Closing the Gap: Offtakers' Willingness to Pay for Low-carbon Hydrogen

Public Report

Introducing Aurora's speakers

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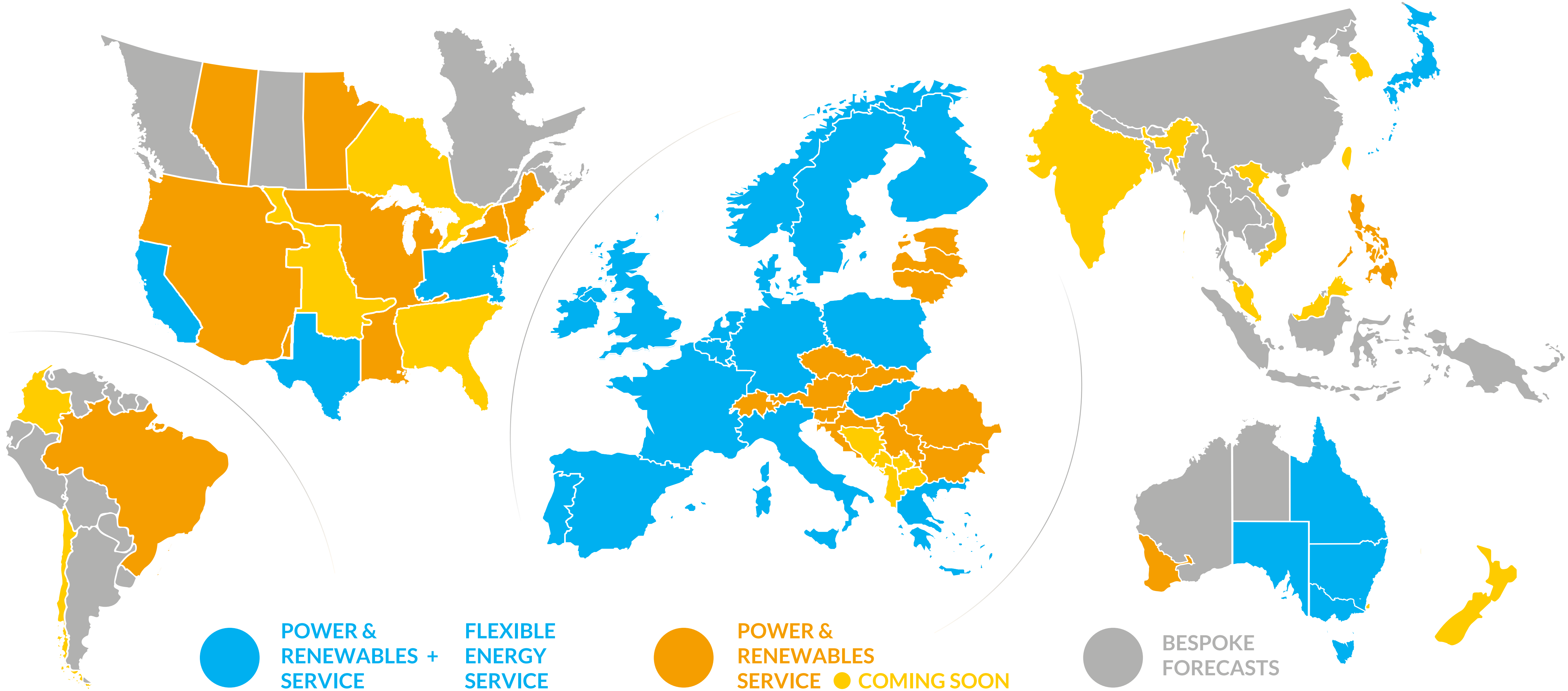

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Upstream gas & networks

REPSOL, Shell, equinor, Naturgy, OGE, nationalgrid, Thyssengas, Vitol, fluxys

Source: Aurora Energy Research

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Source: Aurora Energy Research

What's coming up in the European Hydrogen Market Service?

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Major deliverables of European Hydrogen Service in 2024

- **Jan. 2024**
- **February** – Hype to HPA: Crafting Offtake Strategies and Purchase Agreements
- **April** – Hydrogen Market Report (HyMaR)
- **June/July** – Closing the Gap: Offtakers' Willingness to Pay for Low-carbon Hydrogen
- **25th September** – Aurora's Hydrogen Conference in London
- **October** – Hydrogen Market Report (HyMaR)
- **December** – Power purchasing strategies
- **Jan. 2025**

Selected existing reports[1]

Strategic Insights

- Analysis of European Hydrogen Bank auctions
- Seas of opportunity: economics of hydrogen from offshore co-location
- A traded hydrogen market in Europe: what will prices and market structures look like?
- The economics of hydrogen imports: better to stay local?
- Financing electrolysers: overview of market trends in Europe
- Hydrogen in mobility: understanding the economics and incentives
- Shades of green (hydrogen) – part 2: in pursuit of 2 €/kg

Country deep-dives

- Hydrogen in the NLD: from natural gas to green hydrogen hub
- The role of green hydrogen in the I-SEM
- Policies, regulation, and economics of green hydrogen in France
- Green hydrogen in Germany – could colocation become a new business model for renewables?
- The role of green hydrogen in Iberia
- Hydrogen for a Net Zero Great Britain
- Low carbon hydrogen in the Nordics
- Net Zero and the role of hydrogen for the Italian power system

Source: Aurora Energy Research

Aurora is launching a Multi-Client Study focusing on the development of e-fuels in Europe

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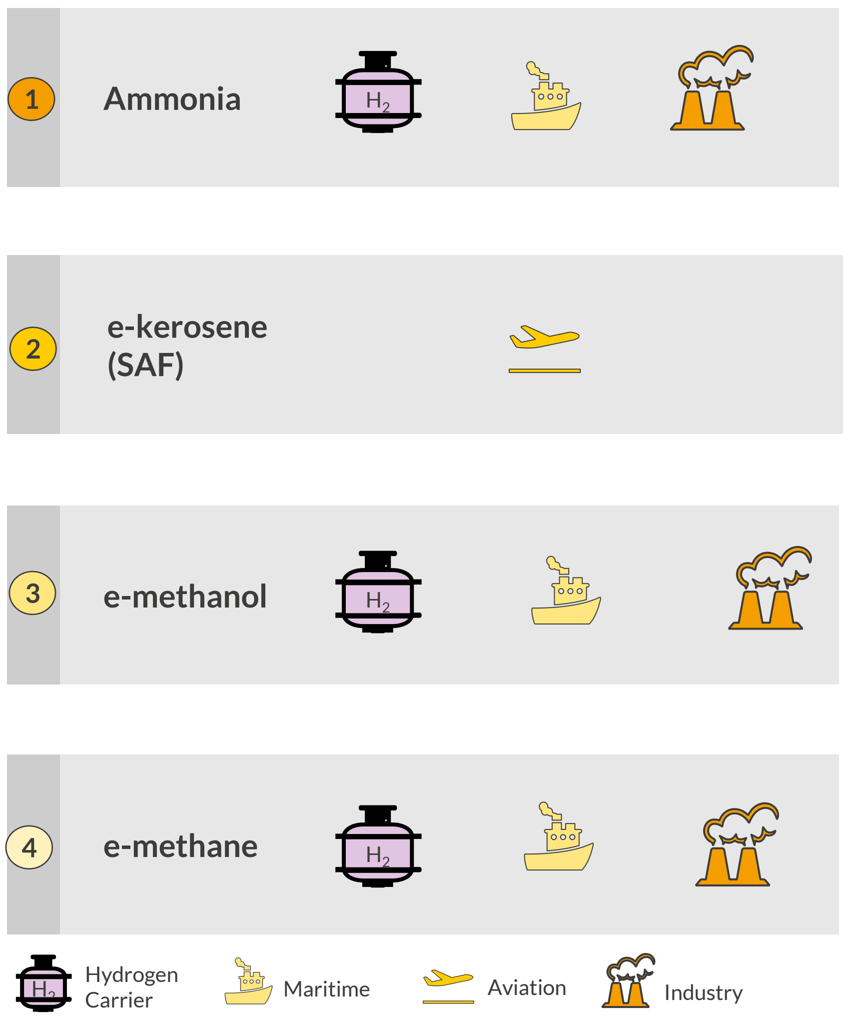
- The study aims to provide in-depth insights into the market and pricing dynamics of four key e-fuels, via a **Multi-Client-Study (MCS).** This allows us to create a **comprehensive analysis at a competitive rate,** while simultaneously **bringing key players in the e-fuel sector together**. The critical questions we aim to answer are:
  - What are the drivers of e-fuel demand?
  - Which e-fuels will be crucial for the decarbonisation of industry, aviation, maritime, and road transportation?
  - What is the market size for e-fuels?
  - What factors will determine the competitive advantage of e-fuel producers across Europe?
  - How will cost and price developments evolve for each e-fuel?
  - How will costs vary under different business models for e-fuel producers?

For more details on our approach and scope please reach out to us directly

Contact: Kevin.Caballero@auroraer.com

e-fuels in focus



Agenda

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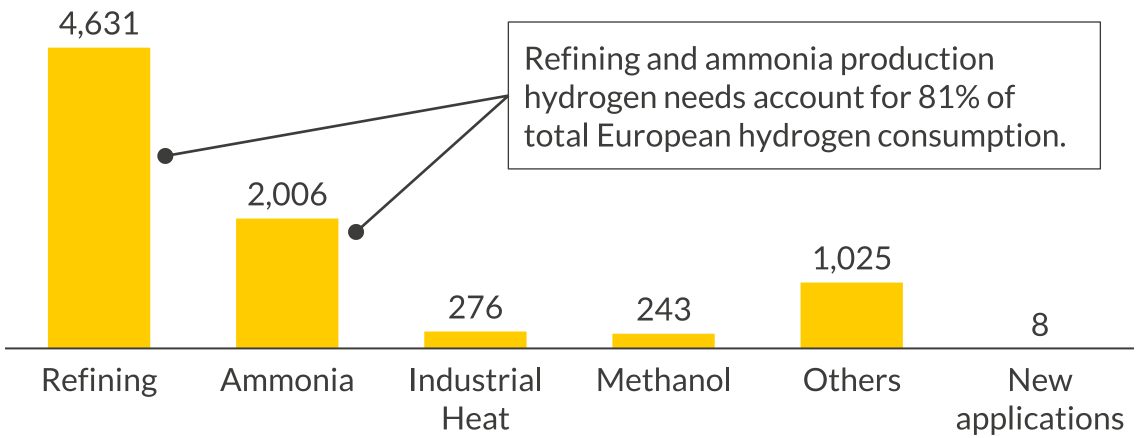
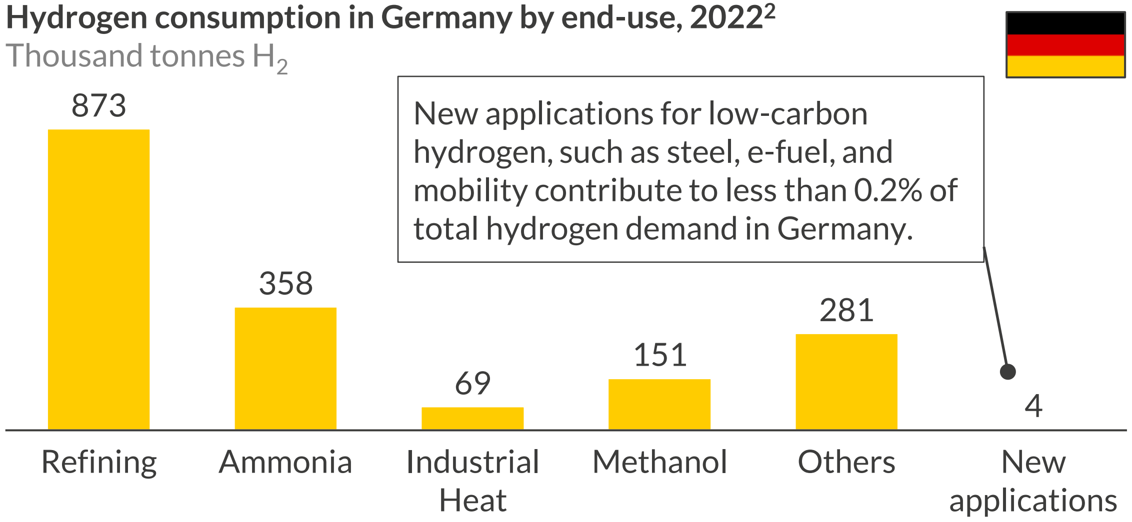
Hydrogen is a key feedstock in industry, used primarily in refining and ammonia production, and is predominantly fossil fuel-derived

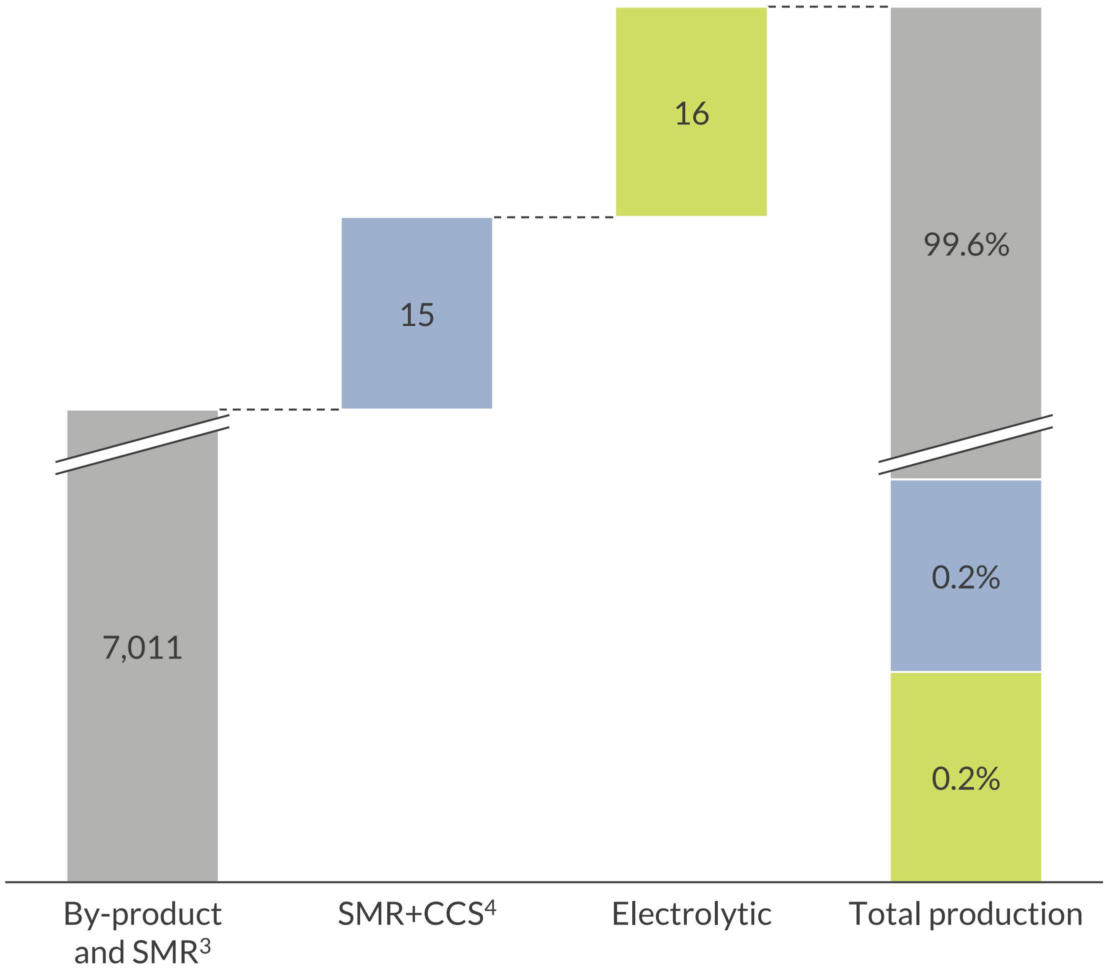
Hydrogen consumption in Europe[1] by end-use, 2022[2]
Thousand tonnes H_2



Hydrogen consumption in Germany by end-use, 2022[2]
Thousand tonnes H_2



European[1] hydrogen production by technology in 2022[2]
Thousand tonnes H_2



1) Only include countries covered by European Hydrogen Observatory. 2) Latest available data. 3) SMR: Steam methane reforming. 4) CCS: Carbon capture and storage.

Sources: Aurora Energy Research, European Hydrogen Observatory

Low-carbon hydrogen will be instrumental to decarbonising hard-to-abate sectors, but high production costs present challenges for adoption

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While switching to low-carbon hydrogen is fundamental to decarbonise sectors currently consuming grey hydrogen, the deployment of low-carbon hydrogen-based solutions in other sectors depends on the level of policy support and hydrogen's cost-competitiveness against other alternatives.

← New applications →

	Current hydrogen consumers	Hard-to-abate industries	Hard-to-abate transport	Others
First-mover sectors[1]	Ammonia, Refining	Steel	n.a.	n.a.
Other sectors	Methanol[2] and others[3]	Process heat, Power generation	Maritime, Aviation	Road transport, Space heating
Decarbonisation alternative	n.a.	Natural gas, RES[4] based electrification, CCS[5]	Biofuels, Electricity	Biofuels, Electricity
Competitiveness of hydrogen	◕	◑	◑	◑

The main obstacles to low-carbon hydrogen deployment in the most promising sectors is the **gap between offtakers' willingness to pay and high costs for producing low-carbon hydrogen.**

1 **Focus sector: Ammonia**

Based on public information, four out of seven European Hydrogen Bank winning projects are dedicated to ammonia, marking it as the most promising offtaker.

2 **Focus sector: Steel**

Europe has at least 52Mtpa hydrogen-ready steel capacity in pipeline, backed by multiple private funding and 9.6bn € of state aid.

1) Sectors with the highest offtake potential for low-carbon hydrogen in the short-term based on public offtake information. 2) Majority of methanol production relies on hydrogen currently. Biomass could contribute to mass production of methanol in the future. 3) Other includes hydrochloric acid production, hydrogenation, hydrogen as a coolant, etc. 4) RES: Renewable energy sources. 5) CCS: Carbon capture and storage.

Sources: Aurora Energy Research, The Chemical Engineer

Several policy instruments can bridge the cost gap between low-carbon hydrogen and the incumbent technology

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Policy instruments, implemented in certain countries and industries, aim to accelerate the switch to low-carbon hydrogen with a 'carrot and stick' approach: on the one hand, public funding is provided for producers and offtakers of low-carbon hydrogen to support the formation of an ecosystem. On the other hand, penalties benchmarked to GHG[1] emission and RFNBO[2] consumption mandates can bring relative disadvantage to incumbent carbon-intensive technologies.

	For producers	For producers and offtakers	For offtakers
Incentivising Policies that provide incentives for the switch to low-carbon hydrogen.	**Production side support** More than 10bn € are dedicated to support low-carbon hydrogen production across Europe via different schemes.	n.a.	**Offtake side support** Germany financial support to offtakers by its 4bn € Carbon Contract for Difference (CCfD) scheme.
Incentivising and Penalising Market-based schemes benchmarked to emission.	n.a.	**Emission pricing** Low-carbon hydrogen reduces carbon costs and provides additional revenue from free allowances for both producers and offtakers.	**Low-carbon certificates** Low-carbon hydrogen helps with meeting emission quotas in the transport sector in Germany and the UK.
Penalising Policies that penalise the decision to not switch to low-carbon hydrogen.	n.a.	n.a.	**RFNBO[2] consumption mandates** The Fit-for-55 package sets binding RFNBO mandates for key sectors, with penalties in place for aviation and maritime transport.

1) GHG: Greenhouse gas. 2) RFNBO: Renewable fuels of non-biological origin.

Sources: Aurora Energy Research, European Commission, UK Department for Transport, German Federal Ministry of Justice (BMJ)

We define the "floor" to willingness to pay as the price hydrogen has to reach to match the cost of the reference competing technology

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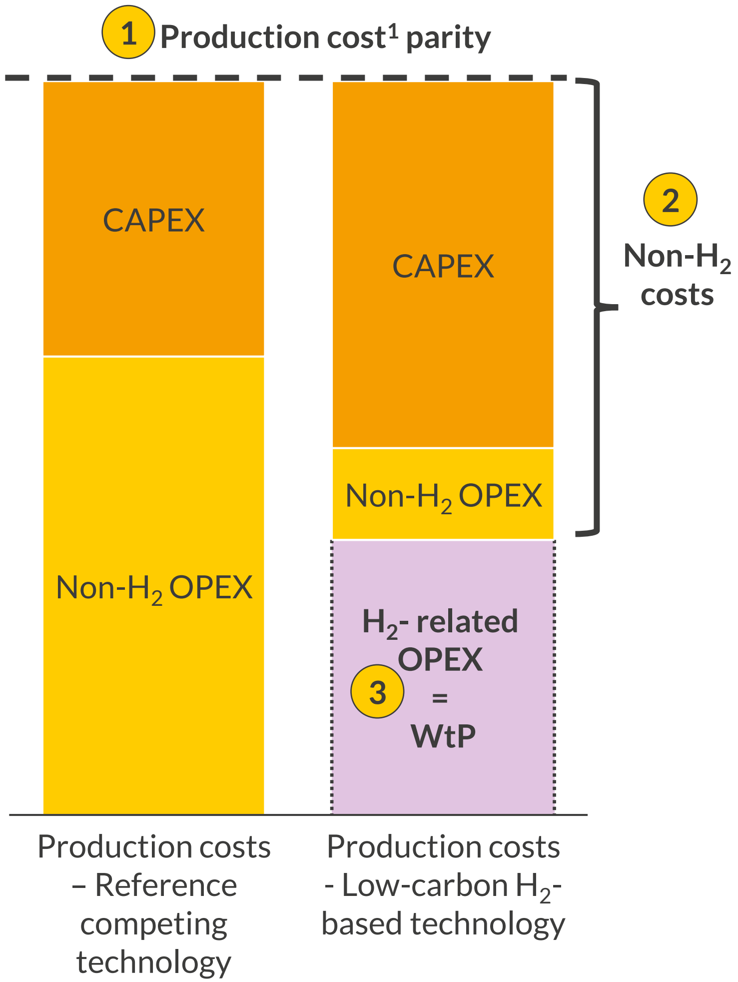
Illustrative alternative technology costs



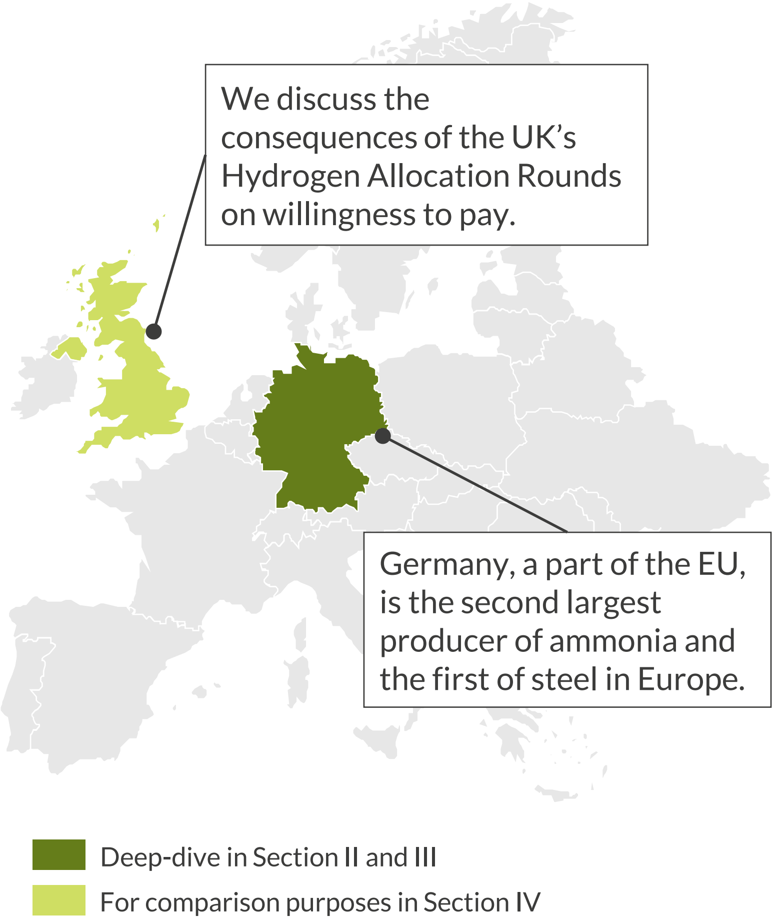
Estimating willingness to pay for H_2

1. From a purely techno-economic standpoint, offtakers are typically only willing to adopt low-carbon H_2 technology if production costs for H_2-based production is equal to, if not lower than, the reference competing technology.
2. Assuming cost parity, **the difference in non-H_2 costs is the amount offtakers are willing to pay for H_2**. This constitutes the "**floor**" to WtP[2].
3. WtP for low-carbon hydrogen is transformed to per unit of hydrogen from the H_2-related OPEX, by accounting for the H_2 intensity of the process.

The following elements could add on top of the floor to WtP in specific countries, industries, and projects.

- Green premium
- Subsidy
- Avoided penalty

Geographical coverage



1) Production costs between different technologies are compared on a levelised basis. 2) WtP: Willingness to pay.

Source: Aurora Energy Research

Agenda

I. Setting the scene

II. Willingness to pay for hydrogen in the ammonia sector

III. Willingness to pay for hydrogen in the steel industry

IV. UK's Hydrogen Allocation Rounds and willingness to pay

V. Key takeaways

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Low-carbon hydrogen is key to decarbonising ammonia production and downstream chemical industries

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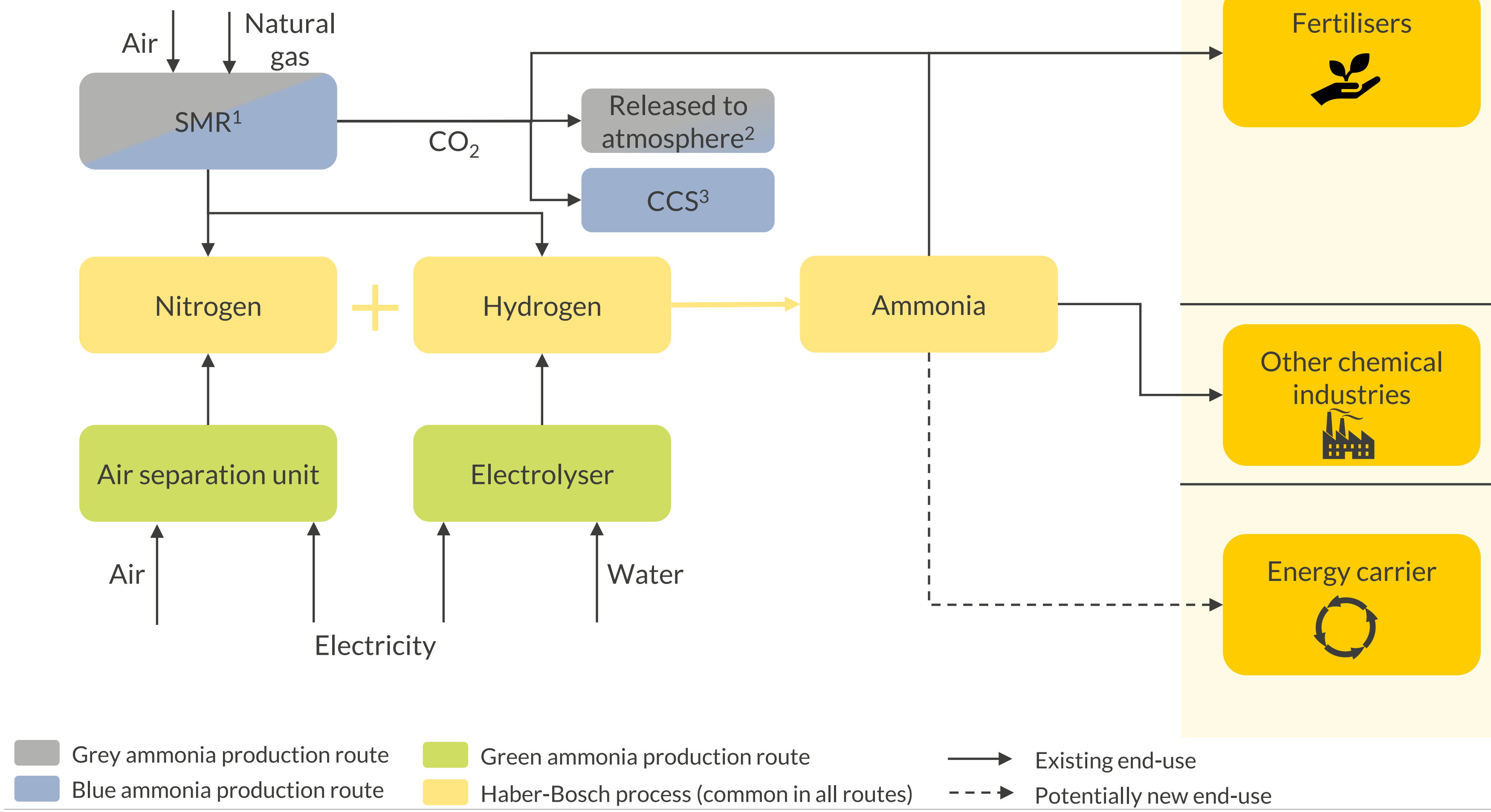
Simplified flow chart of ammonia production

End-use sectors for ammonia



- In 2021, 109.2 Mt[4] of nitrogen-based fertilisers have been consumed globally, more than phosphor-based (47.8 Mt[4]) and potassium-based (38.4 Mt[4]) fertilisers combined.
- 70%[5] of ammonia is used in the production of nitrogen-based fertilisers.
- 9.3% of nitrogen-based fertiliser is consumed in West and Central Europe.

- In addition to fertilisers, ammonia is also used as a refrigerant gas, for purification of water supplies, and in the manufacture of many products, such as plastics and explosives.

- In future, ammonia may play a role in the decarbonisation of aviation, seaborne transport and power sectors. It can also act as a carrier for transporting hydrogen.

1) SMR: Steam methane reforming. 2) About 5-10% of CO_2 cannot be captured economically with current blue hydrogen technologies. 3) CCS: Carbon capture and storage. 4) According to 2021 assumption by the IEA. 5) Based on nutrient content.

Sources: Aurora Energy Research, International Energy Agency (IEA), International Fertiliser Association

Redacted version. Figures available to subscribers.

Willingness to pay for low-carbon H_2 accounts for current grey H_2 costs, net carbon revenues, and costs for additional equipment

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Levelised floor WtP[1] for RFNBO[2] hydrogen, Germany (COD[3] 2030)

€/kg H_2 (real 2023)

The first component of WtP accounts for the cost of operating the SMR[5] unit, which is comparable to the standalone production of grey H_2.

Carbon costs are a significant contribution to WtP as carbon emissions from grey H_2 production are to be paid for in accordance with the EU ETS[7].

Additional to saved emissions, the producer will continue to receive free carbon allowances, which could be sold for extra revenue.

Adopting electrolytic hydrogen will require the installation of an air separation unit at a levelised cost of ≤0.05 €/kg H_2.

Floor WtP is formulated based on considerations on grey H_2 cost, net carbon revenues, and additional equipment cost.

In this study, the cost for procuring low-carbon hydrogen is estimated upon HPA price forecast under Aurora Central.

Grey H_2 LCOH (no carbon costs) | Grey H_2 carbon costs | Revenues from free carbon allowances | Additional equipment cost | WtP | RFNBO HPA Price

1) WtP: Willingness to pay. 2) RFNBO: Renewable fuels of non-biological origin. 3) COD: Commercial operation date. 4) LCOH: Levelised cost of hydrogen. 5) SMR: Steam methane reforming. 6) HPA: Hydrogen purchase agreement. Based on the cheapest option for variable offtake, published in Aurora's Apr-24 HyMaR databook. 7) ETS: Emission trading scheme

Source: Aurora Energy Research

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The incorporation of RED III[1] mandates on a national level can increase WtP[2] and reduce the need for subsidies and/or a green premium

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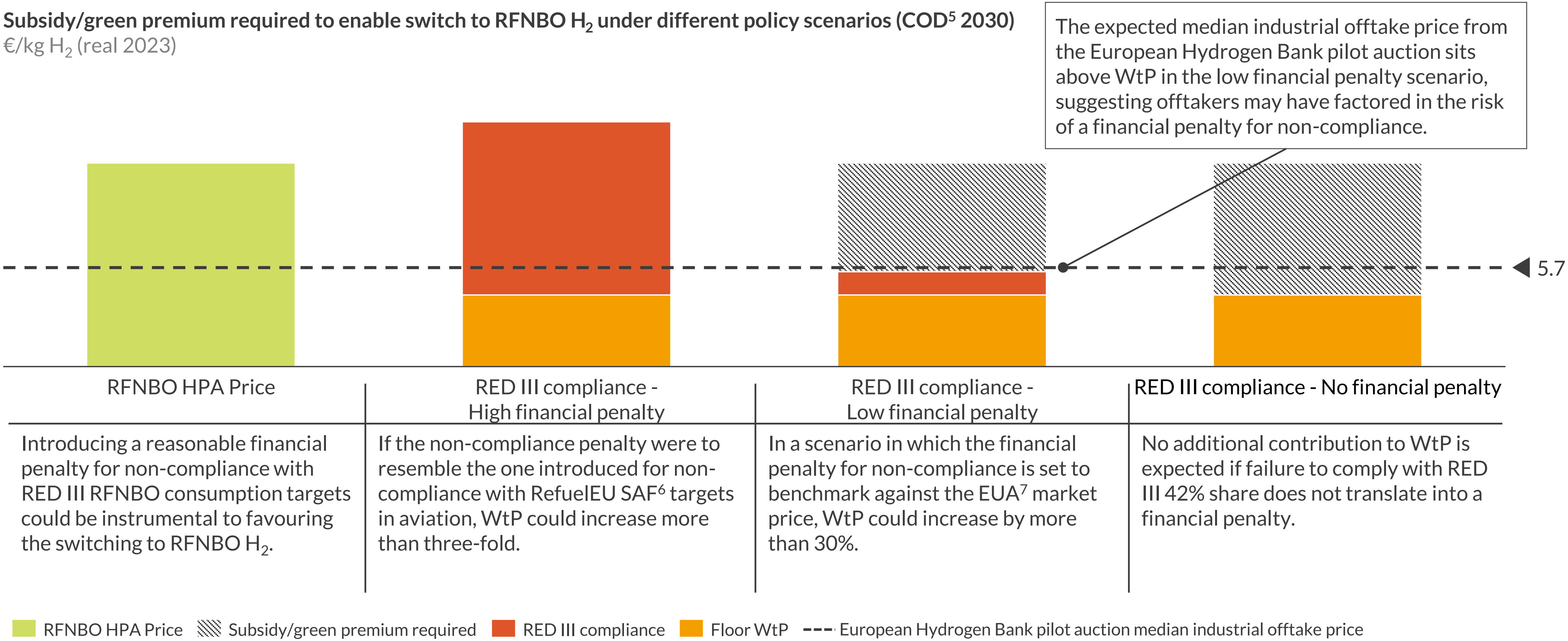
RED III set a binding mandate for RFNBO[3] use in industry. With Union-level precedents[4] of penalties for non-compliance, it is possible that Member States will implement financial enforcement measures to ensure mandates are realised. Amid the uncertainty of penalties, we designed three scenarios to assess potential impacts on WtP.

Subsidy/green premium required to enable switch to RFNBO H_2 under different policy scenarios (COD[5] 2030)

€/kg H_2 (real 2023)



RFNBO HPA Price	RED III compliance - High financial penalty	RED III compliance - Low financial penalty	RED III compliance - No financial penalty
Introducing a reasonable financial penalty for non-compliance with RED III RFNBO consumption targets could be instrumental to favouring the switching to RFNBO H_2.	If the non-compliance penalty were to resemble the one introduced for non-compliance with RefuelEU SAF[6] targets in aviation, WtP could increase more than three-fold.	In a scenario in which the financial penalty for non-compliance is set to benchmark against the EUA[7] market price, WtP could increase by more than 30%.	No additional contribution to WtP is expected if failure to comply with RED III 42% share does not translate into a financial penalty.

1) RED III: Renewable Energy Directive, i.e. (EU) 2018/2001 revised by (EU) 2023/2413. 2) WtP: Willingness to pay. 3) RFNBO: Renewables fuels of non-biological origin. 4) Precedents include penalties in RefuelEU directives and others such as penalty on non-surrender of allowances in ETS. 5) COD: Commercial operation date. 6) SAF: Sustainable aviation fuels. 7) EUA: EU allowance.

Sources: Aurora Energy Research, European Commission

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Europe produces 7% of the world's steel and shows a robust pipeline of DRI[1] based projects aimed at decarbonising primary steel production

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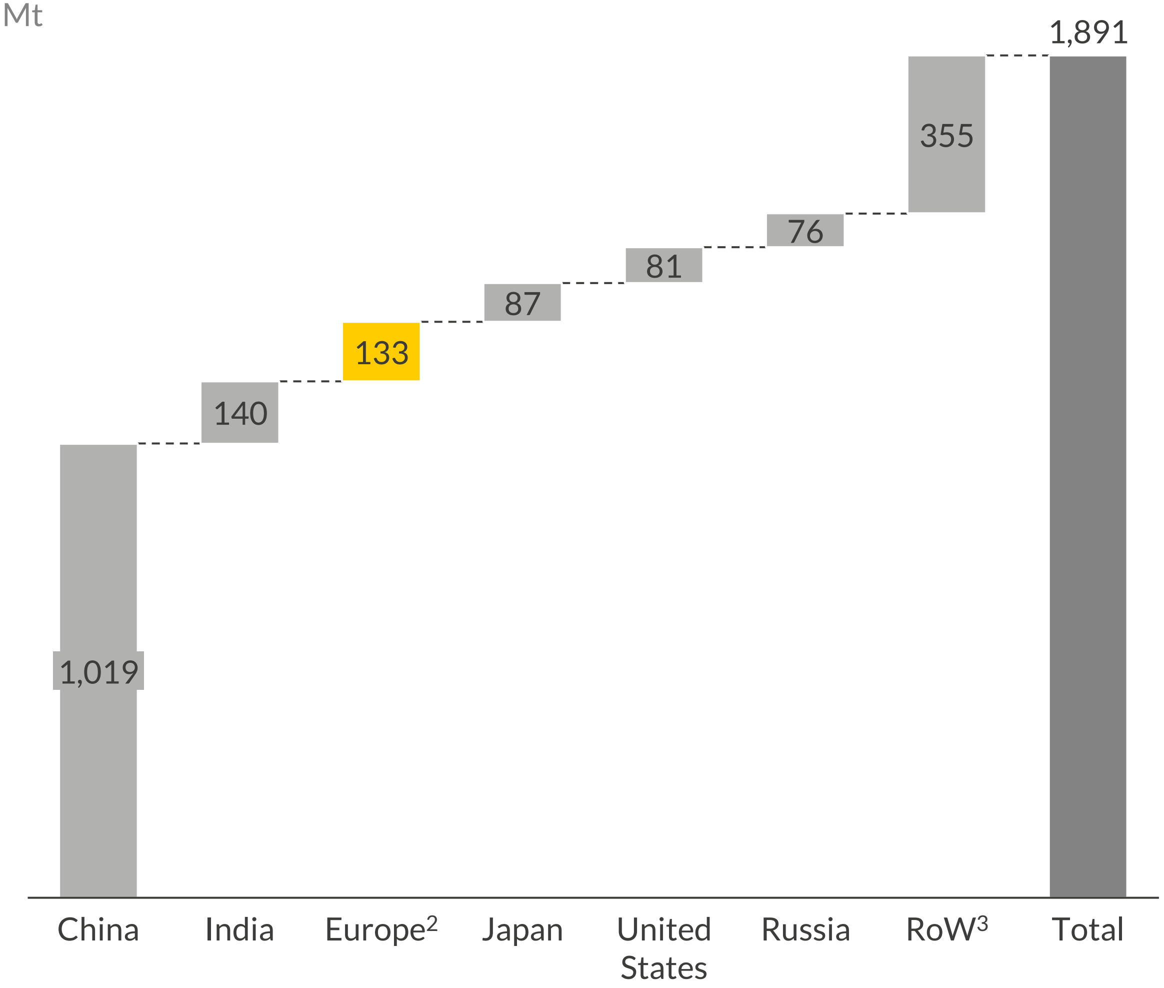
Overview of the steelmaking industry

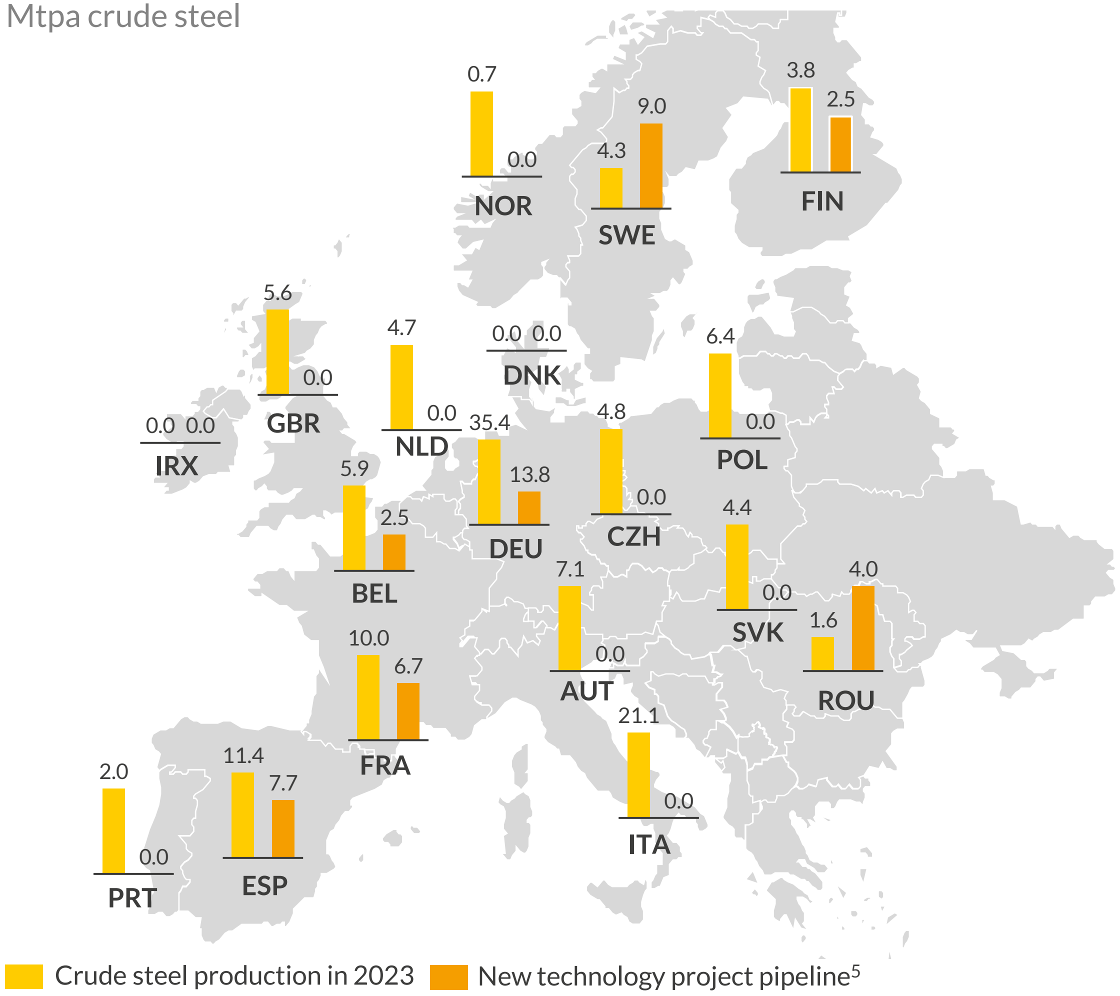
Global crude steel production by region, 2023

Mt



Crude steel production 2023 and capacity of DRI project pipeline[4]

Mtpa crude steel



1) DRI: Direct reduced iron. 2) EU27 + UK + Norway + Switzerland. 3) RoW: Rest of world. 4) Only HyMaR countries and other non-EU countries with production greater than 1.5Mtpa are shown. 5) DRI only & DRI-EAF (electric arc furnace) plants are considered. Where DRI capacity is not known, the crude steel capacity is shown. 6Mtpa DRI plant by Blastr not shown on the map due to location uncertainty.

Sources: Aurora Energy Research, World Steel Association, European Commission, Bundesministerium für Wirtschaft und Klimaschutz

We estimate the floor offtakers' willingness to pay for low-carbon H_2 in the steel sector by comparing four different production technologies

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Conceptual framework of the analysis

Step I

Four steel production routes are compared. Only processes which can also produce primary steel are considered.

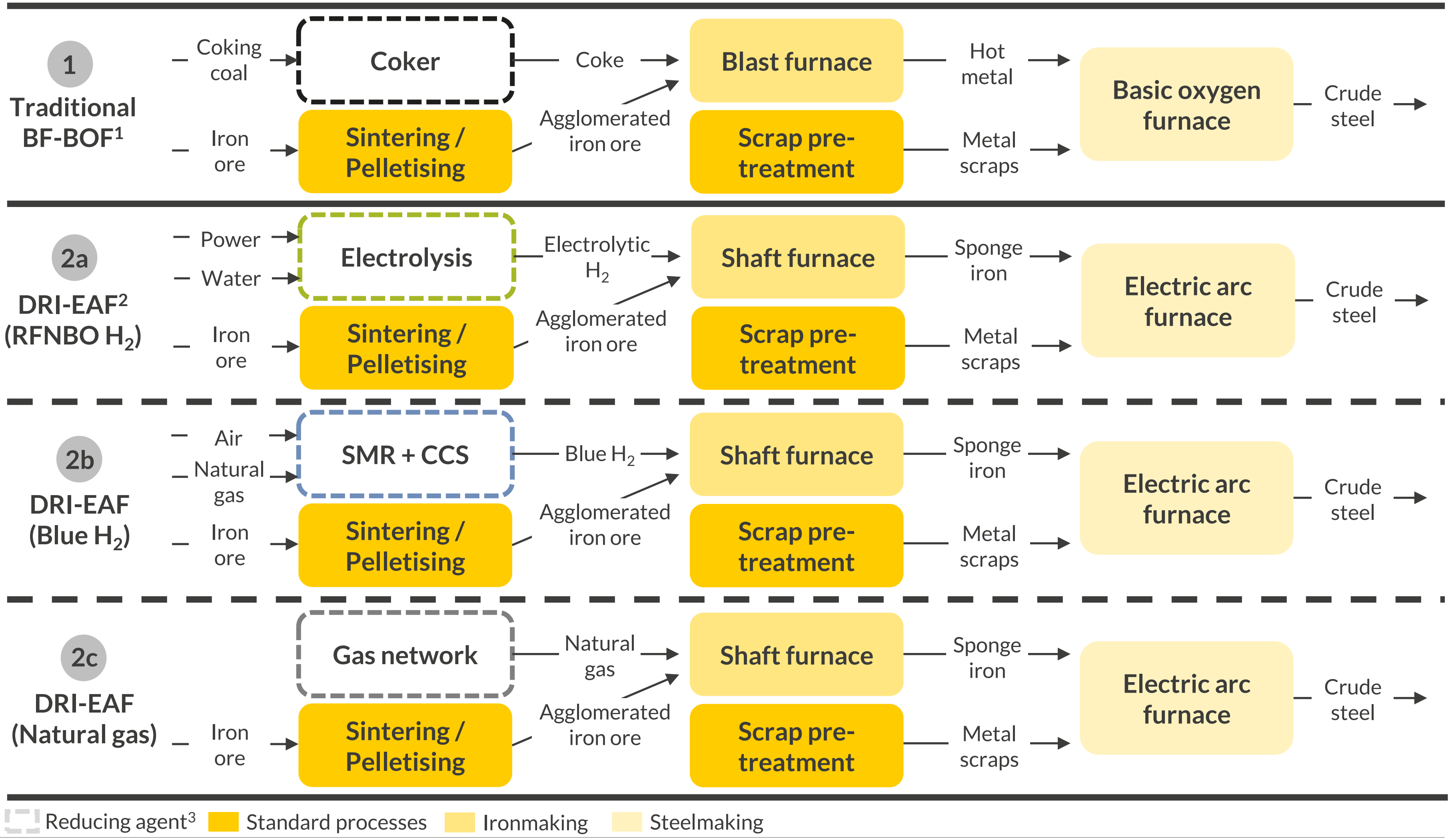
Step II

The levelised cost of steel (LCOS) for each production route is assessed. Energy commodity prices reflect Aurora's forecasts.

Step III

Floor willingness to pay for low-carbon H_2 is determined. Deep-dive on the methodology on the next slide.

Steel production routes considered in our analysis



1) BF-BOF: Blast furnace-basic oxygen furnace. 2) DRI-EAF: Direct reduced iron-electric arc furnace. 3) Reducing agent is the commodity used to convert iron ore (oxide) to metal iron.

Source: Aurora Energy Research

Redacted version. Figures available to subscribers.

The floor H_2 willingness to pay can be defined as the price that would make the H_2-based technology competitive with the traditional one

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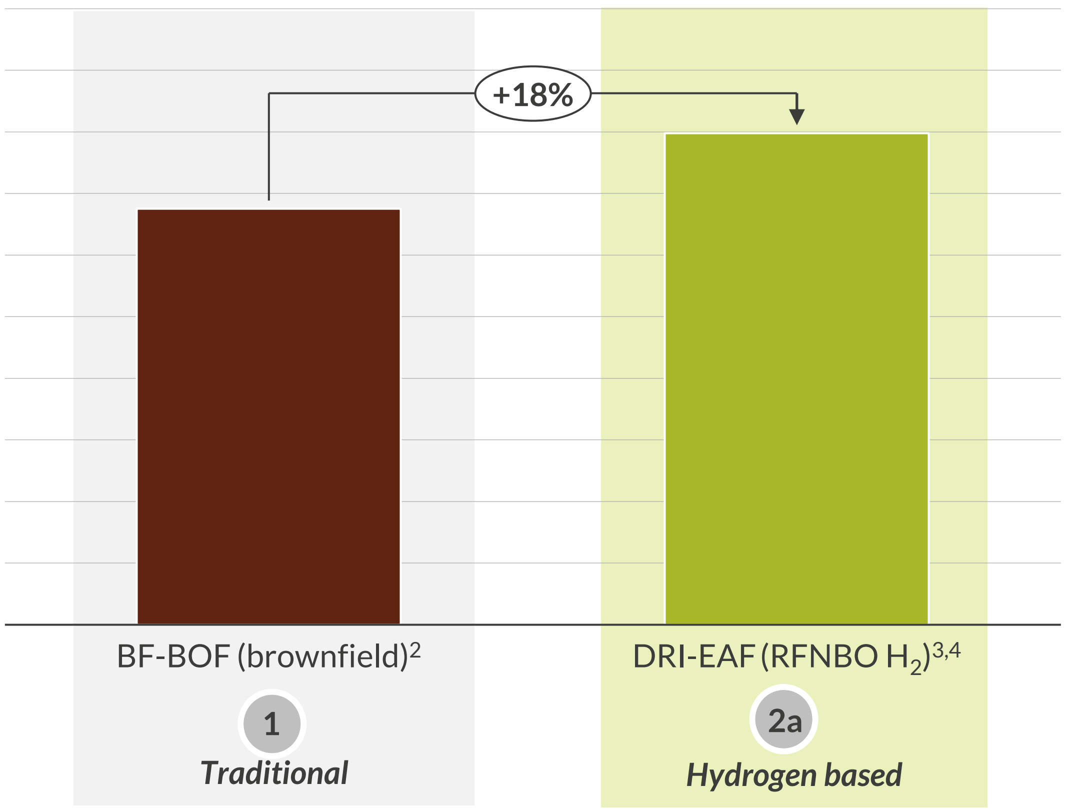
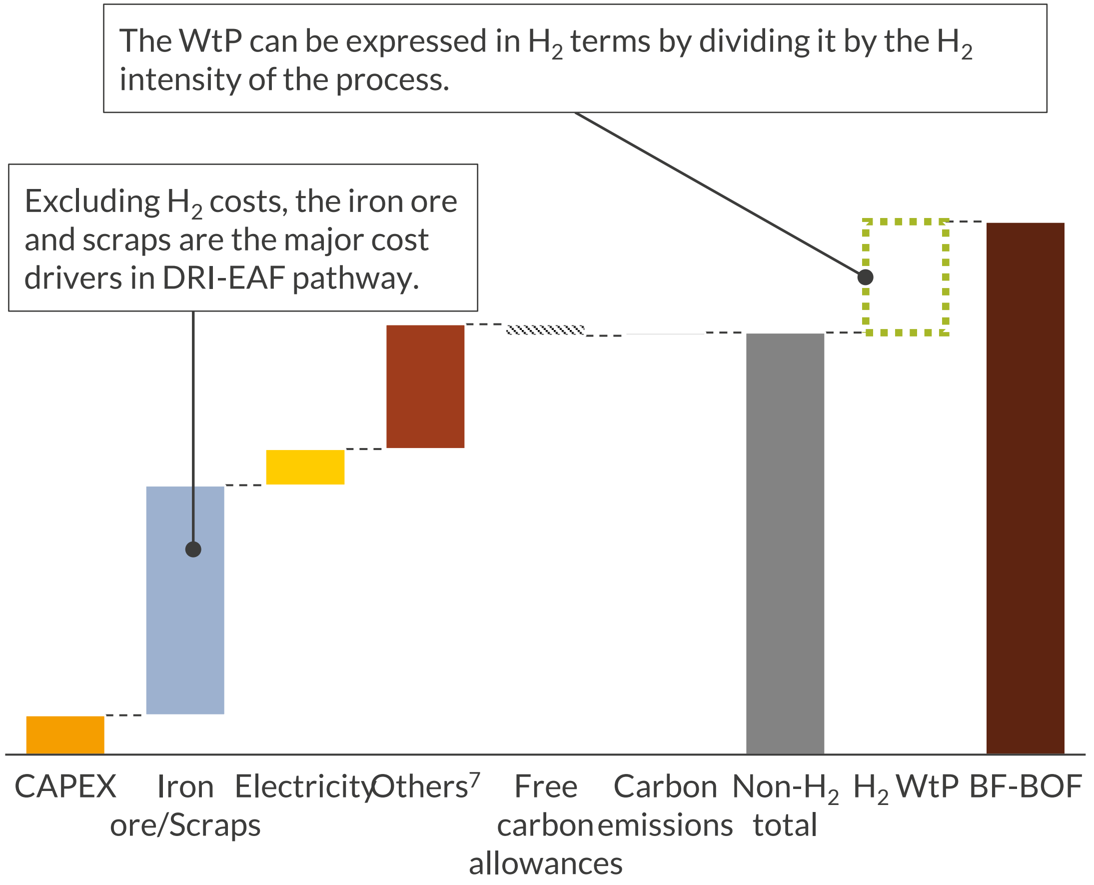
Assessment of levelised cost of steel for different production routes

Levelised cost of steel (COD[1] 2030)
€/tonne crude steel



Methodology to estimate the willingness to pay in the steel sector

WtP[5] estimation for hydrogen-based steel production[6] (COD 2030)
€/tonne crude steel (real 2023)



1) COD: Commercial operation date. 2) BOF: Blast furnace-basic oxygen furnace. 3) DRI-EAF: Direct reduced iron-electric arc furnace. 4) RFNBO: Renewable fuels of non-biological origin. 5) WtP: Willingness to pay. 6) For a metal scrap recycling rate of 50%. 7) Others include FOM, feedstock transport, delivery, industrial gases, ferroalloys, fluxes and labour.

Source: Aurora Energy Research

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While the UK and EU share similarities in implementing ETS[1] and a CBAM[2], notable differences are found in the design of their hydrogen auctions

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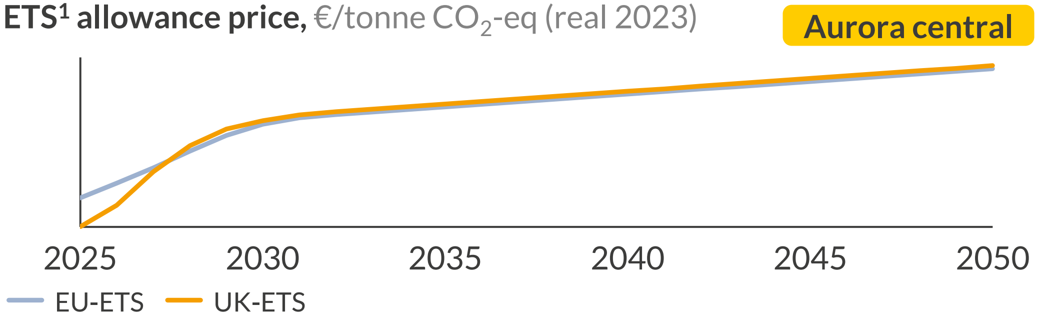
	European Union	United Kingdom
Consumption mandates	▪ RED III[3] introduced RFNBO[4] consumption mandates in industry. ▪ RefuelEU set consumption mandates for aviation and maritime sectors.	▪ No consumption mandates in industry.
Auction design for hydrogen	▪ EHB[5] auctions allocate financial support in the form of a fixed premium. ▪ The first round cleared at 0.48 €/kg H_2.	▪ UK Hydrogen Allocation Rounds (HAR) provide operational support via a contract for difference (CfD) scheme. ▪ The first round, HAR1, cleared at a weighted average strike price of £241/MWh (~£9.5/kg H_2), with natural gas price setting the floor price.
Carbon border adjustment mechanism	▪ Transition phase ("reporting only") between 2023 and end of 2025. ▪ Electricity, **hydrogen**, cement, fertilisers, aluminium, iron and steel sectors are included. ▪ EU importers must surrender EU CBAM certificates priced at the EUA[6] price at the time of surrendering.	▪ No transition period. Fully operational from 2027. ▪ Ceramics, glass, **hydrogen**, cement, fertilisers, aluminium, iron and steel sectors are included. ▪ UK CBAM will be operated as a levy similar to other import taxes, the price of which would be sector-specific and set quarterly by the government.

Emissions trading scheme

ETS[1] allowance price, €/tonne CO_2-eq (real 2023)



- The UK launched its own emission trading scheme in 2021.
- The phaseout of free allowances in the UK-ETS is only concrete for the aviation sector by 2026. However, for our analysis we assumed that the pace of the phaseout will follow benchmarks and phaseout factors as set in the EU ETS.
- Industries are exposed to the UK-ETS without the carbon price support (CPS).

1) ETS: Emissions Trading Scheme. 2) CBAM: Carbon border adjustment mechanism. 3) Renewable Energy Directive, i.e. (EU) 2018/2001 revised by (EU) 2023/2413. 4) RFNBO: Renewable fuels of non-biological origin. 5) EHB: European Hydrogen Bank. 6) EUA: European Union allowance. 7) CPS: Carbon price support.

Sources: Aurora Energy Research, European Commission, Department for Energy Security and Net Zero

Redacted version. Figures available to subscribers.

Willingness to pay for low-carbon H_2 in the ammonia sector is expected to exceed the floor price[1] set in the CfD[2] scheme from HAR1[3]

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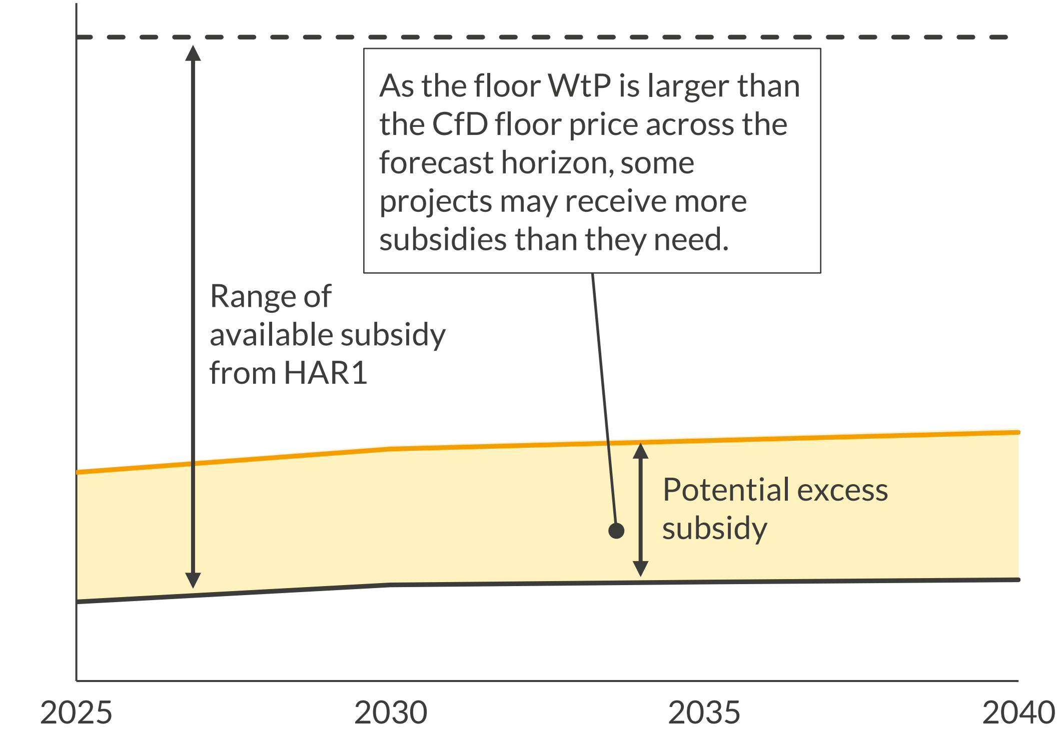
According to our analysis the potential willingness to pay for low-carbon H_2 for ammonia production is well above the floor price[1] set in HAR1 for the CfD across the forecast horizon.

HAR1 CfD components and low-carbon H_2 WtP[4] in ammonia sector

£/MWh_{HHV} (real 2023)



Floor WtP in the ammonia sector — CfD floor price (Aurora Central)[1] — Weighted average CfD strike price

How does the design of the CfD floor price relative to WtP impact different stakeholders?

Stakeholder	Impact
Electrolyser project developers	+ Securing an offtake is facilitated. + Offtakers are incentivised to sign HPAs[5] with longer tenure, reducing electrolyser projects' merchant tail.
Hydrogen offtakers	+ Cost to decarbonise is reduced. + Low-carbon H_2 price risk is reduced. + Current consumers of grey H_2 may be able to save money relative to their current costs by switching to low-carbon H_2.
Government	+ Propels low-carbon H_2 economy. – Little incentive to low-carbon H_2 producers to try to secure a higher offtake price. – Risk of over-subsidisation.

1) 120% of Aurora's Apr-24 Central forecast of UK natural gas price in alignment with Section 9.9 of the Low-carbon Hydrogen Agreement regarding hydrogen use as feedstock. 2) CfD: Contract for difference. 3) HAR1: Hydrogen Allocation Round 1. 4) WtP: Willingness to pay. 5) HPA: Hydrogen purchase agreement.

Sources: Aurora Energy Research, Department for Energy Security and Net Zero

Agenda

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I. Setting the scene

II. Willingness to pay for hydrogen in the ammonia sector

III. Willingness to pay for hydrogen in the steel industry

IV. UK's Hydrogen Allocation Rounds and willingness to pay

V. Key takeaways

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Key takeaways

A key barrier to adopting low-carbon hydrogen in end use sectors is the gap between the cost of the hydrogen and the incumbent, fossil-fuel based technology.

In Germany, offtakers' willingness to pay for low-carbon hydrogen in the ammonia sector is expected to grow over time. The gap between willingness to pay and German domestic HPA[1] prices remains substantial across the forecast horizon but could be mitigated by the implementation of a financial penalty for non-compliance with RED III[2] RFNBO[3] consumption targets.

The growth of willingness to pay for low-carbon hydrogen in the steel industry is driven by the strong sensitivity to the rise in the carbon price of the traditional coal-based production route.

Similar levels of willingness to pay for low-carbon hydrogen are expected in the UK. Although the CfD scheme delivered through Hydrogen Allocation Rounds can expedite the commercial closure of projects, its current design carries the risk of excessive subsidisation.

1) Hydrogen purchase agreement. 2) Renewable Energy Directive, i.e. (EU) 2018/2001 revised by (EU) 2023/2413. 3) Renewable fuels of non-biological origin.

Source: Aurora Energy Research

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