with low-carbon steel production;
- Mechanisms such as CfD or CCfD to bridge the full cost gap by reducing overall costs and incentivizing the adoption of low-carbon technologies;
- Measures to mitigate the cost of electricity supply in projects by using electrolytic hydrogen and ensuring affordable and sustainable energy sources.

In addition, policies must ensure the harmonization of the cost of carbon for internationalized markets. In Europe, the upcoming introduction of the Carbon Border Adjustment Mechanism (CBAM) aims to safeguard the steel industry through anti-leakage mechanisms applied on EU importers of specific non-EU products such as electricity, cement, aluminum, fertilizer and iron and steel products.[30] Given the highly globalized nature of the steel market, it is important to recognize the products' lower-carbon content. Implementing specific quotas for the use of low-carbon energy feedstocks can further support the production of green steel.

End-use markets

In end-use markets, there has been a notable shift in market dynamics, with a growing willingness to accept higher green steel prices in recognition of its decarbonization potential. This trend manifests in the automotive industry, which is responsible for 12% of global steel **use.**[31]

Importantly, end-users are signaling their commitment to green steel, as more than ten automotive companies have signed a Memorandum of Understanding setting an ambitious pathway to using 100% green steel by **2050.**[32] This demonstrates a rising demand for sustainable materials, as manufacturers and consumers promote the use of green steel to align with their sustainability goals and climate targets.

Example: Green steel's commitments in the automotive sector

Volvo has taken a significant step towards sustainable steel production by committing to exclusively using green steel in its manufacturing processes by 2050. This commitment is part of the industry-driven SteelZero initiative, which aims to promote the adoption of environmentally friendly steel production methods.

Similarly, Mercedes Benz has partnered with SSAB, a steel company, to procure green steel from the HYBRIT project in Sweden. This collaboration showcases their dedication to sourcing sustainable materials for their vehicles. Ford has pledged to incorporate 10% of green steel into its operations in line with the World Economic Forum's First Movers Coalition by 2030. This coalition, launched at the United Nations Climate Change Conference (COP26) in 2021, brings together industry leaders committed to taking early action to tackle climate change.

Moreover, the H2GreenSteel project, located in Boden, Sweden, has garnered support from shareholders including customers from the automotive sector. With shareholders investing in the project, H2GreenSteel has secured contracts to produce 1.5 million metric tons of steel annually. This demonstrates industry players' growing demand for and interest in sustainable steel solutions.

The willingness to pay a premium for green steel differs across markets and calls for tailored policy support to facilitate its adoption. To encourage the use of low-carbon steel, end-use markets aim to minimize steel price sensitivity and avoid cost increases in their final products. Several incentives can effectively stimulate the adoption of low-carbon steel:

- Taxation schemes that provide favorable treatment for low-carbon steel production and penalize high-carbon alternatives or allow consumers to claim tax offsets for products using green steel;
- The gradual implementation of quotas, greenhouse gas (GHG) thresholds or carbon pricing that set limits on carbon-intensive steel and promote low-carbon alternatives;
- The establishment of standards for products made from low-carbon steel that increase demand and facilitate the trading of emissions credits in emissions trading schemes;
- Similarly, the progressive modification of standards in steel applications, such as evolutions in building codes to incorporate requirements for using low-carbon steel, which ensures its integration into construction projects and infrastructure development.

Such policy measures aim to create a conducive environment for the widespread adoption of low-carbon steel by supporting its market growth and facilitating the transition to more sustainable production practices.

Economy-wide support

Two key measures can effectively boost volume demand for low-carbon steel and facilitate its widespread adoption:

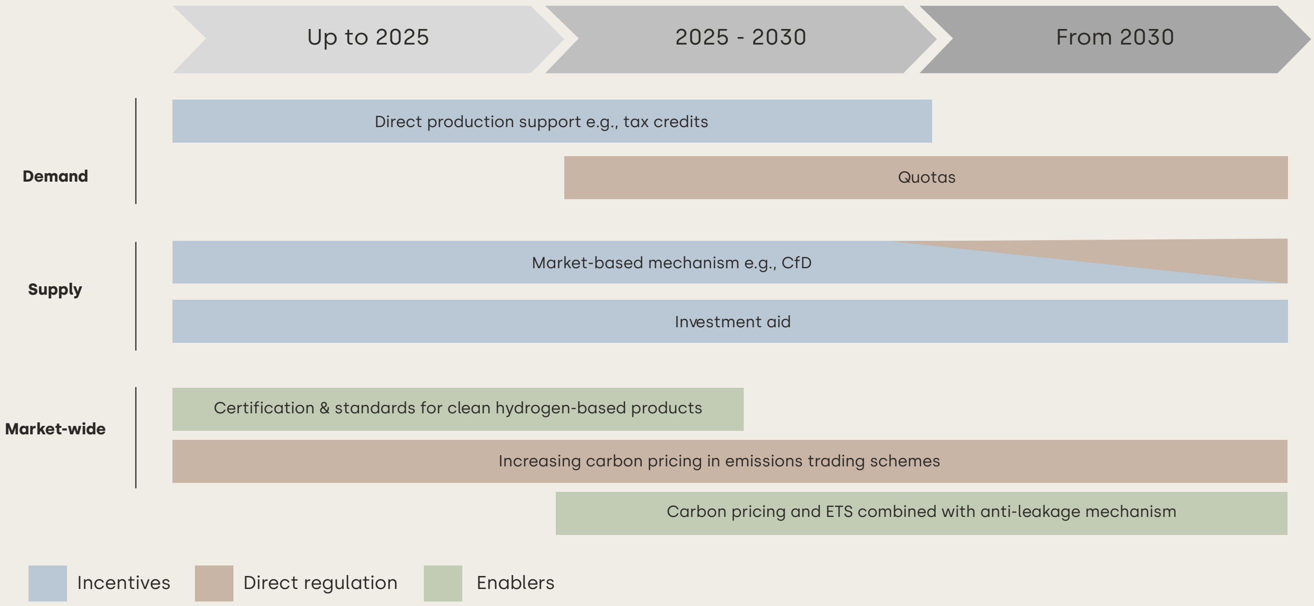
- Implementing a comprehensive carbon tax across the value chain: A carbon tax applied at various stages of steel production, from raw material extraction to final product manufacturing, can incentivize the transition to low-carbon steel by internalizing the environmental costs associated with high-carbon production methods. This would make low-carbon steel cost-competitive and encourage steel producers and end-use markets to prioritize its use.

- Promoting the development of international low-carbon steel standards and certifications: Establishing globally recognized standards and certifications specifically for low-carbon steel would facilitate trade and market acceptance. These standards would value the lower carbon footprint of low-carbon steel, providing assurance to end-use markets and consumers. By harmonizing requirements and promoting transparency, these standards would enable easier cross-border trade of low-carbon steel and foster a global market for sustainable steel products, including with end-customers (e.g., automotive, residential buildings).

By understanding and addressing the needs of the green steel market's demand and supply sides, countries can develop tailored policy approaches that align with their specific circumstances and priorities. This flexible approach allows for optimal policy measures that effectively promote the transition to low-carbon steel while considering each country's broader economic, social and environmental objectives. The question about who will bear the consequences of the cost reduction measures is crucial to the successful implementation of these policies. It requires further examination.

Figure 9 presents a comprehensive set of policy recommendations aimed at stimulating and supporting the growth of the green steel market.

Figure 9: Policy roadmap to support the transition to hydrogen use in steel manufacturing



Note

The policy roadmap presented above guides the transition to low-carbon steel but does not claim to be an exhaustive list or a one-size-fits- all solution. In the graph, the demand side refers to steel end-user markets, encompassing sectors such as construction, automotive and appliances that use steel in their products. The supply side represents steel production, including steel producers and the associated infrastructure and technologies.

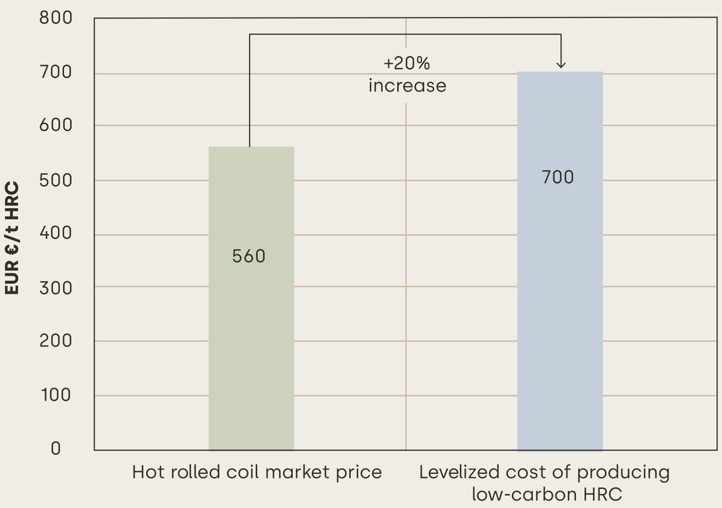
Policy impact on the cost gap between green steel production and market prices

Producing steel via hydrogen currently incurs significantly higher costs than prevailing market prices. To analyze the cost dynamics, we used a Levelized Cost Model to show how a European low-carbon hot rolled coil (HRC) project works. HRC is a primary steel product commonly used in applications such as automobile parts (such as frames and wheel rims), construction materials (like I-beams) and railroad equipment (such as tracks and railcar components).

Using a steel DRI technology that uses a blend of natural gas (40%) and hydrogen (60% in volume) as a reducing agent to convert iron ore would reduce CO2 emissions by 60% to 70% compared to replace a traditional coal-fueled blast furnace.

The project is set to begin using 100% natural gas in 2025 and gradually transition to the target mix of natural gas and hydrogen by 2030. Over the lifetime of the production asset, estimates show that the levelized production cost of the low-carbon HRC is 20% higher than conventional HRC.

Figure 10: Comparison between HRC levelized cost of production and its market price



(Real) project characteristics
- DR Plant using 30% H2 (energy), 60% H_2 (volume), 100% DRI to produce HRC
- 60-70% emissions avoidance compared to the conventional route

Main assumptions - LCOP
- Production capacity: ~2 Mt/y
- CapEx: EUR €1-1.5 billion compared to ~EUR €500 million for conventional route
- OpEx: EUR €450-500/t
- Weighted average cost of capital: :6%-7%

HRC market price
- Average 2018 - STHRE00 - Flat Products/
- Platts North European HRC / N. Europe domestic EXW Ruhr €/t

This cost difference arises from the higher capital expenditure of the DRI plant and the higher cost of energy (hydrogen and natural gas compared to coal) and feedstock (DRI pellets). Factors such as the additional infrastructure required, the availability and cost of hydrogen and the scale of production contribute to the higher cost of low-carbon steel than conventional steel produced using fossil fuels.

Despite the substantial initial investment cost of establishing a DRI plant, amounting to approximately EUR €1-1.5 billion in this case, CapEx constitutes only 8% of the total levelized cost of production. In contrast, the energy requirements, including hydrogen, account for 30% of the production cost (hydrogen amounts to 10% to 15% in this project).

Figure 11: Structure of steelmaking cost

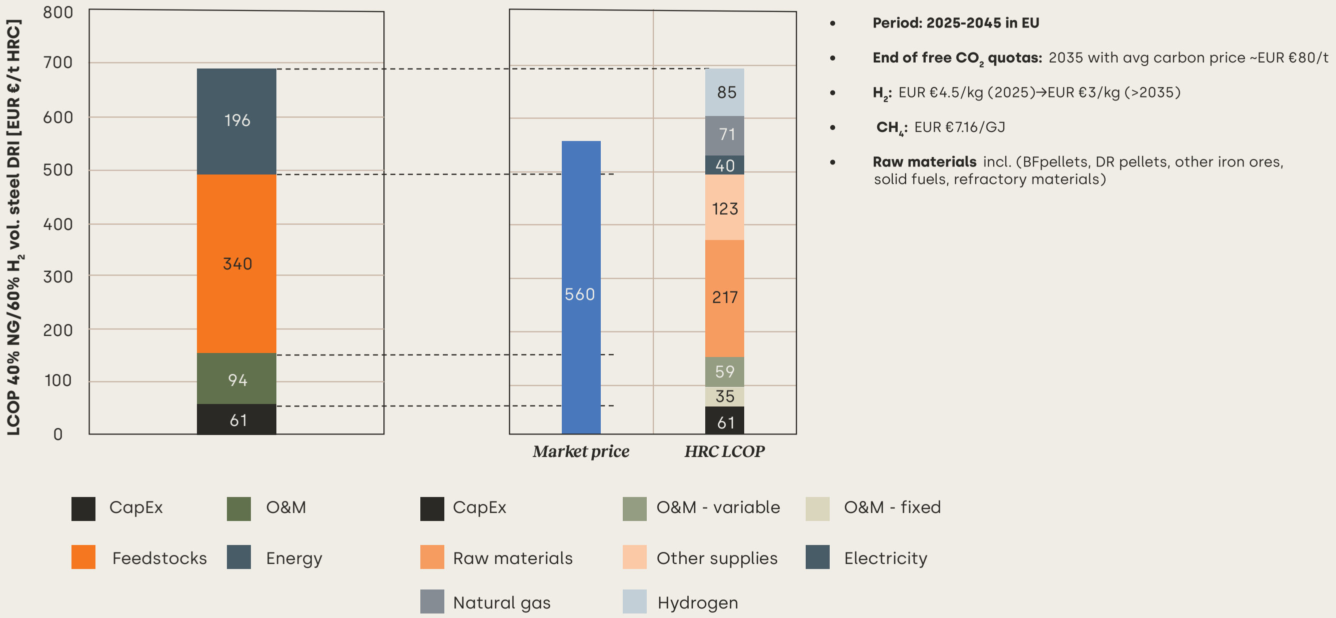


Figure 11 shows that OpEx represents over 90% of steel production costs. This underscores the significance of mechanisms that support OpEx, such as CfDs or CCfDs, as they offer promising avenues for cost optimization.

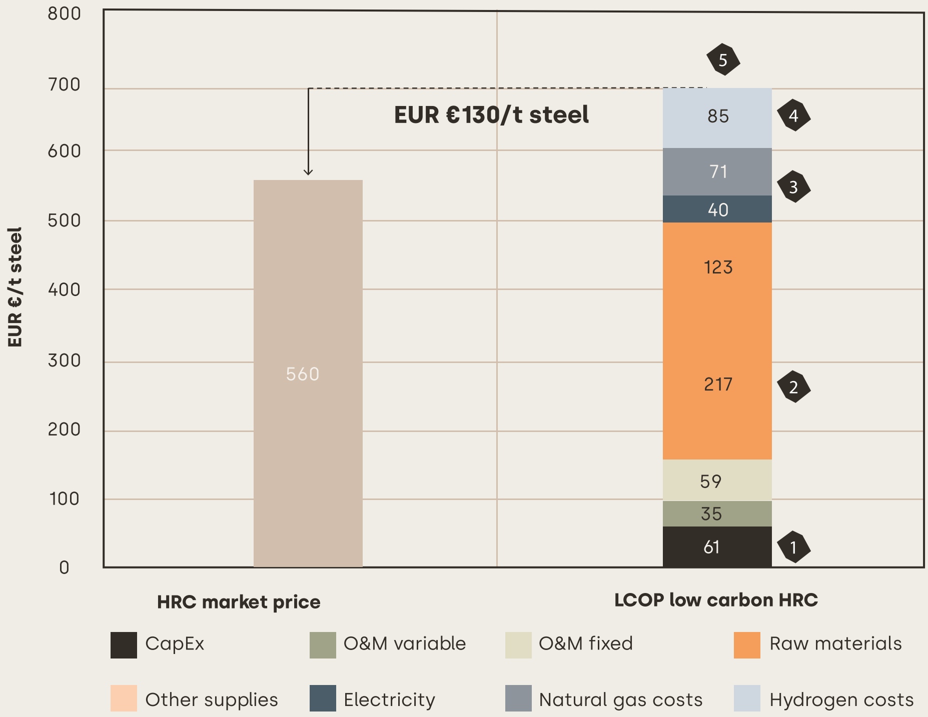
Despite the various policy instruments that can be implemented to reduce the cost of green steel, its potential decrease is limited to half of the total cost gap. This is because the costs of iron feedstocks are mainly driven by electricity and natural gas prices. Hence, the current power and commodity market conditions make it challenging to lower these costs. But, it is still possible to achieve significant reductions by adopting DRI technology and cost-effective hydrogen supplies.

Figures 12 and 13 explore potential cost reductions. They show that even a substantial decrease in the cost of hydrogen feedstock, from EUR €4.5 to EUR €2/kg, achieved through mechanisms like CfD, would only narrow the cost gap by 30% (equivalent to EUR €40/ton of steel).

Direct subsidies, such as CapEx support, can assist early adopters in their transition to green steel production. However, these subsidies alone cannot achieve cost parity with conventional alternatives. For instance, a EUR €300 million subsidy would merely reduce the cost gap by 15% (approximately EUR €20/ton of steel).

Despite an initial cost gap of €130/ton steel, this illustrative example demonstrates that the maximum cost reduction achievable with the measures described above is only of 50%, meaning roughly €70/ton steel.

Figure 12: Potential of production cost reductions



			Max reduction
1	CAPEX subsidy	Subsidizing 30% of the CapEx (EUR €1 -1.5 Billion) only decrease the cast gap by 15%	**EUR €20/ton**
2	Feedstock cost	The DRI pellets cost is likely to increase with the development of steel DRI projects	**EUR €0/ton**
3	Natural gas and electricty prices	Natural gas and electricity prices are expected to remain higher than before COVID-19 pandemic and the Ukraine crisis	**EUR €0/ton**
4	Hydrogen cost	Decreasing the cost of hydrogen from EUR €4.5 /kg to EUR €2/kg (through a CfD for example) would decrease the cost gap by ~30%	**EUR €40/ton**
5	Investment de-risking	Decreasing the WACC by 50% only reduces the tariff gap by EUR €10/tHRC	**EUR €10/ton**
			EUR €70/ton (cost gap reduction = -50%)

Carbon-related instruments promise to close the gap.

While these findings underscore the challenges of cost reduction in green steel production, they also emphasize the importance of a comprehensive approach to reducing costs. 'It involves optimizing energy supply costs and exploring supportive mechanisms beyond direct subsidies.

However, internalizing carbon costs can provide a viable solution to bridge the cost gap in green steel production.

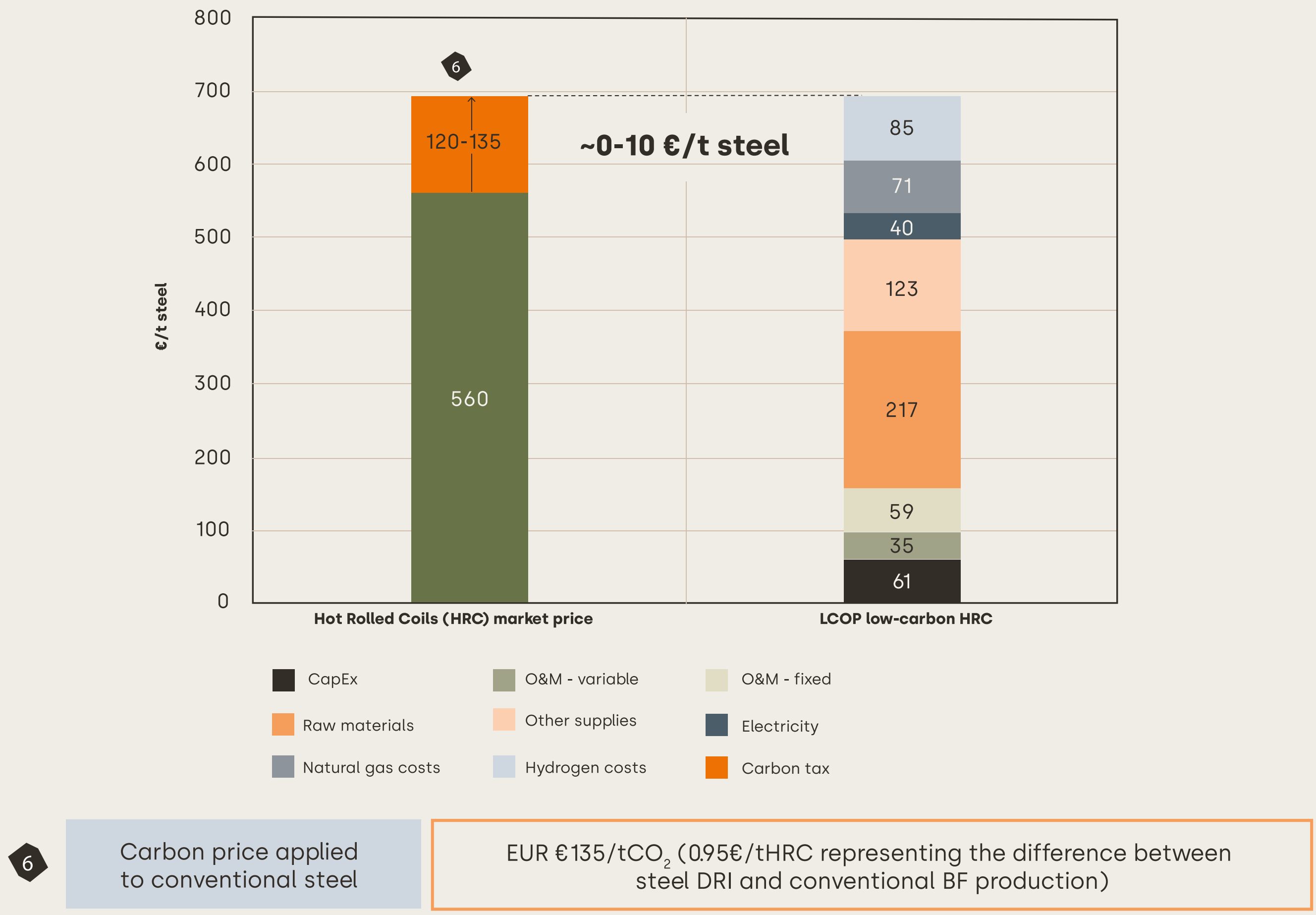
Aligning the price of conventional steel with that of decarbonized steel is raising questions regarding the capacity of steel markets to absorb the green premium. A key stakeholder in the steel market, the automotive industry, has recognized the importance of reducing carbon emissions and promoting sustainability and is willing to embrace green steel despite the potential price differential.

The specific illustrative project outlined above achieves a breakeven point upon implementing a carbon tax of EUR €135/tCO2, resulting in both conventional steel (including natural gas) and lower-carbon steel priced just below EUR €700/ton of steel.

By incorporating the carbon cost into the equation, the steel price can more accurately reflect the environmental impact of its production. A carbon tax ensures accounting for the costs associated with greenhouse gas emissions, creating a level playing field between conventional and lower-carbon steel.

This willingness demonstrates a commitment to environmental responsibility and can be further encouraged through policy support.

Figure 13: Impact of carbon pricing on market prices



Focus: carbon contracts for difference for green steel

How do carbon contracts for difference (CCfD) mechanisms work?

CCfDs operate through contracts between two parties, with the beneficiary receiving compensation for the difference between the effective CO_2 price and the mitigation costs associated with a breakthrough technology, known as the 'strike price'. Over time, as decarbonization efforts progress and CO_2 prices increase, the CCfD subsidy gradually decreases.

In the case of a two-ways CCfD, one party reimburses the other party based on the difference between the strike price and the actual CO_2 market price. If the latter is lower than the strike price, the government pays the difference to the investor, similar to a conventional subsidy. Conversely, if the CO_2 price is higher, private companies reimburse the government for the excess amount. This process applies on a yearly basis.

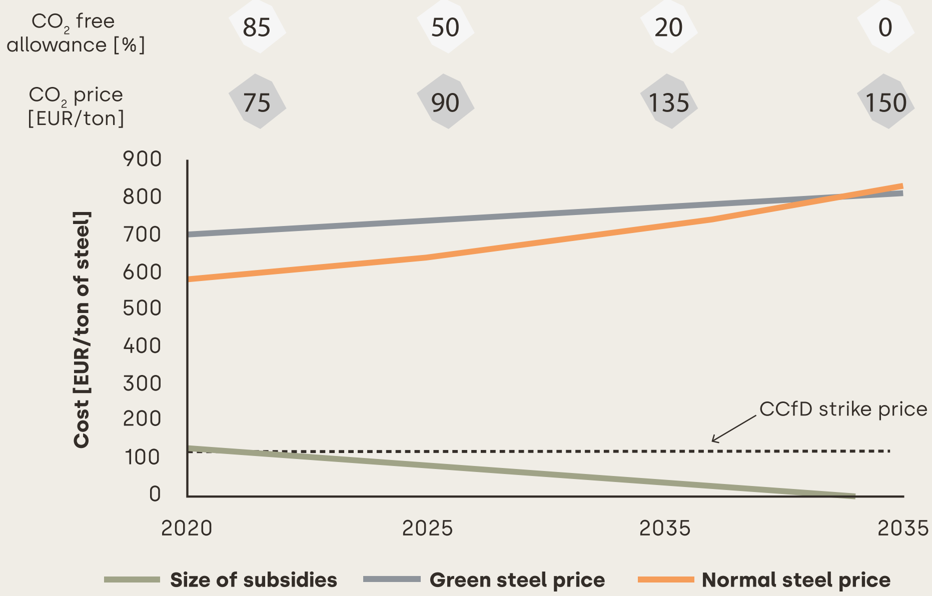
The specific strike price for CCfDs varies depending on the application, which requires a consensus between public and private sector actors to establish a consistent methodology for application-specific benchmarks. In Europe, CCfDs work with the EU Emissions Trading System (ETS) carbon price by compensating for the additional production costs of a CO_2-efficient breakthrough technology compared to conventional, greenhouse gas-intensive alternatives.

CCfDs and the green steel market

To illustrate CCfDs applied to the steel DRI example above, consider a European project where the CO_2-free allowance quota gradually decreases to zero by 2035, as outlined in the Fit for 55 package. In this example, the CO_2 price rises from EUR €75/tCO_2 to EUR €150/tCO_2 by 2035. The breakeven point for the project falls between 2030 and 2035 when the CO_2 price reaches EUR €145/tCO_2.

By implementing CCfDs, the steel industry can bridge the cost gap between traditional production methods and low-carbon alternatives. These mechanisms incentivize the adoption of CO_2 -efficient technologies by compensating for additional costs, thereby encouraging the transition to greener steel production. As CO_2 prices continue to rise, CCfDs can play a vital role in supporting the economic viability and competitiveness of breakthrough technologies in the green steel market.

Figure 14: Illustration of a CCfD mechanism applied to the green steel market



In conclusion, increasing the cost of carbon (e.g., through a carbon tax) at the appropriate level is critical to driving the transition to greener steel production. This measure aligns economic incentives with environmental goals, fostering the adoption of sustainable practices and technologies.

Ammonia

04.

04. Ammonia

Ammonia is one of the highest-volume chemicals globally, with annual production reaching approximately 185 million metric tons (Mt). Companies producing synthetic nitrogen fertilizer use the majority, about 70%, of this ammonia. The remaining portion serves diverse industrial applications, including fertilizers, plastics, explosives and synthetic fibers.

In a decarbonized world, fertilizer production and industrial demand will likely grow steadily in line with population growth. Therefore, the use of ammonia will be essential to meet the needs of the expanding global population, requiring an additional 45 Mt for fertilizer use by **2050.**[33]

In the future, estimates also show ammonia will become a crucial energy carrier for sectors like shipping, power generation and hydrogen transportation. These applications will likely experience significant growth as part of global efforts to decarbonize the world.

→ **Shipping industry.** Ammonia holds the potential to play a pivotal role in the decarbonization of the shipping sector. It can help reduce greenhouse gas emissions and improve air quality by serving as a cleaner alternative to fossil fuels, while enabling the long-distance transportation of clean energy worldwide. Approximately 295 to 670 Mt of ammonia could power 55% to 90% of long-distance shipping fleets annually, replacing 5 to 13 exajoules (EJ) of bunker **fuel.**[34]

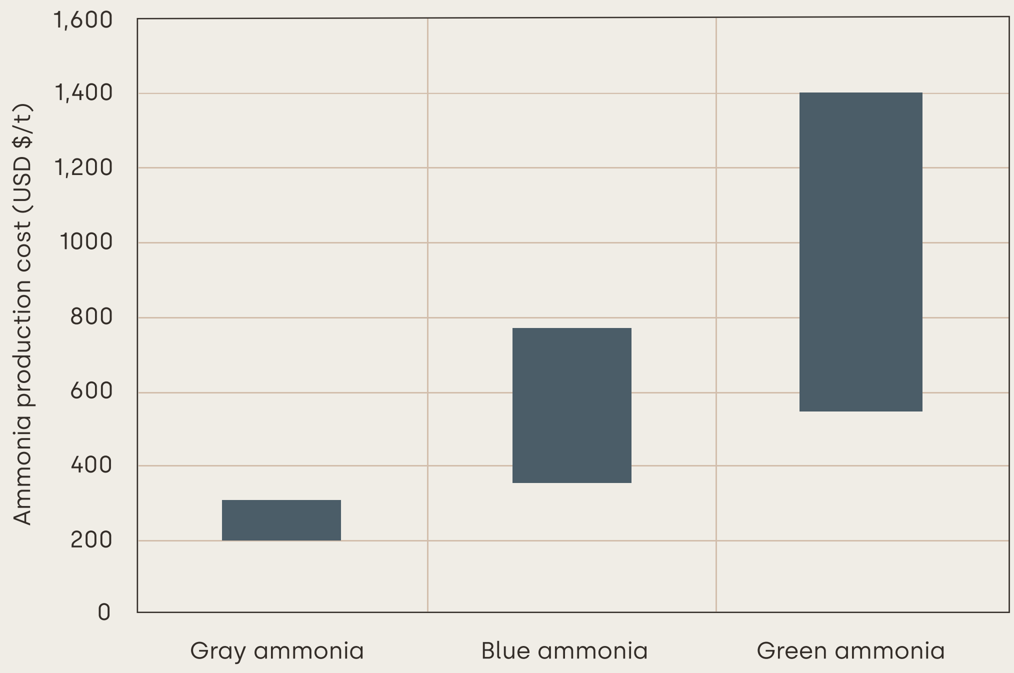
→ **Power generation.** Ammonia offers a renewable energy solution for power generation, particularly in regions with limited land resources, potentially accounting for 35 to 105 Mt of production. It could play a vital role in decarbonizing thermal coal power plants in countries like Japan and South Korea, possibly becoming a necessity for achieving 100% decarbonization.

→ **Hydrogen carrier.** Ammonia shows promise as a hydrogen carrier, allowing for efficient transport and storage of hydrogen. Its high energy density and ease of handling make it a viable option for its distribution, supporting applications in power generation, transportation and industry. Using ammonia as a hydrogen carrier could potentially create significant demand, with up to 10% of global hydrogen (roughly 110 Mt) being transported as ammonia by 2050 due to its cost advantages in shipping.

Ammonia is synthetized from nitrogen and hydrogen. In 2022, ammonia production alone accounted for approximately 60% of the 53 Mt of hydrogen used in **industry.**[35] Because hydrogen production mainly takes place using fossil fuels, the production process, called the Haber-Bosch method, results in significant CO_2 emissions, posing environmental challenges – it contributes to approximately 1% of global GHG emissions. Hence, producing clean ammonia relies exclusively on the decarbonization of hydrogen production.

Green ammonia is more expensive than conventional ammonia, mainly due to high low-carbon hydrogen production costs. Currently, as shown in Figure 15, the production costs of green ammonia range from USD $500 to USD $1,500 per ton, while blue[36] ammonia costs range from USD $350 to USD $700/t. Compared to conventional gray ammonia, historically priced as low as USD $250/t, the green ammonia figures are not competitive. However, it's worth noting that green ammonia can become cost competitive compared to traditional ammonia in a context of high uncertainties on commodity markets (e.g., with elevated gas prices in 2022, the cost of gray ammonia rose to USD $1,000 to USD $1,500/t).

Figure 15: Ammonia production costs for gray, blue and green ammonia



High costs also arise from challenges transitioning to new technologies in ammonia production. One major obstacle is the substantial capital investment required for industrial transformation, coupled with the long lifespan of existing ammonia plants, which can exceed 50 years. These plants often operate with low production margins, leading to resistance to switching to new technologies. Consequently, there is a preference for retrofitting existing assets with carbon capture, utilization and storage (CCUS) systems. Additionally, the current concentration of ammonia production facilities in regions with abundant and affordable coal and gas resources poses a barrier to technology transitions. Unfortunately, these two aspects – existing plants and renewable energy availability – do not always align, further complicating the cost reduction of green ammonia.

The lack of recognition, standardization, and certification of green ammonia does not help cost reductions. Certification would distinguish ammonia by the source of production and carbon intensity and enable the creation of a specific green ammonia market.

On top of that, clear market signals are missing, although fostering large-scale investments in the ammonia industry is crucial. Industrial demand for low-carbon ammonia is currently limited. This includes both existing users and emerging applications like shipping. The absence of clear incentives for industrial transformation and the lack of standards for downstream players discourages them from entering into long-term offtake agreements. The lack of offtake, in turn, hampers investment decisions on the supply side. Without the assurance of market demand, industry players face uncertainties that impede their willingness to invest significantly in low-carbon ammonia production.

The cost of green ammonia is a particularly significant issue due to its potential impact on fertilizer prices, affecting the cost of food worldwide. If producers were to directly pass on the increased production costs of fertilizers, it could significantly impact crop prices. Consequently, the higher costs of near-zero emissions ammonia could hinder its widespread adoption. The transfer of costs will impact the agricultural sector and the broader industry. Producers that bear the additional costs of decarbonization and attempt to pass them on to consumers may face reduced competitiveness compared to those that do not.

Supportive policies for the different applications of green ammonia

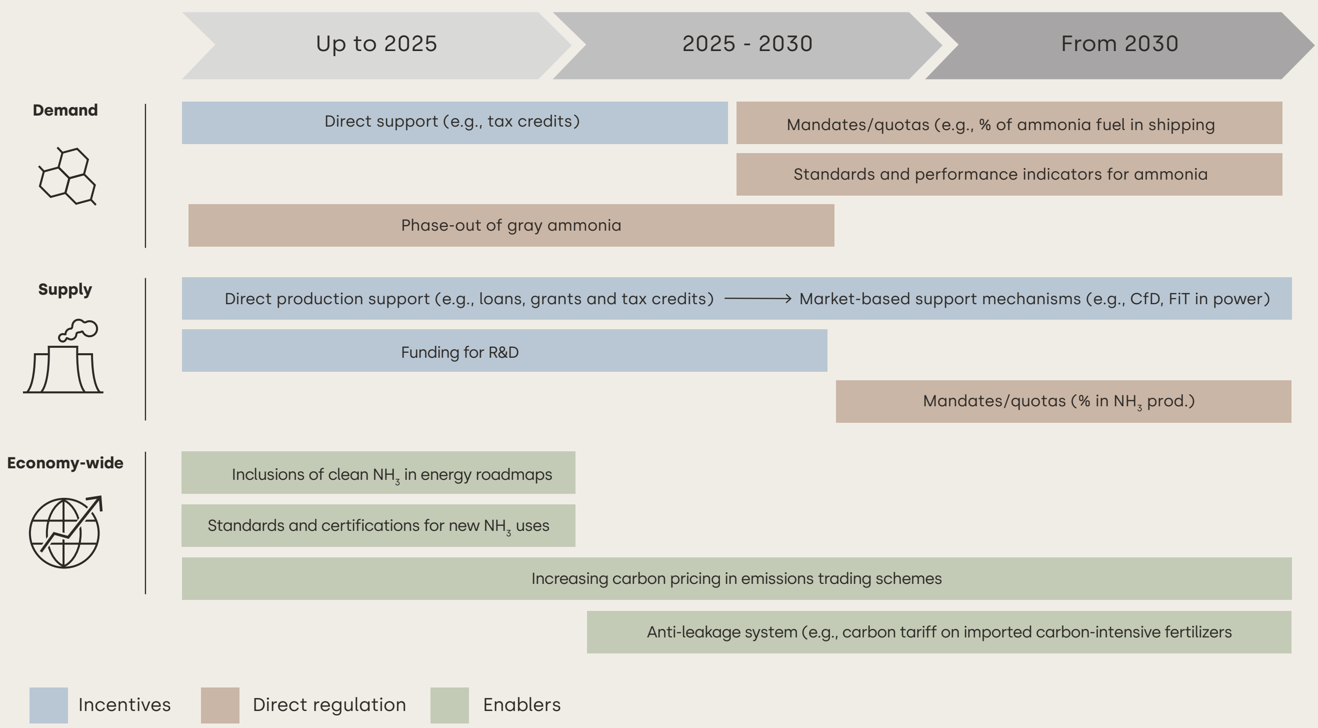
It is crucial to implement appropriate policy and financing mechanisms to support the transition to lower-emissions ammonia production methods. These measures will help mitigate the potential price increase resulting from high ammonia production costs, ensuring they do not disproportionately affect developing countries and vulnerable communities.

Policymakers, industry leaders and financial institutions are crucial in driving the transition to a net-zero emissions ammonia economy. This requires a comprehensive and consistent policy framework encompassing demand and supply measures supported by enabling regulations.

- It is possible to gradually stimulate demand for clean hydrogen and green ammonia in various sectors to transition from conventional to low-emissions ammonia. Until 2025, the focus is on developing clean energy roadmaps to encourage the adoption of green ammonia. From 2025 to 2030, mandates, quotas or preferential market conditions will provide specific targets for ammonia. Beyond 2030, as the market grows, there will be opportunities to restrict or prohibit the use of conventional fossil-based ammonia;
- The adequate scale-up of supply – building production assets, infrastructure and manufacturing capacity – will require mobilizing financial instruments such as carbon contracts for difference, loans, grants and tax credits. Policies should also ensure the availability of critical resources and sustainable feedstocks;
- Policymakers should consider the establishment of market-based mechanisms to overcome environmental costs. While their implementation may pose complexities due to a multi-stakeholder environment, the conditions for their operation should be met between 2025 and 2030 to ensure full effectiveness in the subsequent decade;
- Funding research and development efforts is necessary to accelerate the commercialization and cost competitiveness of the relevant technologies for green ammonia;
- In the next 2-3 years, regulations should also include standards and protocols for safe handling of ammonia. It must address health, safety, security, distribution and environmental concerns. Certification processes are also crucial to differentiate ammonia based on production source and carbon intensity, facilitating its use in new and conventional applications. Transparency and accountability provided by certification enable stakeholders to make informed decisions about the ammonia they use.

Figure 16 presents a comprehensive set of policy recommendations to stimulate and support the growth of the green ammonia market.

Figure 16: Policy roadmap to ramp up decarbonized hydrogen in ammonia production



The following sections provide key recommendations for the different uses of green ammonia.

Fertilizer industry

Governments should implement policies to mandate the adoption of clean ammonia as a primary source of nitrogen-based fertilizers. Such policies should aim to accelerate the uptake of near-zero-emissions ammonia in fertilizer production. Key measures include:

→ By 2025, the introduction of **mandates** requiring stable and increasing low-carbon ammonia content in fertilizer production stimulates demand for green ammonia. For instance, India's draft hydrogen strategy sets a minimum requirement of 5% green ammonia production for the domestic fertilizer sector by 2023-24, with a target of 20% by **2027-28.**[37]

→ By 2030, introducing **market-based mechanisms** (MBMs) can effectively boost the competitiveness of environmentally friendly fertilizers. Mechanisms like CfDs or CCfDs can provide financial support and offset price differences. To ensure a level playing field and ensure the development of fertilizer production in regions with higher environmental standards, governments should implement carbon pricing in the fertilizer sector through strong international collaboration. Initially, policies could include granting free emissions allowances to those operating below a specified benchmark in a cap-and-trade system or implementing carbon border tariffs. Furthermore, the G7's efforts to establish a carbon club can further advance the goal of fostering cleaner fertilizer production on a global scale.

→ Beyond 2030, with the growing availability of competitive clean ammonia fertilizers, it becomes feasible to implement measures such as bans and **phase-out regulations** to eradicate the production of high-emissions fertilizers. These measures will significantly expedite the shift towards more sustainable and environmentally friendly fertilizer production methods.

Shipping industry

The shipping sector is actively working towards the approval of ammonia as a viable maritime fuel, aiming to establish a regulatory framework to accelerate its widespread adoption. The International Maritime Organization (IMO) plays a crucial role in driving the necessary policies to facilitate decarbonization in shipping. To achieve this goal, the IMO needs to enhance its mandate and capacity, to foster broad consensus and initiate harmonized actions across the industry. By taking these steps, the shipping sector can significantly reduce its carbon footprint and pave the way for a more sustainable future in maritime transportation. The critical milestones for the IMO include:

→ Before 2025, the establishment of robust **safety and handling regulations** should accompany the approval of green ammonia as a shipping fuel. It is necessary to address concerns regarding ammonia toxicity to ensure safe vessel usage. Developing proper procedures for refueling and storage is crucial to facilitate widespread adoption.

→ An ambitious **decarbonization roadmap** is needed, expanding on the IMO's 50% emissions reduction target by 2050. Setting a net-zero emissions goal for 2050, along with a significant milestone for 2030, will showcase the sector's strong commitment to decarbonize. Requiring a minimum use of 5% zero-emissions fuels in shipping by 2030, as recommended by influential coalitions, could create the necessary demand to accelerate decarbonization efforts.

→ Achieving the net-zero emissions target requires implementing and strengthening enforcement mechanisms for technical efficiency **standards** to reduce shipping pollution, including the Energy Efficiency Design Index (EEDI) for newbuild ships and the Energy Efficiency Existing Ship Index/Carbon Intensity Indicator (EEXI/CII) for existing ships. Green ammonia is one of the alternative fuels targeted by those standards to make the shipping industry more compliant with climate targets.

→ By 2030, as clean ammonia supply expands and ammonia-powered vessels increase, it is necessary to implement **market-based mechanisms** to address price differences between clean ammonia and fossil fuel alternatives. Policy instruments such as CfDs, CCfDs, subsidies and carbon pricing can be used, along with the establishment of domestic and regional emissions trading schemes (ETS). Incorporating the shipping sector into the EU ETS from 2023 can lay the groundwork for testing an international carbon price for the industry. Experts estimate that carbon prices ranging from USD $50 to USD $100/Mt of CO_2 by 2030, and potentially up to USD $191 to USD $400/Mt of CO_2 by 2050, will be necessary for full decarbonization, with some studies suggesting prices as high as USD $650/Mt of $CO_2$by 2050.

→ Beyond 2030, policy instruments should expand to include a **gradual phase-out** of fossil fuel bunkers and the use of new fossil fuel-powered ships. Similar to bans on new sales of internal combustion engines in the automotive sector, these measures can promote the transition to cleaner alternatives, with the 2030s being a target timeframe for their enforcement.

Power generation

Policies aimed at promoting the use of clean ammonia in power generation within renewable resource-constrained markets adopt a dual strategy: first, they focus on creating demand by showcasing and expanding the capabilities of clean ammonia in energy systems. Second, they establish regulations to phase out highly emitting alternatives.

The main measures to foster the adoption of clean ammonia in power generation encompass the following:

→ By 2025, policies must authorize using clean ammonia in power generation while ensuring compliance with operational health and safety regulations. Policymakers should develop comprehensive **roadmaps** that commit to the long-term integration of clean ammonia into energy systems.

Japan recently introduced its Roadmap for Ammonia in Power Generation, projecting an annual consumption of 30 Mt by 2050. It is necessary to allocate resources for flagship projects through grants, loans and tax incentives to demonstrate the scalability of ammonia-based power generation. Emphasis should be on optimizing co-firing processes and improving overall efficiencies.

→ By 2030, as the integration of clean ammonia into large-scale power generation systems expands, governments should establish targets with the percentage of electricity generated from low-carbon sources, including clean ammonia. Supporting the growth of clean ammonia-generated power through **feed-in tariffs** (FITs) will further bolster its adoption.

→ In the longer term, as clean ammonia solidifies its role and competitiveness in future energy systems, it is essential to implement policies that phase out high-emitting alternatives. There is a need to implement phase-out regulations targeting energy feedstocks with high emissions, such as coal, in power generation systems. Policies could introduce a **carbon penalty system** to ensure a level playing field, positioning clean ammonia as a cost-competitive alternative to coal.[38] This penalty system could reach USD $120/t CO_2e by 2050, considering a 60% co-firing share.

Hydrogen carrier

To accelerate the growth of the hydrogen industry, it is crucial to incorporate policies specifically focused on using ammonia as a hydrogen carrier into broader policy frameworks. These policies should aim to enhance the role of hydrogen in energy systems. Key policies that can contribute to this objective include:

→ By 2025, recognition of the potential **role of clean ammonia** for this application and incorporation into hydrogen strategies and roadmaps.

→ To foster the long-term competitiveness of ammonia as a hydrogen carrier for long-distance transport, it is crucial to allocate **resources to allocate resources to research and development (R&D).** These investments will drive technological advancements, particularly in areas like ammonia cracking, that enhance ammonia's viability in this role.

→ By 2030, implementing economic instruments, such as **CfDs,** will be essential to incentivize replacing fossil fuels with hydrogen in specific applications. CfDs, as seen in the German Government's plan to facilitate the industry's transition to low-carbon technologies, can serve as effective tools for creating financial incentives and driving the adoption of hydrogen.

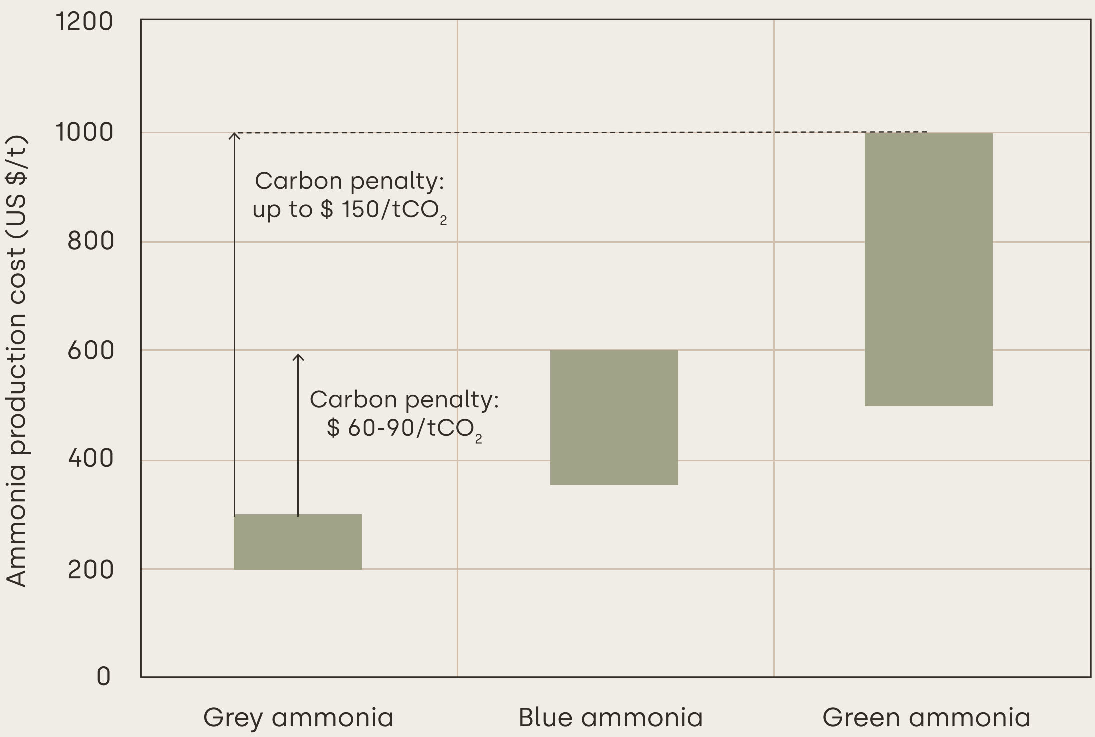
The importance of implementing carbon pricing mechanisms to close the economic gap

Scaling up production to gigawatt-scale is a key factor in reducing costs in the renewable ammonia sector, leading to economies of scale and decreased relative capital intensity.

Another significant factor influencing cost reductions will be the cost of electricity, constituting over 90% of the anticipated cost reduction for renewable ammonia in the upcoming decade. For every decrease of approximately USD $10 per megawatt-hour (MWh) in electricity costs, there is an approximate reduction of USD $100 per ton of ammonia. Based on these projections, renewable ammonia will be in the range of USD $500 to USD $1,000 per ton by 2030.

In a context of high uncertainties of commodity prices, the current rate of electricity cost reductions might not be sufficient to make green ammonia cost competitive. Therefore, increasing the cost of carbon is crucial to bridge the competitiveness gap between the different pathways, as depicted in Figure 15, and achieve full decarbonization. Carbon pricing will be contingent upon the specific end-use application of hydrogen, with varying price ranges applicable for various sectors. For highly competitive applications such as cement or steel, carbon price projections show a range of USD $50 and USD $60 per ton of CO_2. However, for applications like methanol, price projections are higher, reaching approximately USD $139 to USD $145 per ton of CO_2 by 2050. It is important to note that the appropriate carbon pricing should be determined thoughtfully, considering the varying contexts of different sectors and regions.

Figure 17: Economic gap between the different ammonia production pathways



Closing the competitiveness gap through a carbon penalty to reach full decarbonization for ammonia production is estimated at USD $50–$150/t CO_2 by 2030, depending on the low-carbon ammonia technology pathway:

- → USD $60-90 per ton of CO2 is required to bridge the gap between fossil-based ammonia with unmitigated emissions and fossil-based ammonia with CCS; depending on the fossil source and technology (coal-based, SMR-based, ATR-based ammonia;
- → USD $150 per ton of CO_2 would bridge the gap between fossil-based and renewable ammonia.

Oil *refining*

05.

05. Oil refining

There is an urgent need to accelerate the replacement of fossil-based hydrogen in refineries to meet net-zero emissions climate targets by 2050.

Refineries are significant industrial hydrogen consumers, accounting for a substantial portion of the global usage.

In 2020 alone, they consumed approximately 40 million tons of hydrogen, constituting nearly half of the worldwide demand. The production of hydrogen for use in refining resulted in 240 – 380 million tons of CO_2 emitted to the atmosphere in **2022.**[39]

Focus: hydrogen uses in refineries

Hydrogen is fully integrated into refinery operations and is **mostly used in two processes: hydrocracking and hydrotreating.** Hydrocracking is the process of converting heavy and low-quality gas oil into more valuable fuels such as diesel, gasoline, and jet fuel in the presence of hydrogen and a catalyst. Hydrotreating is the process of mixing hydrogen and a metal catalyst with fossil gas or refined petroleum products (e.g. gasoline, jet fuel, diesel) to remove sulphur and other contaminants. In fact, the combustion of sulphurous fuels produces sulphur oxides (SOx). These irritating gases cause serious respiratory problems and contribute to atmospheric pollution. Moreover, sulphur is harmful to the operation of catalytic converters.

There are three main hydrogen supply patterns in refineries. It is first produced as a by-product in oil refineries, for example in catalytic naphtha reforming. However, **by-product** hydrogen is not sufficient to cover the hydrogen demand of larger refineries. About 80% of hydrogen used in refineries in 2022 was supplied through **on-site production**, with 55% resulting from dedicated hydrogen production as opposed to naphtha crackers. A small portion is **purchased through third parties.** Less than 1% of hydrogen used in refineries was produced using low-emission technologies.

Despite the prospective reduction in refinery activities over the long term, prompted by the gradual phasing out of fossil fuels within the global economy (estimated to transition from 140 EJ in 2018 to 14 EJ by 2050, as projected by **IRENA**[40]), the demand for hydrogen within refineries has demonstrated consistent growth over the past decades. If all the announced projects are realized on time, 1.3 Mt of low-emission hydrogen will be produced and used in refineries by 2030, with around 1.1 Mt produced from fossil fuels with CCUS and 0.2 Mt from **electrolysis.**[41]

In addition to the demand for hydrogen stemming from oil refining, there are emerging prospects for further hydrogen consumption within refineries. These potential avenues encompass a range of applications, such as enhancing biofuels, generating low-emission synthetic hydrocarbon fuels (synfuels) and facilitating high-temperature heating for various processes – all of which require a consistent supply of hydrogen feedstock.

In this context of growing hydrogen demand within refineries by 2030, there is an urgent need to decarbonize hydrogen for use in the refining industry and progress toward achieving a net-zero emissions scenario by 2050. The total planned production of clean hydrogen for 2030 accounts for merely 1.5 Mt, representing **a small fraction (2.5%) of global demand in oil refining.** This number is well below the expansion required to stay on track with a net-zero scenario by mid-century. In the IEA's Net Zero Emissions Scenario, more than 4 Mt of low-emission hydrogen are produced and used in refineries by 2030, with around two-thirds produced from electrolysis and low-emissions electricity, and one-third from fossil fuels with **CCUS.**[42]

In ongoing projects, **carbon capture has emerged as a favored solution over retrofitting,** primarily due to its capacity to mitigate the effects on pre-existing assets while also addressing the economic challenges associated with the decarbonization process.

While transitioning to clean hydrogen in the realm of oil refining might seem ostensibly straightforward as a like-for-like substitution rather than a complete fuel switch, it's crucial to acknowledge the intricacies of refinery operations. These facilities are a complex technical infrastructure where implementing substantial changes presents considerable challenges.

- → The conversion of an oil refinery requires the **adaptation of existing equipment** and the resolution of intricate **regulatory and permitting matters,** often protracted and complex processes in themselves.
- → Moreover, **financial constraints** and complexities within the **supply chain** further complicate the transformation process.
- → Adding to this is the **continuous nature** of refining operations, demanding a consistent and uninterrupted hydrogen supply. For instance, the recent introduction of European regulations mandating additional requirements and specific timing for producing decarbonized hydrogen introduces fresh layers of operational complexity.

These challenges have led most transition strategies to center on leveraging existing assets. In this context, producing clean hydrogen for refining purposes primarily hinges on fossil fuel sources with carbon capture, utilization and storage (CCUS). Notably, while promising, electrolytic hydrogen only accounts for a quarter of the projected clean hydrogen production for 2030, with the remaining three-quarters relying on CCUS-enabled processes.

This deliberate approach underscores the pragmatic reliance on established infrastructure and technology to achieve meaningful decarbonization within the complex landscape of refining. Table 3 illustrates the primary barriers and associated driving factors that encumber the evolution of the refining industry toward the adoption of decarbonized hydrogen.

Table 3: Challenges faced by refiners to adopt decarbonized hydrogen

Barriers to the transformation	Challenges
Cost of decarbonized hydrogen	High capital cost of electrolyzers High price of renewable electricity for electrolysis Low carbon prices and existence of free CO2 allowances maintaining cheap conventional hydrogen costs
Transforming brownfield assets	Need to ensure a consistent and uninterrupted hydrogen supply. Adaptation of existing equipment Resolution of intricate regulatory and permitting matters
Nascent market stage	Uncertainty into the operational and economic aspects of 100+ MW to GW installations Limited reservoir of experiential knowledge

The green transformation dilemma of the refining industry

Refiners find themselves caught in a challenging predicament. They cannot position fossil products treated with decarbonized hydrogen as notably eco-friendly as the end product retains its fossil nature.[43] It would be controversial to claim that refined oil is greener. Hence, fossil fuels subjected to decarbonized hydrogen processing struggle to establish an economic argument for their reduced carbon impact. In European regulations, a fossil fuel's carbon footprint stays at 94g CO_2/MJ, even when using clean hydrogen. Therefore, policies aimed at fostering decarbonization should primarily target the transformation processes within refineries rather than concentrating solely on the end-product. For instance, implementing quotas akin to those applicable to biodiesel for diesel treated with clean hydrogen might prove challenging to justify.

Simultaneously, refiners must channel investments into the decarbonization of fuels that will inevitably become obsolete over time while facing mounting taxes or potential bans. The adoption of clean hydrogen should not inadvertently perpetuate the production of fossil fuels. Consequently, the shift to clean hydrogen must be a pivotal component within a holistic strategy to cultivate alternative low-carbon fuels within refineries, with hydrogen as a foundational feedstock.

Such an approach would secure supplementary outlets for clean hydrogen production units and concurrently facilitate the gradual reduction in conventional fossil fuel output over time.

Supportive policies by market development phase

In the context of this dilemma, supportive policies would help the refining industry transform processes and business models. Supporting the diversification of the production of other low-carbon fuels by refineries and providing financial support for the production or purchase of clean hydrogen will foster and accelerate the adoption of decarbonized hydrogen in refineries.

The three primary measures in this sector

1. Increasing clean hydrogen integration in refinery operations

Legislative mandates compelling the augmentation of clean energy constituents in refined products should bolster the market for selling clean hydrogen to refineries. The Renewable Energy Directive (REDIII) sets a **binding target** for the EU to reach a minimum of 42% of hydrogen coming from renewable fuels of non-biological origin (RFNBOs) by 2030 and 60% by 2035 in the industry.

2. Facilitating the transition to low-carbon fuel production for alternative outlets

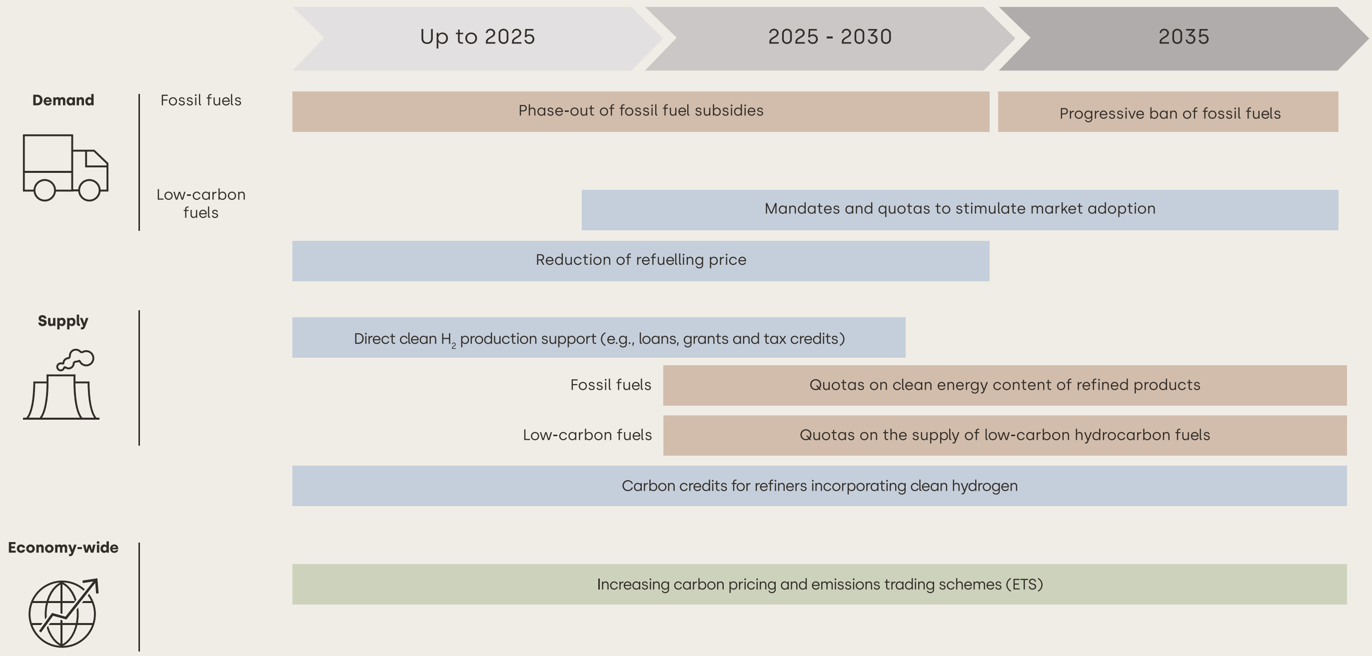
Commercial incentives to introduce low-carbon hydrocarbon fuels, like renewable diesel (RD) and sustainable aviation fuel (SAF) through mechanisms such as **quotas** for transportation companies handling aviation fuels should reinforce the first measure. These initiatives, in turn, necessitate a clearly defined roadmap for the **gradual elimination of fossil fuels.** This involves discontinuing subsidies for these fuels and implementing a progressively escalating **taxation framework,** to reduce fossil-fuel demand over time. The cessation of fossil fuel subsidies is a pivotal component of effective clean energy transitions. The recent global energy crisis has underscored some of the political complexities inherent in such endeavors, as governments often prioritize shielding consumers from detrimental price effects, sometimes at the expense of immediate commitment to subsidy phase-outs.

3. Providing financial support to pioneers and acknowledging supply-side decarbonization

Two pivotal mechanisms for bridging the value disparity between the supply and demand sides encompass **direct financial aid** (such as subsidies, loans and tax incentives) and the use of related **carbon credits.** These credits work in tandem to elevate the cost of gray hydrogen while concurrently reducing the carbon tax burden on refiners. This dual effect serves to enhance the economic viability of green alternatives.

Figure 18 summarizes the policy roadmap supporting the transition to clean hydrogen in the refining industry.

Figure 18: Roadmap for the adoption of decarbonized hydrogen in the refining industry



Example: application of these policy principles in Europe

The Renewable Energy Directive (REDIII) encapsulates a primary policy framework in Europe, introducing sector-specific targets for renewable hydrogen consumption, particularly focusing on renewable fuel of non-biological origin (RFNBO), in both the industry and transport sectors. Under this framework, refineries must meet set targets for renewable hydrogen use in their operations. In exchange, these volumes are quantified, enabling the refinery to claim carbon credits for their decarbonization endeavors. As a result, emissions reductions are attributed to the refinery's efforts rather than the final fossil product.

Sector-specific RFNBO targets have the potential to accentuate the significance of industry-oriented policy mechanisms, such as quota obligations or financial support schemes. These instruments play a pivotal role in guaranteeing steady and substantial demand for renewable hydrogen, ensuring its allocation to sectors where its impact is most critical, such as refining.

The following paragraphs delve into the previously outlined primary measures, aiming to juxtapose them with the terms delineated in European regulation.

1. Increasing clean hydrogen integration in refinery operations

REDIII mandates member states ensure that, by 2030, 42% of hydrogen used in industry is renewable, escalating to at least 60% by 2035. In addition, refinery facilities must contribute to the transport sub-target, involving 5.5% of advanced biofuels and RFNBOs.[44] It's important to note that REDIII's transportation sector encompasses maritime and aviation as well.

2. Facilitating the transition to low-carbon fuel production for alternative outlets

Beyond this, multiple European regulations are steering the adoption of decarbonized hydrogen in the coming years, propelling strategies like Petrogal's Sines[45] transformation plan. Initiatives are fostering foster the adoption of alternative or more sustainable fuels, like:

- ReFuelEU Aviation, aiming to elevate the share of sustainable aviation fuels (SAF) in the European aviation sector, targeting a 20% SAF blend by 2035 and 63% by 2050.
- FuelEU Maritime, part of the Fit for 55 package, introducing progressively more stringent limitations on fuel carbon intensity for vessels starting in 2025.

3. Providing financial support to pioneers and acknowledging supply-side decarbonization

Some early movers in Europe have obtained financial support:

- The Energy Taxation Directive, part of the European Union's energy product taxation framework, offers reduced tax rates for low-carbon hydrogen and associated fuels, with a minimum transitional rate of EUR €0.15/GJ for ten years.
- The EU Carbon Border Adjustment Mechanism (CBAM) aims to harmonize carbon pricing for EU products within the EU ETS and for imported goods. The goal for this mechanism is to safeguard fuels produced at higher costs in Europe from international competition.

The refining sector stands out among the four sectors we have analyzed. It is both a major user of hydrogen and creates products sourced directly from fossil fuels. Why decarbonize the use of hydrogen rather than focus on phasing out the fossil fuel products themselves? While countries are on various decarbonization pathways and timescales to reduce fossil fuels, non-fossil fuel alternatives cannot yet replace many refining products readily at large scales. Since all decarbonization levers are required to limit global warming, pursuing decarbonized hydrogen in the refining sector in the short to medium-term is sensible.

Conclusion

06.

06. Conclusion

The deployment of decarbonized hydrogen is at a very nascent stage and it requires concerted policy efforts to grow uptake like many emerging industries before it. The need is clear and agreed: in view of the climate crisis, it is essential to decarbonize hard-to-abate industries – and even more so as global demand for products will only increase in line with the world's population and economic wealth.

While some countries have supply-side policy instruments in place, those need to work in tandem with demand-side policies as time is of the essence. Waiting for demand to materialize once decarbonized hydrogen is sufficiently cost-competitive would delay its scale-up. Augmenting conventional hydrogen supply with decarbonized hydrogen in the short and medium terms and then phasing out conventional hydrogen in the long term is logical as decarbonized hydrogen, like other low-carbon energy carriers, will need time to establish itself globally. Historically, switching from one energy carrier to another, such as from heating oil to natural gas in homes, typically takes a decade or more as it requires building infrastructure at scale and establishing confidence in a new technology and market.

With the right incentives, industry and markets can move fast

Our policy recommendations are broken down into the short-, medium- and long-term for specific recommendations and approaches to mature supply and demand. Given the world's climate change challenges, the industry and markets need to move fast to adopt clean hydrogen. This can only be achieved if they receive sufficient incentives in a coordinated manner.

As heavy transport, steel production and ammonia production (including ammonia as an energy carrier itself) grow to meet increasing global demand for buildings, industrial infrastructure, fertilizers and textiles, decarbonizing the supply chains for trucks, steel and ammonia will have positive, self-reinforcing consequences. For example, green steel leads to more sustainable heavy transport and buildings. As industries such as solar and wind energy have proven, the supply cost will decrease as the industry innovates and harnesses economies of scale. But a concerted demand-side policy push is needed to accelerate industrial decarbonization and create the market confidence needed to incentivize investment at scale.

Decarbonized hydrogen policy measures and carbon pricing need to align with wider-level economic policies

Our economic analysis demonstrates that, in most instances, it is impossible to overcome the current cost of the supply gap without introducing or increasing the social cost of carbon, meaning conventional and decarbonized hydrogen will compete on equal terms. As an equalizer, carbon-related instruments[46] will spur demand for decarbonized hydrogen, which will become cheaper as the industry (and its required supply chains) learns, innovates, and grows. However, increasing the cost of carbon will impact the costs of household goods and fertilizers to a point that may be hard or impossible to bear, especially in developing countries with vulnerable communities. Each country will need to weigh the introduction of carbon-related policies with wide-reaching economic implications, at least in the short to medium term.

Simply put, our recommended decarbonized hydrogen policy measures need to align with wider-level economic policies, which will differ by country. As countries consider introducing or boosting their existing carbon taxation and pricing mechanisms, countries should collaborate and avoid carbon displacement, i.e., prevent the relocation of carbon-intensive production from low- to high-carbon price jurisdictions. Regional, or even better, international action is required to harmonize carbon pricing systems, which favor decarbonized hydrogen along with other renewable energy carriers.

Finally, international cooperation is required to create a harmonized certification for clean hydrogen to enable global trade and foster its adoption.

Also, our policy recommendations go beyond the cost of supply and creating more demand. All four sectors will benefit from and require further technological innovation. Fuel-cell technology and ammonia as an energy carrier can mature through research and development initiatives, which policymakers accelerate and coordinate.

Significant supply-side policy action is already in place and more demand-side measures are required.

Table 4 summarizes the examples of hydrogen policies we compiled across the four industry sectors. Instruments focusing on the supply side are far more prevalent.

Table 4: Summary of demand- and supply-side policy measures by country

Sector	Country	Policy instrument	Demand- or supply-side instrument?	Policy focus
Heavy Transport	China	Subsidy	Demand	Refueling station & vehicles
	USA	Subsidy	Demand	Vehicle purchase subsidies
		Quotas	Supply	Vehicle sales quotas
		Efficency standard	Supply	Lower GHG emissions levels
	The Netherlands	Incentive	Supply	Carbon-difference contract scheme
		Quotas	Supply	Vehicle sales quotas
	Austria	Subsidy	Demand	Vehicle purchase subsidies
	Germany	Subsidy	Demand	Vehicle purchase subsidies
		Efficency standard	Supply	Lower GHG emissions levels
	Norway	Subsidy	Demand	Vehicle purchase subsidies
	EU	Incentive	Demand	Lower tolling price
Steel	EU	Investment	Supply	Technology research
		Incentive	Supply	Carbon contract for difference
		Import tax	Supply	Carbon border adjustment mechanism
	USA	Investment	Supply	Direct project aid
		Tax credits	Supply	Decarbonized hydrogen production
	Germany	Incentive	Supply	Carbon contract for difference
	Belgium	Incentive	Supply	Green steel production
Ammonia	Morocco	Incentive	Supply	Green ammonia production and export
	Singapore	Investment	Supply	Technology research
	South Korea	Incentive	Supply	Technology research
		Investment	Supply	Ammonia coal co-combustion
	USA	Tax credits	Supply	Decarbonized hydrogen and ammonia production
Refining	USA	Carbon credits	Supply	CCS protocol
	EU	Mandate	Supply	Renewable hydrogen use requirement

Call to action

We call on policymakers to collaborate with industry to develop further supply and demand policy measures that can accelerate investments in and the use of decarbonized hydrogen in key industrial sectors. More national targets and clear roadmaps supporting all value chain stages are crucial to bolster confidence among suppliers, off-takers and investors and create clear market signals. Our recommendations are provided in the executive summary of this document.

Governments must also consider other dimensions. To achieve effective supply- and demand-side policy implementation, it is necessary to take into account the knock-on effects on decarbonized hydrogen supply chains holistically. This includes taking action to grow skilled labor force, source raw materials responsibly and promote international research collaboration.

Annexes

07.

Annex 1: Examples of policy frameworks to stimulate and secure hydrogen demand

Policies aimed at stimulating demand are steadily emerging across different regions worldwide. These policies encompass strategies such as sending robust market signals and ensuring long-term market visibility. They can take the form of quotas, mandates and the inclusion of hydrogen requirements in public procurement processes.

Additionally, governments are trying to bridge the economic gap and facilitate the widespread adoption of low-carbon hydrogen. Strategies like carbon contracts for difference and auctions play a crucial role.

This section illustrates the implementation of various policy instruments worldwide for the different sectors covered in this report.

China

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport (refueling station & vehicles)	Direct subsidies for hydrogen vehicles and refueling stations – applied in specific groups of cities, awarded based on achieving market volumes, hydrogen refueling price threshold and carbon footprint targets	Incentives	Demand-side

In 2020, the Chinese Government introduced a comprehensive hydrogen policy framework to accelerate hydrogen mobility supply chain development in specific city clusters. This initiative aims to foster the growth and adoption of fuel-cell vehicles. Under this policy, city clusters that successfully meet certain targets related to technology application and fuel-cell vehicle promotion can receive substantial subsidies. Each city cluster has the potential to receive up to 1.5 billion yuan (equivalent to EUR €220 million) in subsidies. The amount is determined based on the cluster's capacity to meet specific targets. They include achieving a minimum number of hydrogen vehicles within the cluster (a minimum of 1,000 vehicles), meeting minimum range requirements based on vehicle type and satisfying technical specifications for fuel-cell power and power density.

Furthermore, each city cluster is eligible for an additional 200 million yuan (equivalent to EUR €30 million) specifically allocated to fueling infrastructure development. This funding intends to support the establishment of infrastructure capable of supplying a minimum of 5,000 metric tons of hydrogen per year, ensuring that carbon emissions associated with hydrogen production do not exceed 15 kgCO_2 per kg of hydrogen delivered and reducing the cost of hydrogen at refueling stations to less than EUR €5/kg. These incentives complement existing CapEx subsidies, which already amount to EUR €58,000 per heavy vehicle.

State of California

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	Vehicle sales quotas Carbon-intensity thresholds for newly sold vehicles Vehicle purchase subsidies	Coercive (vehicles sales) Incentive (vehicles purchase)	Supply- and demand-side policies

Emissions Trading Scheme	Carbon pricing	Incentive	

Heavy-duty road transport

California's Advanced Clean Truck (ACT) regulation, pioneered by the State of California, has set a global precedent by establishing the first-ever zero-emissions sales requirements for heavy-duty vehicle manufacturers. Five other states in the US have since adopted this groundbreaking regulation. The minimum sales requirements aim to increase over time and vary depending on the vehicle type. By 2025, the regulation mandates that 11% of new rigid trucks weighing over 6.3 tons must be zero-emissions, while the percentage for new zero-emissions tractor-trailers is 7%. These figures will gradually escalate to reach 75% of sales for rigid trucks and 40% for tractor-trailers by 2035.

California's Low Carbon Fuel Standard (LCFS) program reduces carbon intensity in transportation fuels. The program limits the carbon intensity of transportation fuels, requiring their sale, supply or offering for sale in the state with a CO2 intensity reduction of at least 10% above 2020 levels by 2030. To incentivize the adoption of clean vehicles, the CA VIP Project Eligibility and Incentive Amount provides vehicle purchase subsidies. This program offers up to USD $410,000 in financing for truck replacements, making it more affordable for businesses to transition to cleaner transportation options.

The Inflation Reduction Act (IRA), enacted in August 2022, introduces further incentives for low-carbon hydrogen production. It offers a 10-year production tax credit of up to USD $3 per kilogram of hydrogen produced. These measures aim to address the high costs associated with hydrogen mobility, fostering widespread adoption and contributing to overall emissions reduction efforts.

Transitioning refineries

In California, the Low Carbon Fuel Standard (LCFS) functions as a trading framework aimed at diminishing the carbon intensity of the state's fuel mix. In January 2019, the government established a protocol for carbon capture and storage (CCS) in the LCFS. This protocol extends eligibility for credits to transportation fuels that have undergone CCS to curtail their life-cycle emissions. Additionally, conversions of refineries yield credits for renewable transport fuels under California's stringent LCFS. Moreover, the recently enacted federal Inflation Reduction Act (IRA) provides supplementary tax incentives, further augmenting the support for these initiatives.

The United States of America (USA)

End-use application	Policy instruments	Nature	Value chain positioning
Green steel production	Investment aid	Incentive	Supply-side
Green steel production	Taxation regime	Incentive	Supply-side
Green ammonia production	Tax credit	Incentive	

Green steel production

Investment aid – The Industrial Demonstrations Program has earmarked around USD $6 billion in direct support for projects aimed at decarbonizing high-emitting industries, specifically focusing on decarbonizing existing primary production in the iron and steel sector.

Taxation regime – To incentivize the production of renewable electricity and clean hydrogen, the provision of Inflation Reduction Act tax credits (Investment Tax Credit or Renewable Energy Tax Credit) can significantly reduce the cost of decarbonized hydrogen production. By leveraging these tax credits, it is possible to reduce the cost of producing decarbonized hydrogen for a project starting in 2023 by nearly half, reaching approximately USD $3 per kilogram of hydrogen. The government has strategically designed this measure to make hydrogen more affordable, lowering the cost of important feedstocks for breakthrough iron and steel technologies.

Implementing these programs and tax incentives reflects a commitment to driving the decarbonization of the iron and steel industry by providing financial support and creating favorable conditions for adopting renewable energy sources and clean hydrogen.

Green ammonia production

The Inflation Reduction Act (IRA) is a significant initiative that allocates USD $369 billion for energy and climate projects, focusing on reducing manufacturing and mining costs, promoting clean energy production and introducing a transformative clean hydrogen production tax credit known as 45V. This provision, offering up to USD $3 per kilogram in tax credits, will profoundly impact clean hydrogen development, especially decarbonized hydrogen derived from renewable sources. Lowering the cost of hydrogen can potentially decrease the cost of essential feedstock for producing clean ammonia.

European Union (EU)

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	OpEx support	Incentive	Demand-side
Green steel production	Investment aid	Incentive	Supply-side
Green steel production	Carbon contract for difference	Incentive	Supply-side
Green steel production	International steel trade taxation	Enabler	Economy-wide

Heavy-duty road transport

While some countries, such as Norway and Germany, have already implemented road toll advantages for zero-emissions vehicles, the European Union (EU) aims to extend this support globally. In 2024, the EU plans to introduce the Eurovignette, which will provide at least 50% discounts on road tolls for haulers operating zero-emissions trucks. This initiative aims to promote the adoption of environmentally friendly transport options across Europe.

Green steel production

Investment aid – The Clean Steel Partnership, initiated in June 2021, aims to advance a range of groundbreaking technologies to the technology readiness level (TRL) 8. This initiative will receive funding from Horizon Europe and the Research Fund for Coal and Steel, with the EU contributing EUR €700 million to support this endeavor.

Carbon contract for difference (CCfD) – To facilitate the adoption of decarbonized hydrogen and reduce the cost of H2-DRI steel, the European Commission has introduced CCfD subsidies. These subsidies will enable the deployment of innovative solutions in the hydrogen sector by using competitive bidding in addition to the existing grants program offered by the Innovation Fund.

International steel trade taxation – The forthcoming Carbon Border Adjustment Mechanism (CBAM), scheduled for implementation in 2026, aims to address carbon leakage in high-emitting sectors and impose a cost on imported steel that does not meet sufficient green criteria. By extending the carbon price of the EU ETS to iron, steel and other imported goods, the CBAM ensures a level playing field for breakthrough technologies in the iron and steel industry while discouraging the relocation of production to jurisdictions with more lenient environmental regulations.

These strategic measures by the European Commission signify its commitment to promoting innovation and sustainability in the steel sector, fostering the development of low-carbon technologies, and safeguarding against carbon leakage. The European Commission aims to drive the transition to a cleaner and more resilient steel industry by providing financial support, incentivizing decarbonized hydrogen and implementing carbon pricing mechanisms.

Transitioning refineries

The introduction of mandates for clean hydrogen consumption among industrial users, encompassing oil refining is gaining momentum in Europe through initiatives like the RePowerEU action plan. This plan aims to incorporate 2.3 million tons of renewable hydrogen into refining processes by **2030**.[48] The implementation of specific mechanisms will facilitate reaching this objective, with the European Commission advocating for the adoption of a comprehensive EU-wide scheme, including CCfD. Presently, apart from a limited number of investment assistance programs such as the EU Innovation Fund, there exist minimal incentives for using clean hydrogen in oil refining. The potential introduction of CCfD that encompass total expenditure (TotEx) could wield transformative influence, stimulating the production of decarbonized hydrogen in refineries.

The United Kingdom (UK)

End-use application	Policy instruments	Nature	Value chain positioning
All applications	Carbon Contract for Difference	Incentive	All
Heavy-duty road transport	Quotas	Incentive	Demand-side

The United Kingdom has set its sights on generating 10 gigawatts of low-carbon hydrogen by 2030. This endeavor employs hydrogen CfD, a support mechanism similar to the one that catalyzed the nation's prosperous offshore wind sector.

Heavy duty road transport

Suppliers of relevant transport fuel in the UK must be able to show that a percentage of the fuel they supply comes from renewable and sustainable sources under the Renewable Transport Fuel Obligation.

Germany

End-use application	Policy instruments	Nature	Value chain positioning
All	Contracts for difference (CfDs)	Incentive	Supply- and demand side
Heavy-duty road transport	Tax credits	Incentive	Demand-side
Heavy-duty road transport	CapEx subsidy	Incentive	Demand-side
Heavy-duty road transport	Emissions reduction targets	Incentive	Supply- and demand-side
Green steel production	Carbon Contracts for Difference (CCFDs)	Incentive	Demand side

All

The government's H2 Global program will tender 10-year purchase agreements for hydrogen-based products, giving investors confidence in the low-carbon hydrogen project's bankability. It aims to support especially companies in the steel, cement, lime, and ammonia sectors that demonstrate a strong commitment to reducing CO2 emissions by more than 50% through the implementation of groundbreaking technologies.

Heavy duty road transport

German policy has gone beyond the stipulations of the revised Renewable Energy Directive (RED II) by imposing a more ambitious target: fuel suppliers must achieve a 25% reduction in greenhouse gas emissions for the fuels they distribute by 2030.

Additionally, the Ministry of Economic Affairs and Energy is taking steps to facilitate the adoption of fuel-cell trucks. To this end, the government decided to exempt electric and hydrogen vehicles from the circulation tax for ten years. It also has announced funding that covers up to 80% of the cost differential between low-emissions vehicles and traditional diesel vehicles, with a substantial budget of EUR €1.6 billion available until 2024 for new energy vehicles.[49]

Green steel production

The CCfD pilot program for the steel and chemical industries aim to compensate for the difference between the costs of CO2 reduction and the EU ETS CO2 price. Companies must refund the government the difference if the EU ETS price exceeds the project's CO2 abatement costs.

Portugal

End use application	Policy instruments	Nature	Value chain positioning
All	Targets	Incentive	Supply side

By 2030, Portugal's National Hydrogen Strategy aims to blend 10% to 15 vol% of hydrogen with natural gas.

The Netherlands

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	Carbon-difference contract scheme Fuel sales quotas Vehicle CapEx support	Coercive (vehicles) Incentive (hydrogen supply price)	Demand-side (vehicles) Supply-side (hydrogen supply price)

The Netherlands has demonstrated its commitment to decarbonizing its energy systems through the National Hydrogen Strategy, unveiled in 2020. This strategy highlights the significance of hydrogen and sets ambitious targets for adopting hydrogen technologies, including 15,000 fuel-cell cars, 3,000 heavy-duty fuel-cell vehicles, and 50 hydrogen refueling stations by 2025. The Dutch Government has expanded the Stimulation of Sustainable Energy Transition and Climate Transition (SDE++) scheme to facilitate the transition to hydrogen. As part of this scheme, it has introduced a CCfD program to incentivize hydrogen production. Companies engaged in hydrogen production can receive financial support of up to EUR €300 per ton of CO_2 avoided, reducing hydrogen costs by EUR €2.60 per kg.

The government has integrated this initiative into the Renewable Energy Transition Incentive Scheme, which aims to replace gray hydrogen production with low-carbon alternatives. Recognizing the importance of heavy-duty transport in overall decarbonization efforts, the Dutch Government has committed to establishing subsidy schemes under the National Climate Agreement. These schemes will specifically target heavy transport and support the purchase and operation of fuel-cell trucks, further promoting the adoption of clean and sustainable transportation solutions in the country.

Austria

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	CapEx subsidy	Incentive	Demand-side

The Austrian Research Promotion Agency has recently unveiled a funding program to support the development of zero-emissions commercial vehicles and infrastructure. With a budget of EUR €275 million until 2025, this initiative aims to drive the adoption of cleaner transportation options.

Notably, the program offers an 80% subsidy for the incremental costs associated with zero-emissions vehicles compared to their diesel counterparts. This financial boost is set to incentivize businesses to embrace sustainable alternatives and contribute to reducing harmful emissions.

Norway

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	Tax credit	Incentive	Demand-side
Heavy-road transport	Public procurement	Incentive	Demand-side

In Norway, hydrogen-powered vehicles enjoy incentives equivalent to those of battery-powered vehicles, exempting them from registration tax and VAT and enforcing fee reductions for public parking, ferries and toll roads until at least 2023.

In addition, the government has announced that hydrogen will power the country's main ferry connection.

Switzerland

End-use application	Policy instruments	Nature	Value chain positioning
Heavy-duty road transport	Taxation regime	Incentive	Demand-side

The country adopted the Performance-related heavy vehicle charge (LSVA) road tax, which assesses trucks weighing more than 3.5 tons but waives payments for zero-emissions vehicles.

Belgium

End-use application	Policy instruments	Nature	Value chain positioning
Green steel production	Investment aid	Incentive	Supply-side

As part of the Federal Hydrogen Strategy, the Federal Government of Belgium is set to allocate EUR €6 million from the Recovery and Transition plan to advance the development of green steel within the nation.

By investing in this initiative, the government aims to bolster sustainable and eco-friendly practices in the steel industry, fostering the transition to a greener future.

Morocco

End use application	Policy instruments	Nature	Impact on the value chain
Green ammonia production	Inclusion of clean ammonia in the national energy roadmap	Incentive	Market-wide

Morocco's National Hydrogen Strategy outlines the country's vision for 2050 and includes the integration of green ammonia. In the short term (2020-2030), the strategy focuses on using hydrogen as a feedstock for local green ammonia production.

In the medium term (2030-2040), the strategy envisions the production and export of green ammonia. The action plan for implementing the national hydrogen strategy has three strategic areas: technology, investment and market demand. The objective is to create favorable conditions for export, including developing port infrastructure and favorable taxation measures.

Singapore

End use application	Policy instruments	Nature	Impact on the value chain
Green ammonia production	Funding of R&D programs	Incentive	Supply-side

The Low-Carbon Energy Research (LCER) Funding Initiative (FI) is a collaborative effort among multiple agencies dedicated to advancing low-carbon energy technologies. In 2021, the initiative launched its first grant call, prioritizing the development of low and medium technology readiness level (TRL) technologies (low: TRL 1-3, medium: TRL 4-6).

Notably, this includes projects focusing on exploring innovative methods for hydrogen transportation, using ammonia as a viable alternative.

South Korea

End use application	Policy instruments	Nature	Value chain positioning
Green ammonia production	Inclusion of clean ammonia in the national energy roadmap	Incentive	Economy-wide
Green ammonia production	Funding for R&D	Incentive	Economy-wide
Green ammonia production	Direct support	Incentive	Economy-wide

In 2021, the South Korean government unveiled its ambitious plan to incorporate ammonia and hydrogen as feedstock for thermal power generation. It aims to gradually phase out fossil fuels by introducing these alternatives into the fuel mix by 2030. With a long-term target of 13.8% to 21.5% of national output generated from hydrogen and ammonia-fed gas turbines by 2050, the country plans to operationalize ammonia coal co-combustion in over half of its coal-fired power plants by 2030.

To support these initiatives, it has established a public-private council to spearhead research and established an ammonia storage facility in 2022. Furthermore, the government will offer financial incentives to promote the adoption of both fuels and ensure the stability of the international supply chain.

India

End use application	Policy instruments	Nature	Value chain positioning
Transitioning refineries	Quotas	Incentive	Economy-wide

The government announced that, from 2023/24, renewable hydrogen should fulfill 10% of refinery hydrogen demand (growing to 25% in the next five years) and 5% of fertilizer production demand (rising to 20% in the next five years).

Glossary

Glossary

Capital expenditure (CapEx): Cost of developing or providing non-consumable parts for the product or system.

Carbon border adjustment: This mechanism entails imposing fees on imported goods in proportion to the greenhouse gas emissions generated during production. Border adjustments may also provide rebates or exemptions from domestic policies for producers who export their goods.

Carbon contracts for difference (CCfD): Applies the concept of contracts for difference (CfD) to incentivize emissions reductions in industrial projects. In its basic form, the government or institution agrees with an agent, setting a predetermined effective carbon price for all emissions reductions achieved compared to a conventional technology within a specified timeframe. If the carbon price falls below the strike price, the agent receives additional payments as an incentive.

Carbon leakage: This refers to a scenario where businesses might relocate their production to countries with less stringent emissions regulations due to cost considerations related to climate policies. This situation could increase their overall emissions; certain energy-intensive industries face a higher risk of carbon leakage.

Contract for differences (CfD): A contractual agreement established between a clean hydrogen generator and an offtaker aiming to offer the generator price stability throughout the contract. The CfD ensures that the producer has certainty regarding the price they will receive for the hydrogen delivered over the contract's lifetime.

Direct reduction of iron (DRI): A process that removes oxygen from iron ore by using hydrogen as a reducing agent instead of coal or natural gas.

Haber-Bosch process: Primary method in producing ammonia from nitrogen and hydrogen.

Operating expenditure (OpEx): Ongoing cost for running a product, a business or a system.

Steam methane reforming process: A process involving the use of heat and steam for the conversion of unabated natural gas to hydrogen.

Total cost of ownership (TCO): Financial estimate intended to help buyers and owners determine a product's or service's direct and indirect costs. It includes the purchase price of an asset plus the costs of operation. Hence, it is a way of assessing the long-term value of a purchase for a company or individual.

Endnotes

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2 There is currently no universally agreed-upon standard definition of low-carbon hydrogen. Whenever we use the terms "clean" and "decarbonized" hydrogen in this document, we mean hydrogen with an intensity below 3 kgCO2/kg H2 using a full life cycle analysis, which aligns with various other definitions. When we mention "hydrogen" without any specification, it refers to "decarbonized" hydrogen, not any type of hydrogen.

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Loïc Le Gars

Principal, ERM (Environmental Resources Management)

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