Investment Outlook for Low-Carbon Hydrogen

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Objective

- This analysis aims to provide an overview of the future market size for low-carbon hydrogen, based on the current maturity stage of individual projects. We estimate potential delays in the sector by comparing the original commissioning dates of individual projects with the latest forecasts.
- The analysis examines the geographical distribution of projects across various regions and estimates which production technologies are likely to be used (e.g., electrolyzer/green vs. thermochemical/blue).
- Additionally, the analysis provides estimates of the competitiveness of different technologies, based on certain assumptions, and quantifies the cost gap between low-carbon fuels and fossil fuels. It also offers an overview of major public subsidy schemes, either currently in force or announced.

Conclusions

- Looking to 2030, 95 GW of electrolyzer projects are at least in the pre-FEED phase according to BloombergNEF's Database for Hydrogen Supply Outlook 2024. Of these, 35 GW are in FEED studies, and given past delays and cancellations, one may anticipate a 2030 capacity closer to this range. Currently, 9 GW have reached FID.
- The deployment of power-to-X projects has taken longer than expected over the past two years. The industry has been slowed by rising interest rates, increased material costs, and energy price uncertainty due to the war in Ukraine. Initial assumptions about CAPEX and production scalability were overly optimistic.
- Public funding is just starting to emerge, as shown by the EU Hydrogen Bank's single allocation round for green hydrogen. The US Inflation Reduction Act (IRA) is still not fully finalized, and offtakers are hesitant to commit to long-term agreements in this nascent market. Consequently, few projects have reached a final investment decision (FID).
- Our analysis shows that green hydrogen (via electrolysis) is significantly more expensive than fossil-based hydrogen, with a price differential of 90–160% when using a range of plausible assumptions. By 2030, this gap is likely to narrow to 40–95% due to lower CAPEX and lower electricity costs. However, closing this gap is delayed if the price of natural gas declines as energy markets continues to adjust and normalize on the back-side of Russia's war. Public funding will be vital for closing this gap. Despite cost disparities, we believe public funding and Europe's need to diversify energy sources will drive early green hydrogen deployment, supported by companies committing to offtake agreements and early fuel-blending requirements. Several geographies look to become key players in green hydrogen production due to their ample solar, wind, and land resources for energy projects. This includes Australia, eastern Canada, Northern Africa, and quite possibly China.
- Blue hydrogen (from natural gas with carbon capture) is expected to dominate the low-carbon hydrogen market for the next decade. Currently, blue hydrogen is 10–30% more expensive than fossil-based hydrogen, but by 2030 this gap may close, with prices ranging from -5% to +15%. Based on the price differential to green hydrogen, we believe that blue hydrogen will be a preferred source of low-carbon hydrogen in the short-term barring any unfavorable regulations. As a result, investments will likely concentrate in areas with cheap natural gas, like the USA and Canada.
- The US is expected to produce 80% of its hydrogen from blue sources. Contrary to some forecasts, we anticipate the Middle East will play a larger role than the predicted 5% market share, thanks to its abundant natural gas, solar PV, and wind resources, along with proximity to Europe. In Europe, the UK and Norway have the greatest potential for blue hydrogen production.

The hydrogen economy is a small share of a very large energy demand

› The global energy supply currently totals around 178,000 TWh annually across all energy sources, including oil, gas, coal, renewables, and nuclear.

› Hydrogen presently accounts for 1.8% of global energy supply, all of which is produced using fossil fuels.

› Looking ahead, the IEA projects that hydrogen's share in the global energy mix will rise to 2.6% by 2050 in the STEPS scenario, and to 6.0% in the more ambitious APS scenario. This growth is driven by increasing applications of low-carbon hydrogen to replace fossil fuels.

› However, these projections may underestimate the potential growth of the low-carbon hydrogen economy (green and blue hydrogen), as over time, it will replace the current fossil-based hydrogen production (grey and black hydrogen).

› For context, hydrogen is expected to account for 12% of global renewable electricity generation in the STEPS scenario and 18% in the APS scenario by 2050.

Size of global energy supply and hydrogen demand

Total energy supply (TWh)	**2023**	**2030**	**2035**	**2050**
Announced pledges	178.476	178.198	173.472	176.530
Stated policies	178.476	188.206	189.596	200.716

Hydrogen demand (TWh)	**2023**	**2030**	**2035**	**2050**
Announced pledges	3.176	3.963	5.489	10.562
Stated policies	3.176	3.707	4.067	5.189

Hydrogen as % of total energy supply	**2023**	**2030**	**2035**	**2050**
Announced pledges	1,8	2,2	3,2	6,0
Stated policies	1,8	2,0	2,1	2,6

Source: *IEA, World Energy Outlook 2024.*

IEAs scenarios

- *The 'Announced Pledges Scenario' (APS): Reflects the impact of all announced climate commitments and policies by governments, including net-zero targets and pledges to reduce emissions. Projects global emissions to peak soon and decline, but not fast enough to limit warming to 1.5°C. It aligns with a temperature rise of around 1.7–2.1°C by 2100.*
- *The 'Stated Policies Scenario' (STEPS) is a more conservative outlook, assuming limited progress beyond existing measures. It considers only policies and measures that have been implemented or are under active development. Projects slower emissions reductions compared to APS, leading to a higher warming trajectory, around 2.4–2.7°C.*

Efficient use of energy
Direct electrification before power-to-X

› Converting energy from one form to another consumes energy. Therefore, it is both most energy-efficient and cost-effective to use electricity from wind and solar power directly.

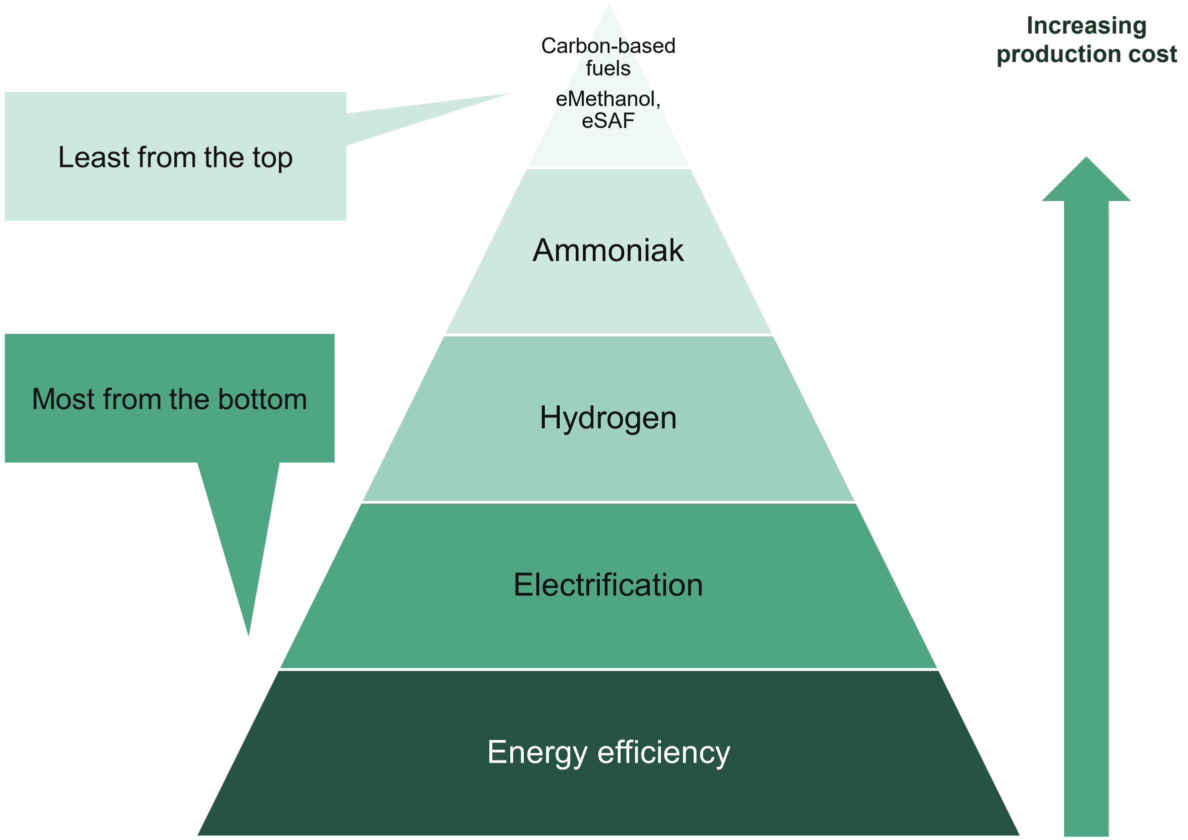
› As a result, the electricity system should remain the central focus of the energy transition. This includes expanding renewable energy production, enhancing the electricity grid, developing energy storage solutions, and promoting flexible electricity consumption.

› Hydrogen and hydrogen-based fuels, however, play a role in certain applications where direct electrification is not a viable solution. These fuels are expensive to produce due to the energy-intensive conversion processes involved and, from an economic perspective, should be limited to applications where direct electrification is not an option.

› From a technical standpoint, these fuels may be necessary in scenarios requiring the ability to store energy, physical molecules, or applications involving high temperatures.

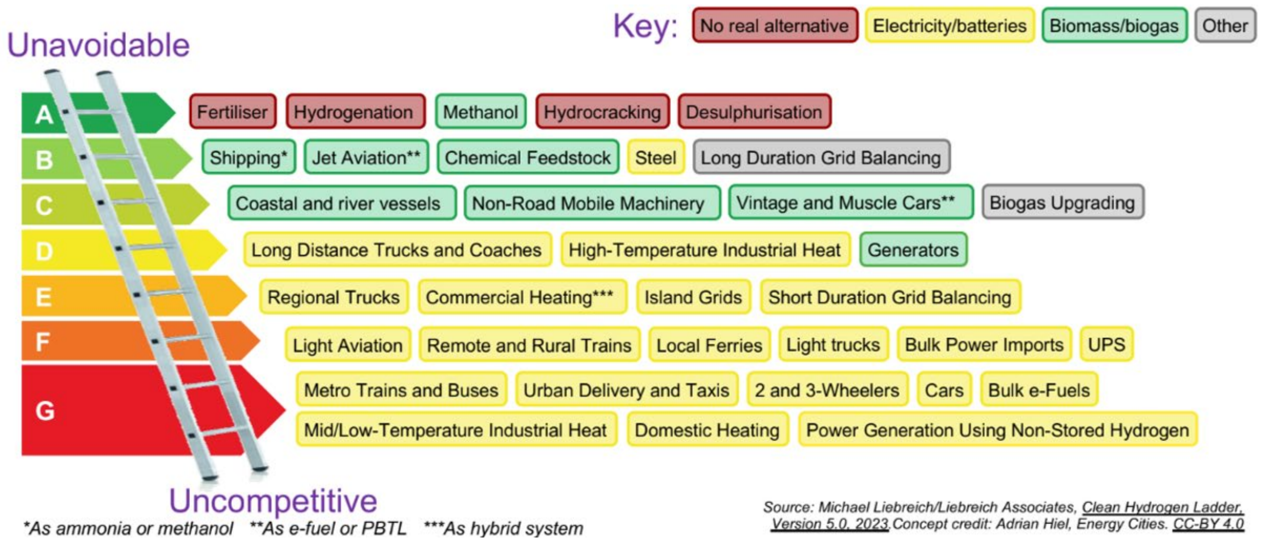
› When hydrogen cannot be used—often due to its low energy density—the next alternative is ammonia, which combines hydrogen with nitrogen (an abundant element in the atmosphere).

› Carbon-based fuels, such as eSAF (electro-sustainable aviation fuel), are among the most expensive options because they involve multiple energy conversion processes and require access to CO_2.



Where to use power-to-X and where to use another form of energy

- The ‘Hydrogen Ladder’, developed by Liebreich Associates, assesses whether power-to-X solutions (such as hydrogen and hydrogen-based fuels) are economically competitive compared to alternative technologies that are technically feasible for a given application.
- The ladder indicates that power-to-X (marked in red) is essential for specific applications like fertilizer production, biogas upgrading (hydrogenation), gasoline and diesel production (hydrocracking), and desulfurization (used in steel production and flue gas cleaning). In these areas, there are no technically or economically viable alternatives.
- Biomass-based fuels (marked in green) are best suited for producing carbon-based fuels needed for certain applications, such as aviation fuel, methanol (used as a chemical feedstock or in shipping), and green diesel. However, if biomass availability is insufficient, it may necessitate the use of low-emission fuels like green and blue hydrogen, despite their higher production costs.
- The ladder also highlights a range of applications where direct electrification (marked in yellow) is preferable. These include both light and heavy road transport, short-distance aviation, rail operations, residential heating, process heating, and grid balancing.



Source: *Liebreich Associates, Hydrogen Ladder v. 5.0*

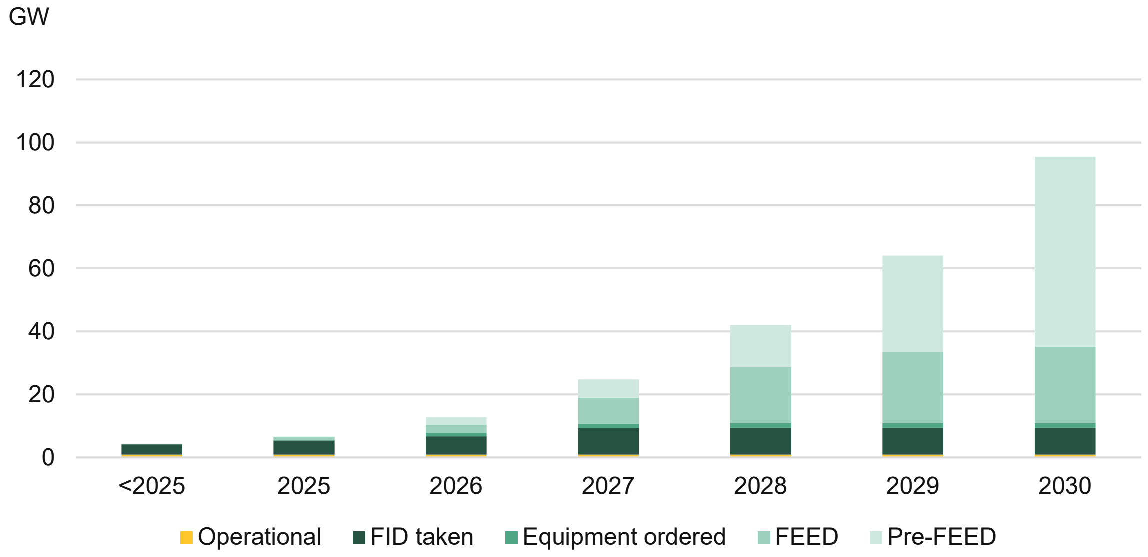
Pipeline

Global pipeline of green projects BNEF estimates

BNEF maintains a 'bottom-up'-style database of hydrogen projects and which they follow each project and provides a forecasted Commercial Operational Date. The database shows current projects status; operational, FID, equipment ordered, FEED, pre-FEED. This is useful to gauge a detailed status of the global project pipeline.

- At a global level, BNEF forecasts that up to 95 GW of electrolyzer capacity could be operational by 2030. This forecast accounts for potential changes to the commissioning timeline based on project-level assessments.
- Of this total capacity, 35 GW (37%) is in advanced stages of development, making it the most certain. We define advanced development stages as those that include the FEED stage (Front-End Engineering Design, which involves detailed engineering), equipment being ordered, FID (Final Investment Decision) being made, or projects that are already operational.
- The remaining 60 GW (63%) are in the pre-FEED stage, which is a preliminary step taken before detailed engineering work and is used to broadly assess the technical and economic feasibility of the project. Although this capacity is part of the overall forecast, it is naturally less certain. Projects that have not yet entered the pre-FEED phase and are still in the conceptual phase have been excluded from this forecast.
- FID has already been made for 8.5 GW (9%) of the global capacity, which is expected to be operational by 2030.
- BNEF's forecasted pipeline, which includes projects up to the pre-FEED stage, represents about 50% of the IEA database capacity expected by 2030. In the IEA database, projects still in the 'concept phase' have already been filtered out.

Global pipeline of GREEN hydrogen production capacity by current stage of project maturity



Cumulative electrolyzer capacity by project status

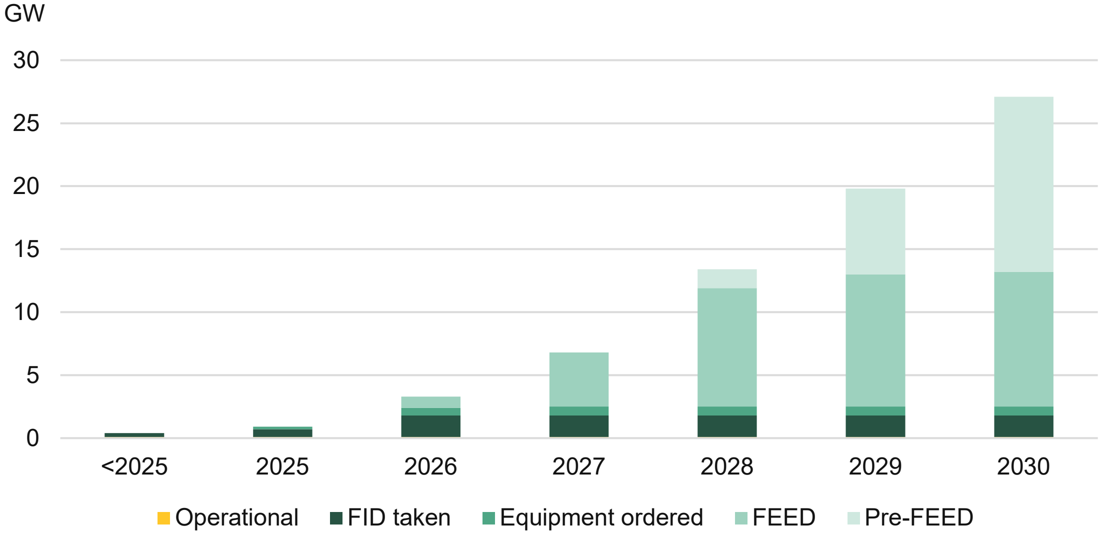
	<2025	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Operational	0,9	0,9	0,9	0,9	0,9	0,9	0,9
FID taken	3,3	4,5	5,8	8,4	8,5	8,5	8,5
Equipment ordered	0,0	0,2	1,1	1,5	1,5	1,5	1,5
FEED	0,2	1,0	2,7	8,2	17,7	22,7	24,2
Pre-FEED	-	-	2,3	5,8	13,5	30,5	60,4
Total	**4,4**	**6,7**	**12,8**	**24,8**	**42,1**	**64,1**	**95,4**

Source: *BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

European pipeline
Home of the electrolyzer

- Europe is expected to have 27 GW of electrolyzer capacity by 2030.
- Of this capacity, 13.2 GW (49%) is currently in advanced planning stages (FEED study and more mature phases). Unfortunately, this isn't always sufficient, as demonstrated by Orsted's decision to abandon its Swedish Flagship 1 methanol project, even though the FID was taken in 2022.
- The remaining 13.9 GW (51%) is in the pre-FEED phase. Projects still in the ‘concept phase’ are not included in this forecast.
- Currently, about 0.1 GW (0.4%) is operational. FID has been taken on 1.7 GW (6.3%), and equipment has been ordered for an additional 0.7 GW (2.6%).
- When comparing this pipeline forecast to the EU’s REPowerEU target of 40 GW capacity (and Denmark’s target of 4–6 GW), it becomes clear that we are likely to miss the target by a significant margin.
- 70% of hydrogen production is expected to be green, with blue hydrogen production anticipated in both the UK and Norway. By 2030, Europe’s annual low-carbon hydrogen production is expected to reach 4.0 MT/y.

Europe GREEN hydrogen production capacity by current stage of project maturity



Cumulative electrolyzer capacity by project status - EUROPE

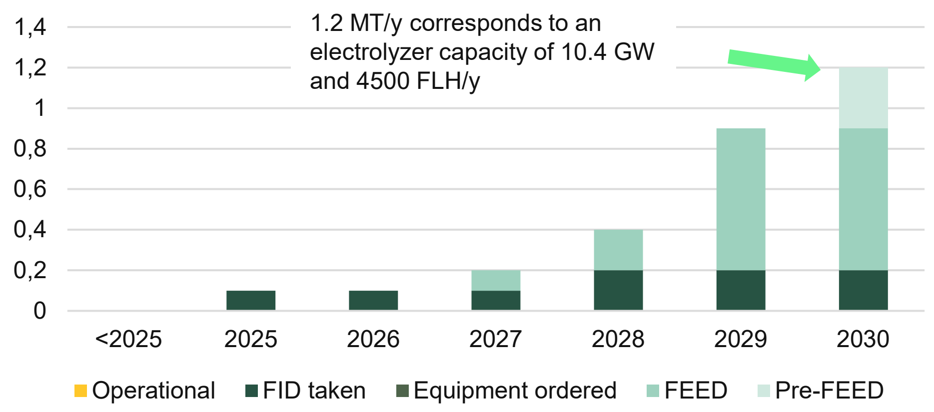
	<2025	2025	2026	2027	2028	2029	2030
Operational	0,1	0,1	0,1	0,1	0,1	0,1	0,1
FID taken	0,3	0,6	1,7	1,7	1,7	1,7	1,7
Equipment ordered	0,0	0,2	0,6	0,7	0,7	0,7	0,7
FEED	-	0,0	0,9	4,3	9,4	10,5	10,7
Pre-FEED	-	-	-	0,0	1,5	6,8	13,9
Total	**0,4**	**1,0**	**3,4**	**6,8**	**13,5**	**19,9**	**27,1**

***Source:** BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

US pipeline
80% of production expected to be blue H2

- By 2030, 80% of hydrogen production in the USA is expected to be blue.
- Large-scale blue hydrogen production is projected to start 1–2 years ahead of green hydrogen projects in the U.S.
- Both the U.S., and to a lesser extent Canada, are expected to become the dominant producers of low-carbon hydrogen.

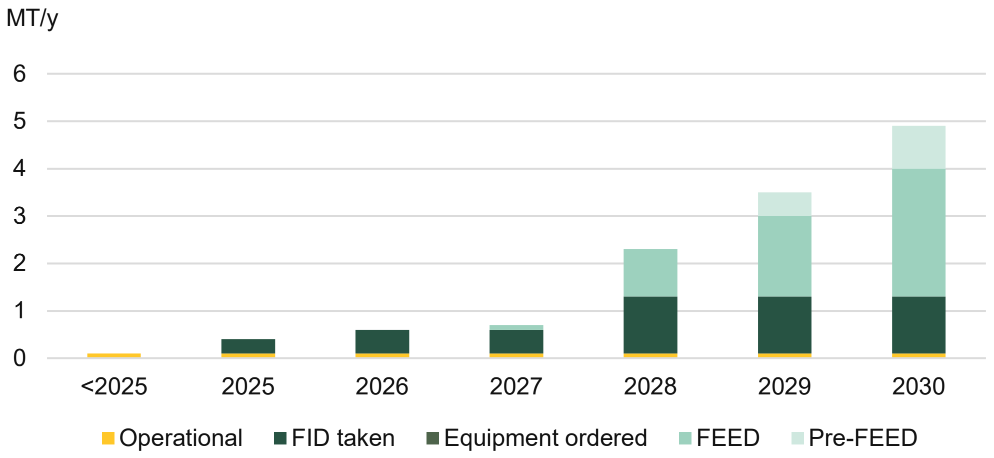
USA annual GREEN hydrogen production



Annual hydrogen supply by project status – USA

	<2025	2025	2026	2027	2028	2029	2030
Operational	0,0	0,0	0,0	0,0	0,0	0,0	0,0
FID taken	0,0	0,1	0,1	0,1	0,2	0,2	0,2
Equipment ordered	-	-	0,0	0,0	0,0	0,0	0,0
FEED	-	-	-	0,1	0,2	0,7	0,7
Pre-FEED	-	-	-	-	-	0,0	0,3
Total	**0,0**	**0,1**	**0,2**	**0,3**	**0,4**	**0,9**	**1,2**

USA BLUE hydrogen production



Annual hydrogen supply by project status - USA

	<2025	2025	2026	2027	2028	2029	2030
Operational	0,1	0,1	0,1	0,1	0,1	0,1	0,1
FID taken	-	0,3	0,5	0,5	1,2	1,2	1,2
Equipment ordered	-	-	-	-	-	-	-
FEED	-	-	0,0	0,1	1,0	1,7	2,7
Pre-FEED	-	-	-	-	-	0,5	0,9
Total	**0,1**	**0,4**	**0,6**	**0,6**	**2,2**	**3,5**	**4,8**

Note: *MT/y is million tons per year.*
Source: *BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

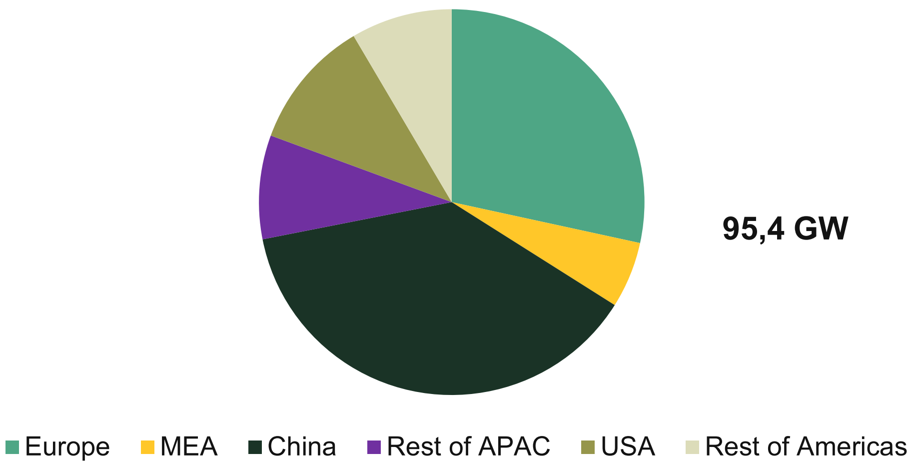
Global pipeline of green projects

› Europe accounts for 28% of the global electrolyzer pipeline (from pre-FEED to operational) and 38% of all projects in advanced stages (FEED to operational). USA holds about half of Europe's electrolyzer capacity.

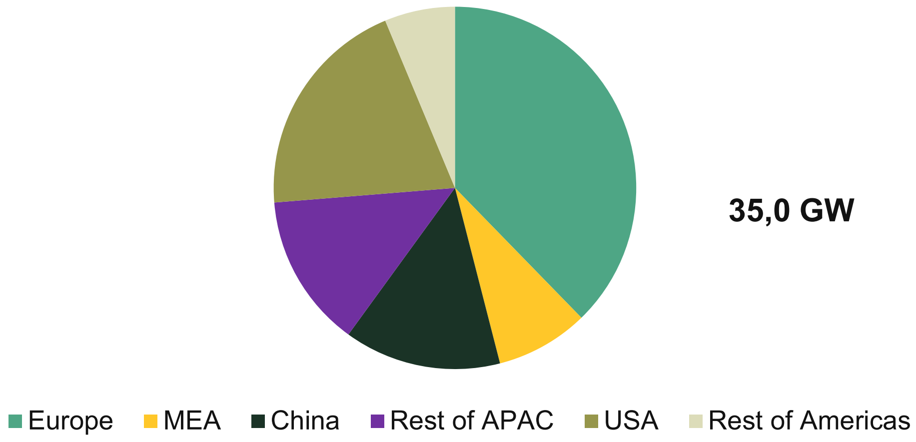
› The advanced pipeline is primarily concentrated in Western countries, including the EU, USA, and Australia (part of 'other APAC'). Middle East project pipeline seems too low compared to the its endowment of natural resources.

› China is expected to account for 38% of total capacity by 2030 across all stages but holds only 14% of the capacity in advanced stages.

Electrolyzer capacity by 2030
All development stages from pre-FEED to operational



Electrolyzer capacity by 2030
Advanced planning (FEED to operational)

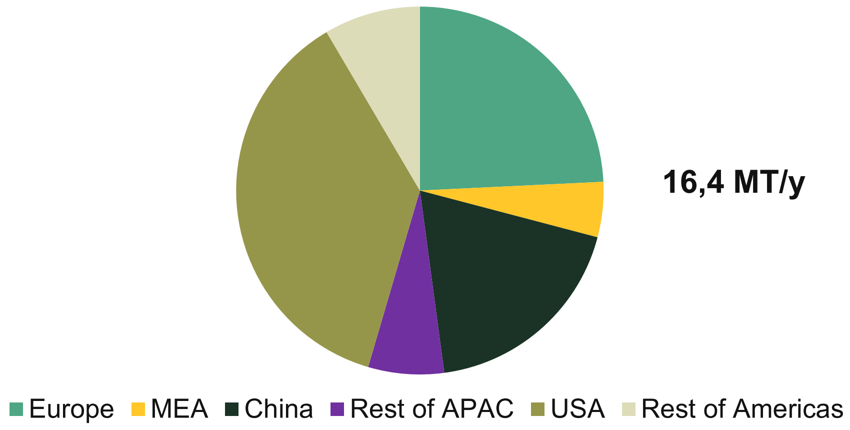


Source: *BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

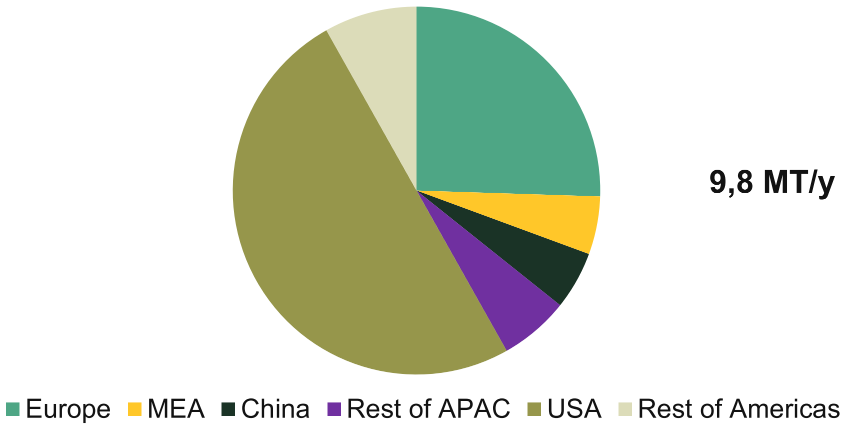
Global pipeline of low-carbon projects (green + blue)

- Globally, 58% of all low-carbon hydrogen production is expected to be green, while 42% is projected to be blue.
- By 2030, the USA is anticipated to become the dominant producer of low-carbon hydrogen, with a 37% share of the global pipeline, and 50% of this in advanced stages.
- Europe is expected to produce 25% of the world's low-carbon hydrogen.
- Interestingly, the Middle East is projected to account for only 5% of the project pipeline by 2030. This is particularly interesting, since our back of the envelope calculations show that blue hydrogen is expected to be cost competitive with fossil hydrogen by 2030.

Low-carbon hydrogen production by 2030
All development stages from pre-FEED to operational



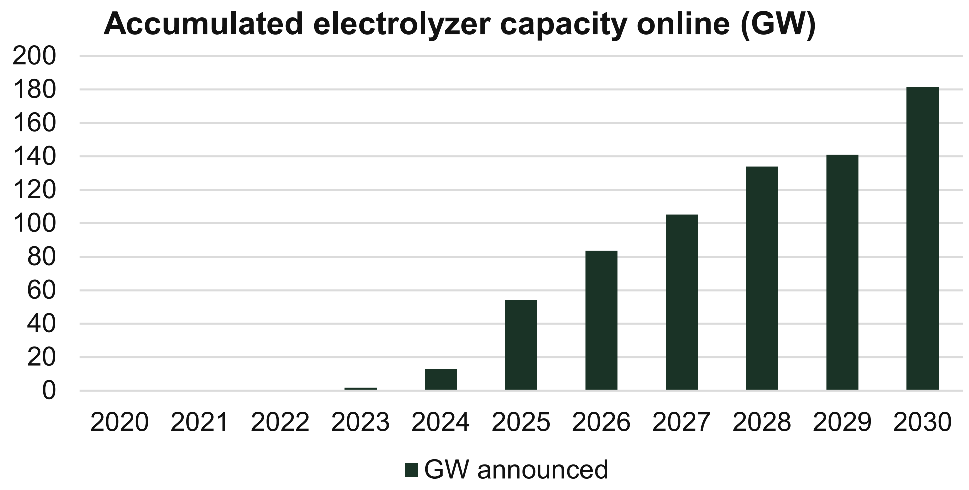
Low-carbon hydrogen production by 2030
Advanced planning (FEED to operational)



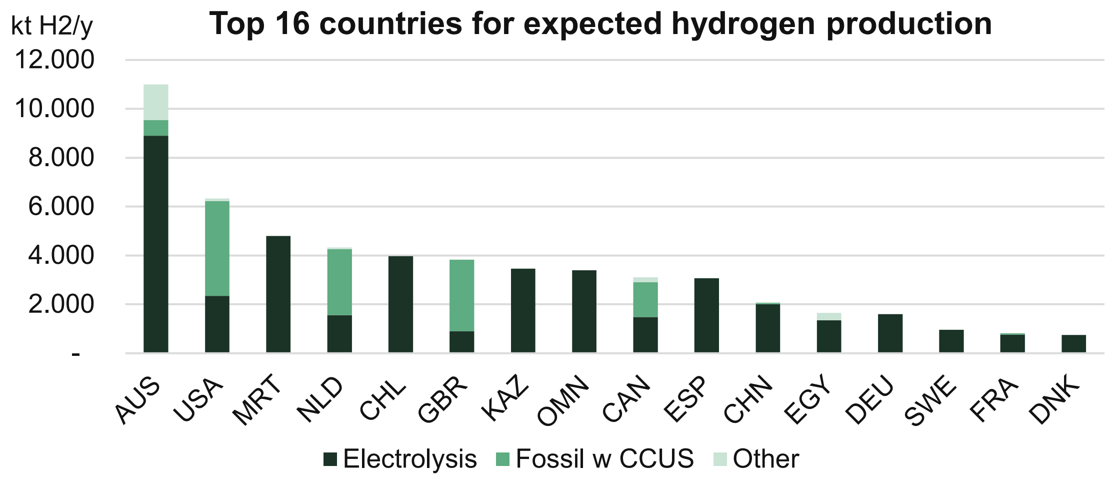
Note: *MT/y is million tons per year.*
Source: *BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

Investment in hydrogen globally According to IEAs database

- The figure on the left shows the accumulated operational electrolyzer capacity by year, as reported in the most recent IEA database (November 2023).
- Generally, the IEA's database projects nearly twice the capacity to be operational by 2030 compared to BNEF's database, even after removing projects in the 'concept phase' from the IEA's data. By 2025, the IEA predicts 54 GW of capacity to be online, while BNEF forecasts less than 7 GW.



- The IEA data also enables us to map the geographical distribution of the low-carbon hydrogen pipeline. The top three regions are Australia, the USA, and – surprisingly – Mauritania. Denmark ranks 16th.
- In comparison, the IEA database seems overly optimistic and somewhat disconnected from the more conservative outlook presented by BNEF.



***Note:** The figure covers projects that have reached at least the 'feasibility study' phase in IEA's terminology. The figure shows the year projects are expected the become operational. Projects that are in the 'concept phase' are excluded from the data.*
***Source:** IEA, Hydrogen Projects Database, November 2023.*

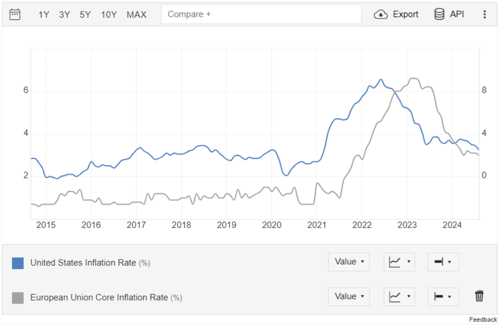
Pipeline delays

High-level perspective on development in challenges that has contributed to delays

Challenge	Direction
High interest rates increase the cost of financing projects	Interest rates are declining. The market expects the Federal Reserve to reduce its interest rate from the current 5.0% to 2.9% over the next three years
High inflation complicates the estimation of revenue and costs	Inflation in both the USA and Europe peaked in 2022/2023 at 6-8%. Current inflation rates stand at 3%, and this downward trend is expected to continue towards the target of 2%
Expensive raw materials	Copper is still 40% more expensive now than it was in 2020. Steel peaked in 2022, reaching prices 2-3 times higher than pre-COVID levels (2020-2019). However, prices have since returned to those levels, aided by a slowdown in construction activity in China
Waiting game: First projects incur the highest CAPEX and faces all the children's diseases	Still true
Offtakers are hesitant to commit to long-term offtake agreements	That remains true. Perhaps customers are gradually becoming accustomed to the idea of purchasing under different terms (longer contracts) than they are used to. Additionally, blending requirements are slowly approaching
Public funding is currently insufficient	Public funding is ramping up, led by the US and Europe. However, the allocation of funding to projects is progressing too slowly; for example, only one round of funding from the EU Hydrogen Bank has been allocated so far

US FED rate

Inflation, US, EU



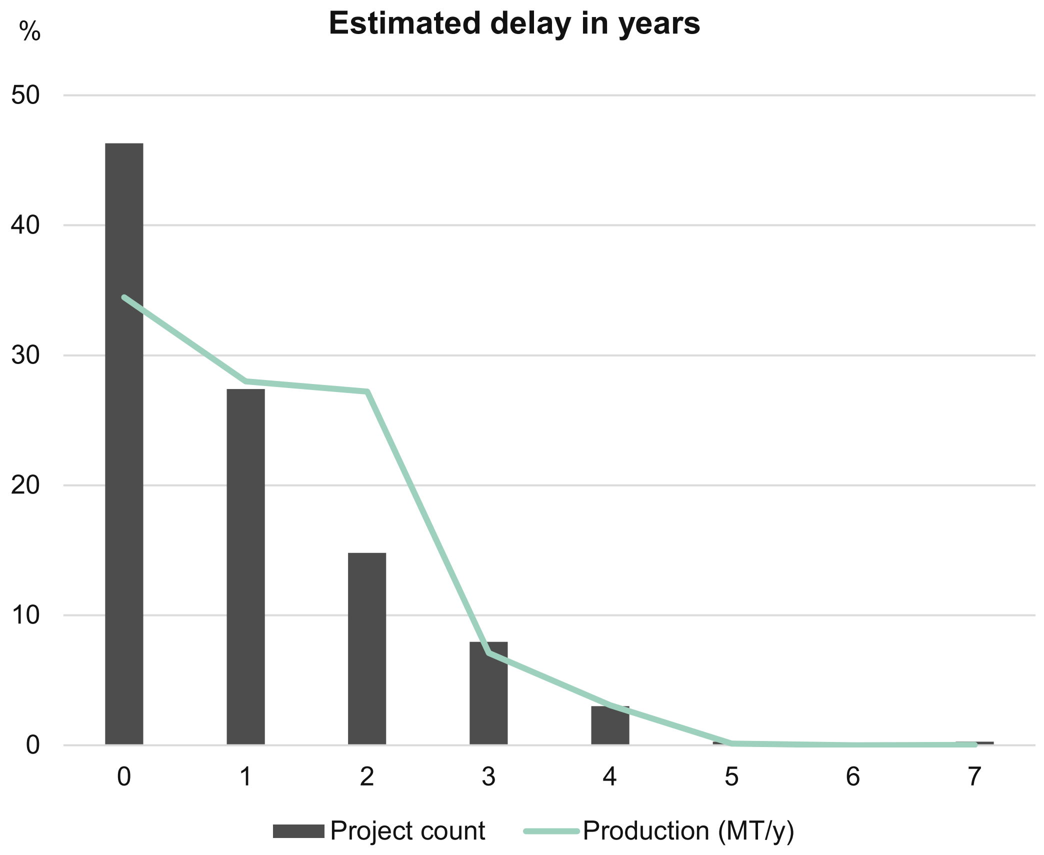
Copper price

Steel price

Source: *Trading Economics.*

Estimated delays in commissioning

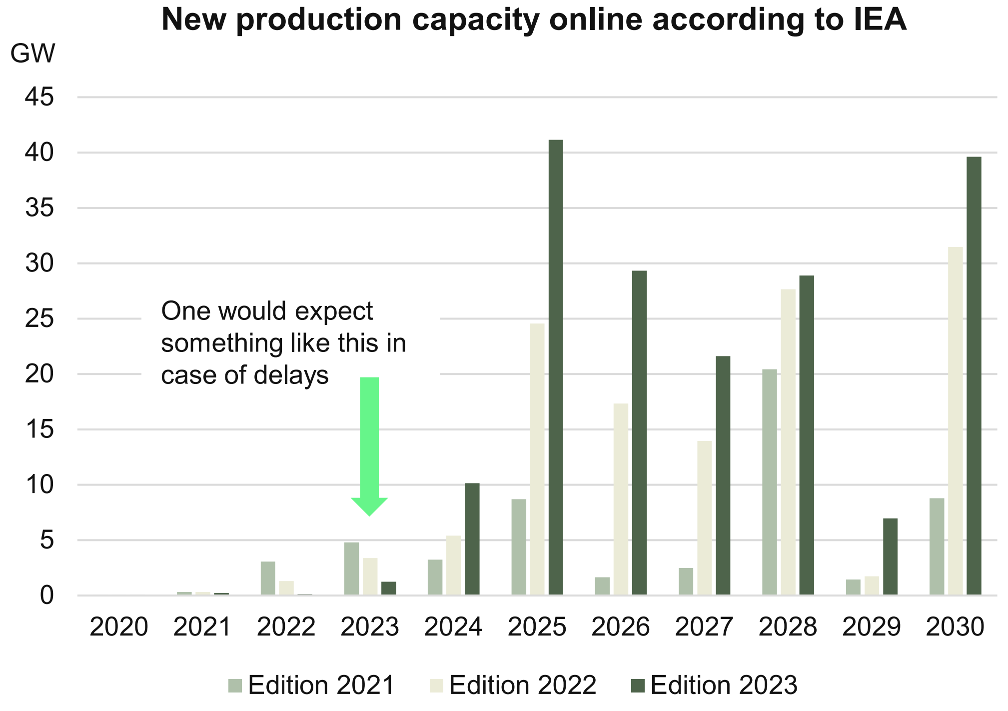
- The figure provides an overview of the estimated delays in the commissioning of low-carbon hydrogen projects, based on BNEF's project database for the Hydrogen Supply Outlook 2024.
- We calculated the delay by comparing the announced commissioning dates of 365 projects with BNEF's forecasted commissioning dates. The figure includes both electrolysis projects (green) and thermochemical projects (blue).
  - 54% of all projects are delayed by at least 1 year (accounting for 65% of the total volume).
  - 26% of projects are delayed by at least 2 years (representing 37% of the volume).
  - 11% of projects are delayed by 3 years or more (comprising 10% of the volume).
- The data may underestimate actual delays for two reasons:
  - While a delay may be recognized, the exact duration is often uncertain at the beginning of a project. As a result, initial forecasts may suggest a 1–2-year delay, which can later extend to 4 years. With so few projects having become operational, it is difficult to establish a standard delay.
  - Projects with announced commissioning dates later in the decade are harder to estimate regarding delays, as they have more time until their scheduled completion, allowing for greater potential to catch up.



Source: *BNEF, Database for Hydrogen Supply Outlook 2024: Projects.*

Can we track project delays in IEAs database? It is not immediately clear

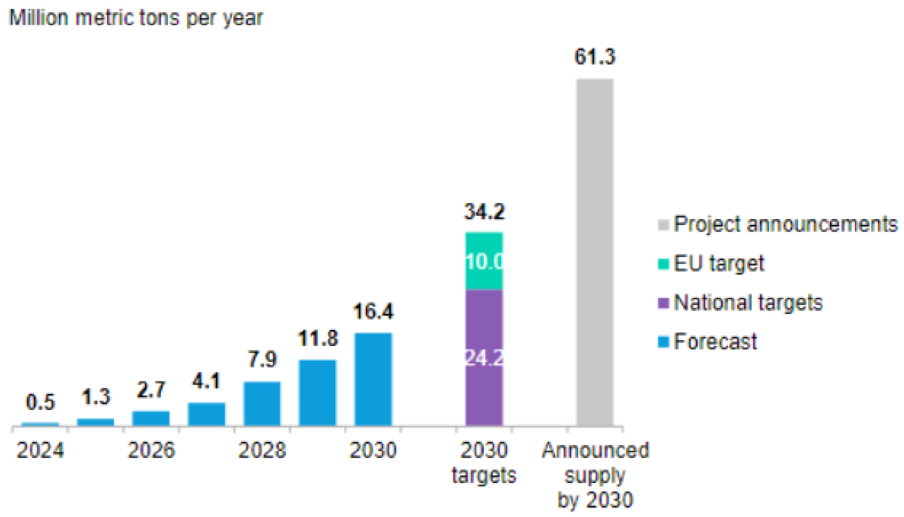
- The IEA publishes an annual database of hydrogen projects globally, detailing several factors, including expected commissioning year, production capacity, and technology.
- By comparing the 2021, 2022, and 2023 editions of the database, we aim to determine whether there is a trend of project timelines being pushed back. This is done by summing the expected production capacity reported for each year across the three editions of the database.
- Based on the data, it is difficult to isolate a delay effect. In fact, the data suggests that more capacity is expected to come online during most years in the most recent database compared to the oldest database. This increase may be attributed to new projects being added over time; the 2023 edition of the database contains more projects than the 2021 edition, which inflates the expected incoming capacity. This 'new volume effect' may overshadow any delays in individual projects.
- An exception is the '2023 launch year,' where the most recent database expects less capacity to come online than in previous editions.



Note: *Project sizes are measured in kt H2/y which allows us to compare projects across hydrogen production technologies. All projects gave progressed beyond the 'concept phase'.*
Source: *IEA Hydrogen Production Projects Database, 2021, 2022, 2023.*

Comparison of forecast to political targets and project announcements

- It is interesting - similar to what BNEF has done in the figure below - to compare the current forecast of operational capacity by 2030 with political targets and individual project announcements at the global level.
- The conclusion is that the current forecast of low-carbon projects (green + blue) falls significantly short of political ambitions, by about half. If we consider only the portion of the forecasted pipeline that is currently in advanced development stages, it represents less than 30%.



V The Commission did not undertake robust analyses before setting the EU's renewable hydrogen **production and import targets**. These were not broken down into binding targets for member states and not all member states set their own targets. When they did so, these national targets were not necessarily aligned with the Commission's targets. In fact, the EU targets turned out to be overly ambitious: based on the available information from member states and industry, the EU is unlikely to meet them by 2030. The Commission did not set any EU targets for low-carbon hydrogen.

European Court of Auditors, July 17, 2024

Note: *MT/y is million tons per year.*
Source: *BNEF, 1H 2024 Hydrogen Market Outlook. Targets Meet Reality. May 20, 2024.*
European Court of Auditors, The EU's industrial policy on renewable hydrogen, July 17, 2024.
Special report 11/2024: The EU's industrial policy on renewable hydrogen (europa.eu)

Competitiveness

Levelized Cost of Hydrogen Calculation

- Levelized Cost of Hydrogen (LCOH) Calculations enables us to estimate how the hydrogen price depends on key variables such as CAPEX, WACC, and electricity prices.
- We calculate the LCOH of green hydrogen across two scenarios. These scenarios are then compared to the cost of grey and blue hydrogen to assess its competitiveness.
- The difference in costs allows us to evaluate the need for public subsidies in the short term and the additional green premium that consumers need to pay.
- While many scenarios are possible, we have selected parameters that we believe are broadly representative of both low-cost and mid-cost projects, although they should be regarded as being back-of-the envelope calculations. See the assumptions in the tables on the right.
- Comparing these cost estimates to the disclosed average levelized cost of RFNBO hydrogen following the first auction round of the EU Hydrogen Banks is fairly well aligned (figure on lower right).
- These cost estimates of green hydrogen are significantly higher than BNEFs, and we believe that they are currently revising their CAPEX projections upwards. CAPEX assumptions in these calculations are based on Rambøll's Whitepaper which draws on their practical expertise from previous pre-FEED and FEED studies.

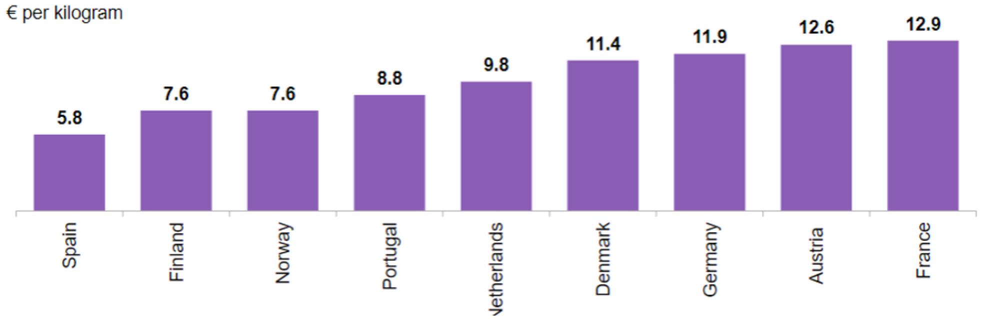
Low-cost scenario: LCOH = EUR 6.0/kg = USD 6.7/kg

Electrolysis unit	Unit	User inputs in yellow fields
Installed power	MW	1.000,0
CAPEX (stack, EPC, electrical, BoP)	EUR/MW	2.250.000
O&M	% of CAPEX	3
Technology choice: Conversion loss from power to H2	%	35
Tenor	years	20
WACC	%	7,0
Electricity source - PPA (behind meter)		
Operating hours	h/year	6.000
Average electricity costs	EUR/MWh	70,0

Mid-cost scenario: LCOH = EUR 8.3/kg = USD 9.2/kg

Electrolysis unit	Unit	User inputs in yellow fields
Installed power	MW	1.000,0
CAPEX (stack, EPC, electrical, BoP)	EUR/MW	2.800.000
O&M	% of CAPEX	3
Technology choice: Conversion loss from power to H2	%	35
Tenor	years	15
WACC	%	9,0
Electricity source - PPA (behind meter)		
Operating hours	h/year	6.000
Average electricity costs	EUR/MWh	90,0

Disclosed average LCOH of RFNBO hydrogen in EU Hydrogen Bank's first auction

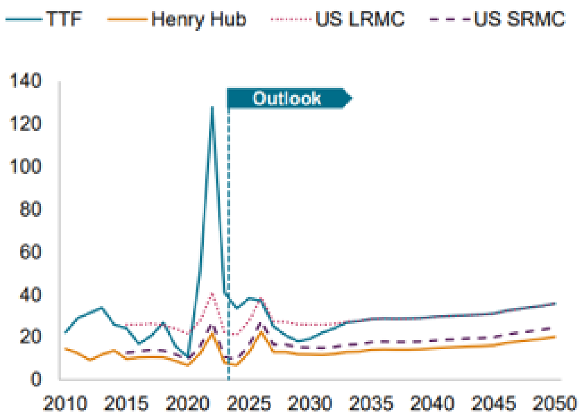


Source: *EIFO, Levelized Cost of Hydrogen Calculator. EU Hydrogen Bank results via BNEF. Rambøll, 'Achieving affordable green hydrogen production plants', November 2023.*

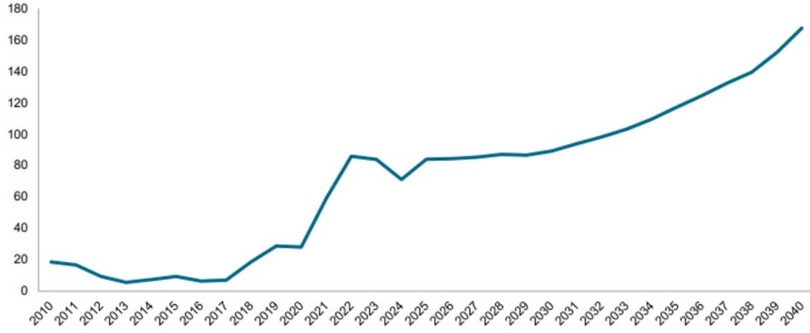
Calculating the cost of producing grey (and blue) hydrogen

- **LCOH grey hydrogen**
  - Production cost of grey hydrogen:
    - Price of natural gas in Europe EUR 36/MWh = USD 40/MWh (TTF price, September 2024).
    - Conversion efficiency in the thermochemical reforming process is 65%
    - Law of physics: 1 MWh = 30 kg H2
    - This indicates that the pure production cost of grey hydrogen is USD 2.1/kg
  - Fixed costs: We use an estimated CAPEX cost of USD 0.5/kg based on dialogue with market participants and deduced from BNEF '2023 Hydrogen Levelized Cost Update'.
  - Carbon cost of grey hydrogen: On average, producing 1 kg of gray hydrogen emits about 10 kg of CO2. In 2024, the price of CO2 emissions under the EU ETS is around EUR 90 per ton of CO2, this adds EUR 0.90/kg (or about USD 1.00/kg) in carbon costs for every kilogram of gray hydrogen produced.
  - Summing these three parts: USD 3.6/kg at current prices in Europe.
- **LCOH blue hydrogen**
  - Each kg of hydrogen emits 10 kg of CO2. Blue hydrogen will need to pay for storage of this amount of CO2 but will however save the carbon cost.
  - The Danish Energy Agency estimates that the cost of CCS for the full value chain in Denmark is between USD 140 - USD 210 per ton of CO2 corresponding to a cost of USD 1.4 - USD 2.1 per kg of hydrogen produced. We use these numbers in our calculations. For comparison, BNEF estimates the cost of CCS of USD 0.6/kg to USD 1.4/kg which are based on US data.

European gas prices outlook (real 2023 EUR/MWh)



European carbon prices (real 2023 EUR/t)



Source: *Danish Energy Agency, 'Appendix 1: Techno-economic assessment of CCS technologies', appendix_1_-_techno-economic_assessment_of_ccs.pdf (ens.dk)*
Source: *BNEF, '2023 Hydrogen Levelized Cost Update', July 2023.*
Source: *S&P Global. EU ETS prices ultimo august 2024. Gas prices as of September 9, 2024.*

Back of the envelope: Competitiveness of low-carbon hydrogen in EU

Production cost (USD/kg)	Reference: BNEF 2023 Avg. Western Europe	Green Low-cost scenario	Green Mid-cost scenario	Blue Low-cost scenario	Blue High-cost scenario
Green hydrogen	5.0	6.7	9.2	-	-
Blue hydrogen	-	-	-	4.0	4.7
Grey Hydrogen	3.6	3.6	3.6	3.6	3.6
Cost gap	**1.4**	**3.1**	**5.6**	**0.4**	**1.1**
Cost gap % vs fossil	**39%**	**86%**	**156%**	**11%**	**31%**

- Based on our assumptions, we conclude the following:
- Green hydrogen is significantly more expensive than grey hydrogen, with a cost that is 86% higher even in our low-cost scenario. This indicates a substantial funding gap that needs to be addressed through public funding and a greater willingness to pay from offtakers.
- Our estimates are higher than BNEFs estimate from 2023 coming in at USD 5/kg. We believe that BNEF is in process of revising their methodology and taking more CAPEX elements into account.
- Blue hydrogen is much cheaper than green hydrogen but still more expensive than fossil-based hydrogen. As carbon storage and transport technologies continue to mature and become commercially available, blue hydrogen will likely emerge as a viable option.
- However, blue hydrogen's viability depends on the establishment of CO2 storage facilities and transport options, as well as the absence of unfavorable regulations from a production standpoint—such as the forthcoming EU delegated act on low-carbon hydrogen.
- Additionally, the production of blue hydrogen in Europe could be further complicated by the limited availability of natural gas, which is sometimes scarce. From a political perspective, natural gas may be prioritized for direct industrial use, rather than being utilized as feedstock for hydrogen production.

Assume no change in natural gas prices

Back of the envelope: forecast 2030 Competitiveness of low-carbon hydrogen in EU

Production cost (USD/kg)	Reference: BNEF 2023 Avg. Western Europe	Green Low-cost scenario	Green Mid-cost scenario	Blue Low-cost scenario	Blue High-cost scenario
Green hydrogen	2.0	5.3	7.4	-	-
Blue hydrogen	-	-	-	3.7	4.3
Grey Hydrogen	3.8	3.8	3.8	3.8	3.8
Cost gap	**-1.8**	**1.5**	**3.6**	**-0.1**	**0.5**
Cost gap % vs fossil	**-47%**	**39%**	**95%**	**-3%**	**13%**

- Green hydrogen naturally becomes more competitive with lower capital expenditures (CAPEX) and reduced electricity prices. However, by 2030, its cost is still expected to be approximately 50% to 100% higher than grey hydrogen, assuming natural gas prices remain unchanged.
- In contrast, blue hydrogen is projected to be nearly on par with grey hydrogen by 2030 and should easily become the preferred source of low-carbon hydrogen in the short term.

How the assumption in the forecast for 2030 compares to 2024 numbers:

- Assume 20% lower CAPEX for electrolyzer and 20% lower electricity prices in both scenarios
- Assume 20% decrease in the cost of CCS
- Assume 20% increase in price of EU ETS
- Assume unchanged natural gas prices

Back of the envelope: forecast 2030 Competitiveness of low-carbon hydrogen in EU

Assume 30% decrease in gas prices

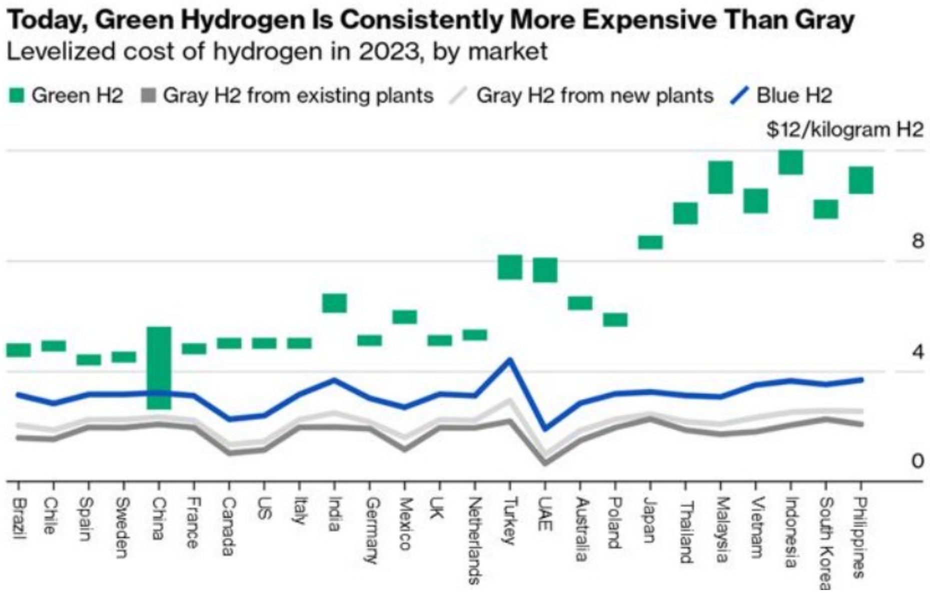
Production cost (USD/kg)	Reference: BNEF 2023 Avg. Western Europe	Green Low-cost scenario	Green Mid-cost scenario	Blue Low-cost scenario	Blue High-cost scenario
Green hydrogen	2.0	5.3	7.4	-	-
Blue hydrogen	-	-	-	3.0	3.6
Grey Hydrogen	3.1	3.1	3.1	3.1	3.1
Cost gap	**-1.1**	**2.2**	**4.3**	**-0.1**	**0.5**
Cost gap % vs fossil	**-35%**	**71%**	**139%**	**-3%**	**16%**

- A decrease in gas prices makes green hydrogen relatively less competitive. We have assumed a price reduction from EUR 36/MWh to EUR 25/MWh which is in line with S&P Global's projection from the early 2030s.
- Despite reductions in both CAPEX and electricity prices, the cost gap between green hydrogen and grey hydrogen in 2030 remains largely unchanged from 2024, primarily due to the continued decline in gas prices. This lower natural gas cost delays the anticipated competitiveness of green hydrogen over time and slows the rollout of power-to-X technologies.
- However, the competitiveness of blue hydrogen compared to grey hydrogen remains unaffected by the drop in gas prices.

How the assumption in the forecast for 2030 compares to 2024 numbers:

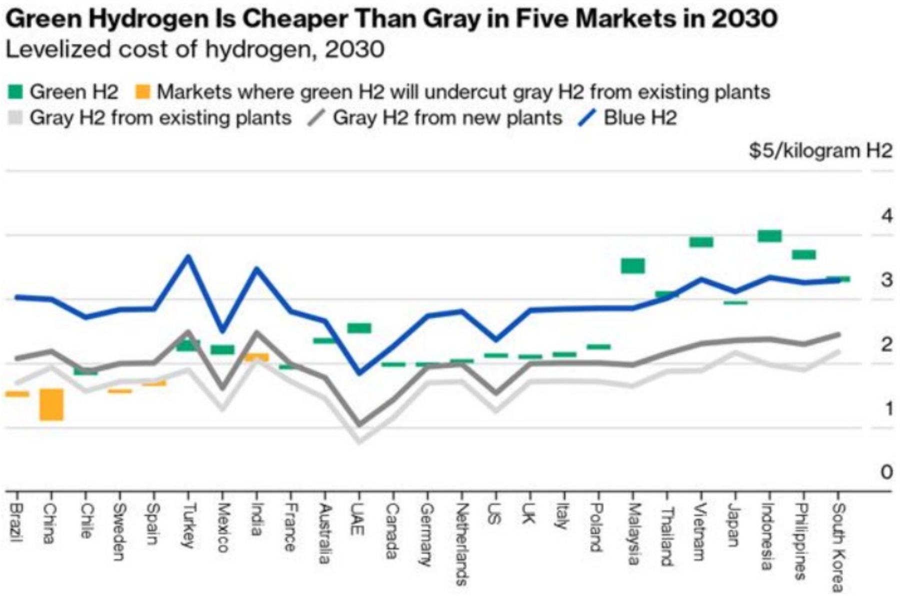
- Assume 20% lower CAPEX for electrolyzer and 20% lower electricity prices in both scenarios
- Assume 20% decrease in the cost of CCS
- Assume 20% increase in price of EU ETS
- NEW: Assume decrease in price of natural gas to from EUR 36/MWh to EUR 25/MWh (aligned with S&P forecast)

For reference: BNEF 2023 estimates of production costs of hydrogen



BNEF estimates an LCOH of green hydrogen in Germany of EUR 5/kg. Our cost calculations are 34% (low-cost scenario), resp. 84% (mid-cost scenario), higher.

Our cost estimate is 20% higher than BNEFs estimate for Germany if one factors in the cost of carbon emissions (ca. USD 1/kg).



BNEF estimates a LCOH of green hydrogen of USD 2/kg in Germany by 2030. To deliver this, CAPEX needs to be reduced by 17% in our low-cost scenario AND electricity needs to be free 6,000 hours per year. This seems unlikely.

BNEF's cost estimate of grey hydrogen produced in Germany in 2030 is broadly identical to their 2023-estimate, and therefore does not assume a reduction on the price of natural gas.

Note: *BNEF does not take into account the cost of carbon emissions and for this reason the LCOH of grey hydrogen is USD 1.0 - USD 1.2 lower than our estimates per kg of hydrogen produced.*
Source: *BNEF,* Green Hydrogen to Undercut Gray Sibling by End of Decade | BloombergNEF (bnef.com)

Factors positively influencing the competitiveness of green hydrogen

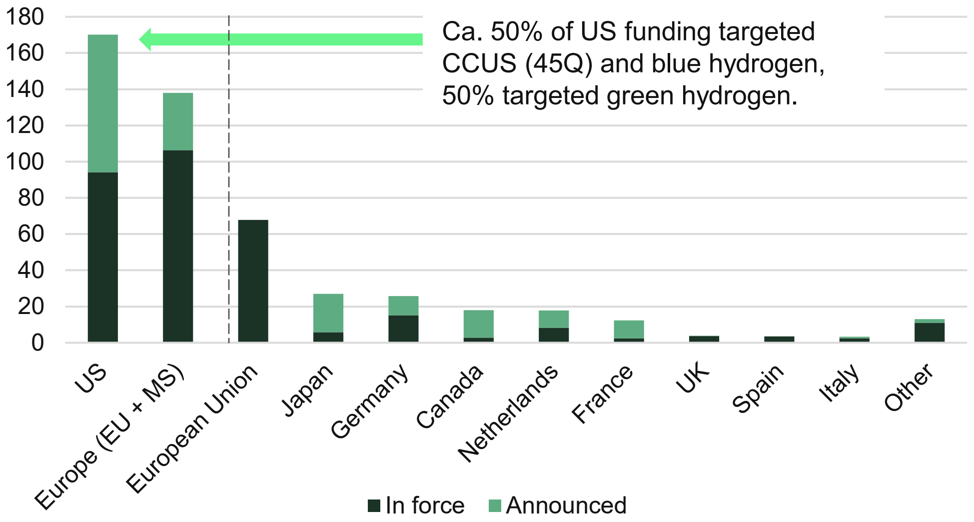
- Industrial scale production of electrolyzers: The production of electrolyzers at an industrial scale is expected to reduce CAPEX. BNEF expects a 10-15% decrease if total system costs by 2030.
- Renewable energy expansion: As renewable energy production expands, there will be more hours per year with low electricity prices.
- Hydrogen infrastructure: A hydrogen grid that connects to customers via pipelines, coupled with a tariff structure, will enable a long payback period for investments.
- Electrical infrastructure: A stronger electrical infrastructure, particularly if the plant is located in a higher-cost price zone, can help lower electricity costs. Increased usage of the grid will also reduce transport unit costs.
- Interest rates: Lower interest rates will further facilitate investment in hydrogen projects.
- Carbon emissions costs: The rising cost of carbon emissions, such as an increasing EU ETS price, will make gray hydrogen alternatives more expensive.
- Fossil energy costs: Higher costs for fossil energy sources, such as natural gas, will also contribute to the economic viability of hydrogen production.

Policy

Public funding

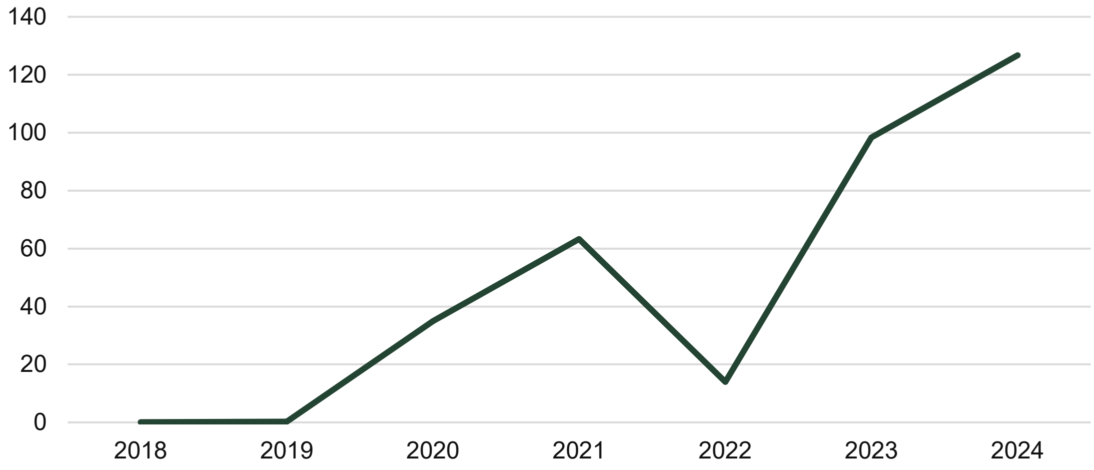
- The USA and Europe offer the most funding for low-carbon hydrogen. The US provides targeted funding for hydrogen production in the form of tax incentives, which offers developers a known level of political support, provided they meet certain requirements.
- In contrast, the EU tends to favor technology-neutral funds, from which hydrogen projects can apply. The data reflects BNEF's estimate of the size of these funds applicable to hydrogen, indicating the portion that hydrogen projects will attract. These funds are typically allocated in a competitive setting, where projects with the least need for support receive funding.

Total funding (USD bn.)
In force and announced



- Our clients often prefer the US system because it guarantees support, eliminating the risk of missing out on public funding during future auction rounds. This reduces project development risk and removes a significant obstacle.
- There has been a strong increase in allocated or pledged funding for hydrogen, rising from 2019 to 2024, with more than USD 120 billion in new funding expected to be offered from 2024 onwards.

Program budget (USD bn.) and effective starting year of funding



Source: *BNEF, BNEF Hydrogen Subsidies Tracker, April 30, 2024*

Top subsidy programs supporting low carbon hydrogen production

Market	Name	Mechanism	Funding type	Status	Effective start date	Expiration date	Available budget ($ million per year)	Total budget ($ million)
US	45Q Carbon Capture and Storage Tax Credit	Tax credit	Targeted support for H2	In force	2023	2032	6.574	78.886
US	45V Hydrogen Production Tax Credit	Tax credit	Targeted support for H2	Announced	2024	2032	7.404	74.039
EU	EU Innovation Fund	Grant program	Industry decarbonization	In force	2020	2030	4.033	28.234
Japan	Contract-for-difference scheme to develop H2 and NH3 supply chains	CfD	Targeted support for H2	Announced	N/A		1.409	21.140
EU	Next Generation EU Funds: ERDF, CF, REACT-EU	Grant program	Technology-neutral	In force	2021	2027	2.260	15.820
Canada	Investment Tax Credit for Clean Hydrogen	Tax credit	Targeted support for H2	Announced	2024	2034	1.106	13.270
EU	Modernisation Fund	Grant program	Technology-neutral	In force	2021	2030	1.182	9.458
Netherlands	Climate Fund	Grant program	Targeted support for H2	Announced	2024	2030	923	9.230
Germany	IPCEI state aid - domestic projects	Grant program	Targeted support for H2	In force	2021	2027	1.092	8.735
US	Regional Clean Hydrogen Hubs	Grant program	Targeted support for H2	In force	2022	2026	1.600	7.000
Germany	Decarbonisation of Industry and Hydrogen Budget	Grant program	Industry decarbonization	Announced	2024	2027	1.638	6.551
Netherlands	SDE++ Stimulation of Sustainable Energy Transition Auction Pgrm.	Fixed premium	Technology-neutral	In force	2020	2025	1.037	6.223
EU	Horizon Europe	R&D funding	Technology-neutral	In force	2021	2027	726	5.079
France	Support for the production of low-carbon hydrogen	CfD	Targeted support for H2	Announced	2024	2026	1.456	4.367
Germany	H2Global	CfD	Targeted support for H2	Announced	2024	2033	393	3.931
Spain	EU Recovery Plan	Grant program	Targeted support for H2	In force	2021	2026	573	3.439
EU	European Hydrogen Bank	Fixed premium	Targeted support for H2	In force	2023		328	3.275
EU	Just Transition Fund	Grant program	Technology-neutral	In force	2021	2027	452	3.164
France	IPCEI	Grant program	Targeted support for H2	Announced	2024		3.113	3.113
US	Annual budget for DOE's hydrogen research	R&D funding	Targeted support for H2	In force	2005		285	2.565
UK	Hydrogen Production Business Model Round 1	CfD	Targeted support for H2	In force	2023	2025	169	2.542
France	IPCEI	Grant program	Targeted support for H2	In force	2024		2.456	2.456
US	48 Investment Tax Credit for Energy Property	Tax credit	Technology-neutral	In force	2023	2032	209	2.094
France	France 2030	Grant program	Targeted support for H2	Announced	2021	2030	207	2.074
Japan	Green Innovation Fund	R&D funding	Targeted support for H2	In force	2021	2030	180	1.797
Netherlands	IPCEI	Grant program	Targeted support for H2	In force	2022	2030	218	1.747
Canada	Investment Tax Credit for Carbon Capture, Utilization, and Storage	Tax credit	Industry decarbonization	In force	2022	2030	215	1.723

***Source:** BNEF, BNEF Hydrogen Subsidies Tracker. Latest release of database is April 30, 2024.*

Real-life hydrogen production support and auction results

- Public support is intended to help close the cost gap between low-carbon hydrogen and fossil hydrogen. It is particularly interesting to follow those programs that offer production subsidies instead of grants and CAPEX support. This is because they offer are more direct insight into the required level of support for projects to be economical.
- EIFO has tracked several programs and their results to see where the market stands. It is, however, difficult to draw strong conclusions due to the small sample across various jurisdictions.
- European competitive auctions (e.g., Denmark, EU Hydrogen Bank) show relatively low support levels, ranging from USD 0.5 to 1.0 per kilogram of hydrogen. In India it is even lower at 0.33 per kilogram.
- In contrast, the IRA program offers a politically set subsidy of USD 3 per kilogram, and Australia provides a USD 1.32 tax incentive.
- The UK's HAR1 auction uses a Contract for Difference (CfD) model, offering an estimated subsidy of USD 7.3 per kilogram—significantly higher than elsewhere. UK consultancy Wood Mackenzie attributes this to reduced competition in UK auctions.
- Most programs, particularly those in Europe and India, have shown low levels of support due to strong competition among bidders. This suggests a belief that offtakers are willing to bear the majority of the cost difference. However, there is also the risk of the "Winner's Curse," where the winning bidders are those with the most optimistic projections of future risks and costs.

Subsidy scheme	USD/kg
Denmark - Tender 2023	0,95
USA – IRA	3,00
India	0,33
EU Hydrogen Bank	0,47
Australia – from 2027	1,32
UK - HAR1	7,30* (own estimate)

***Source:** EIFO, 'Low-Carbon Hydrogen Auction Results Tracker'.*

Production cost (USD/kg)	BNEF 2023 Avg. Western Europe	Green Low-cost scenario	Green Mid-cost scenario
Green hydrogen	5.0	6.7	9.2
Grey Hydrogen	3.6	3.6	3.6
Cost gap	**1.4**	**3.1**	**5.6**

***Source:** EIFO's Levelized Cost of Hydrogen Calculator.*

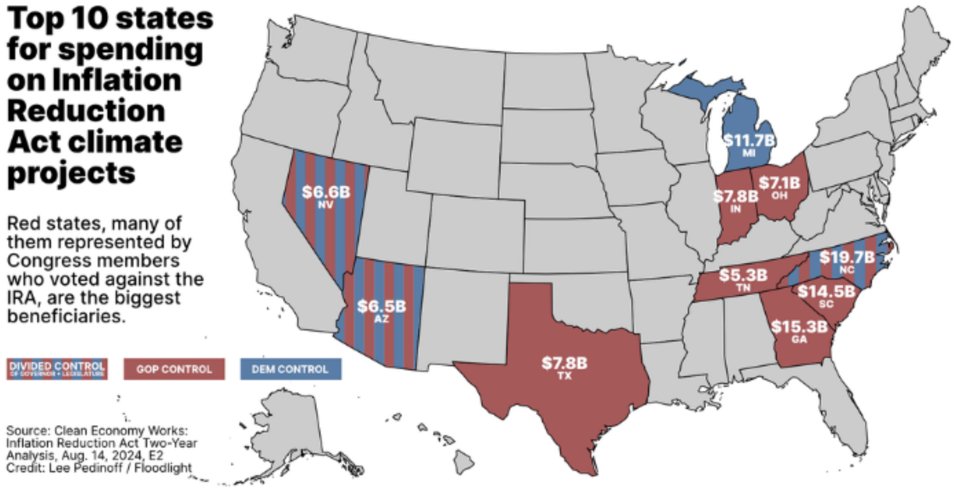
Trump-administration unlikely to fully repeal IRA but may adjust program for the worse

› A new Trump administration is expected to prioritize economic growth and fossil fuel energy production over climate ambitions. At the same time, Trump has expressed a desire to reduce government debt. Therefore, it is natural to consider how this may impact support for hydrogen projects under the Inflation Reduction Act (IRA), potentially affecting industry development in the U.S.

› With Republicans holding majorities in both the House and Senate, they have several pathways to amend the enacted legislation. S&P Global, along with several other analysts, believes that a full rollback of the IRA is unlikely. This is partly because the IRA has broad support from both sides of the political spectrum. However, it is possible that there could be changes, such as the removal or adjustment of tax incentives within the program. The IRA particularly benefits investments in Republican states, making it more difficult to scale back the program (see figure).

› The IRA currently provides a subsidy of USD 3 per kilogram of hydrogen, and in comparison with other tenders, the IRA subsidy is quite generous. This could argue for a reduction in the support level. Both production and investment tax credits are currently valid for over 10 years, and this parameter could come into play. The federal IRA is not the only source of financial support in the U.S., as there may also be support available at the state and municipal levels.

› Another reason the IRA may be scaled back is that many projects plan to sell their U.S.-produced and IRA-supported hydrogen in Europe. This would create jobs but not lower fuel prices or reduce the carbon footprint in the U.S.



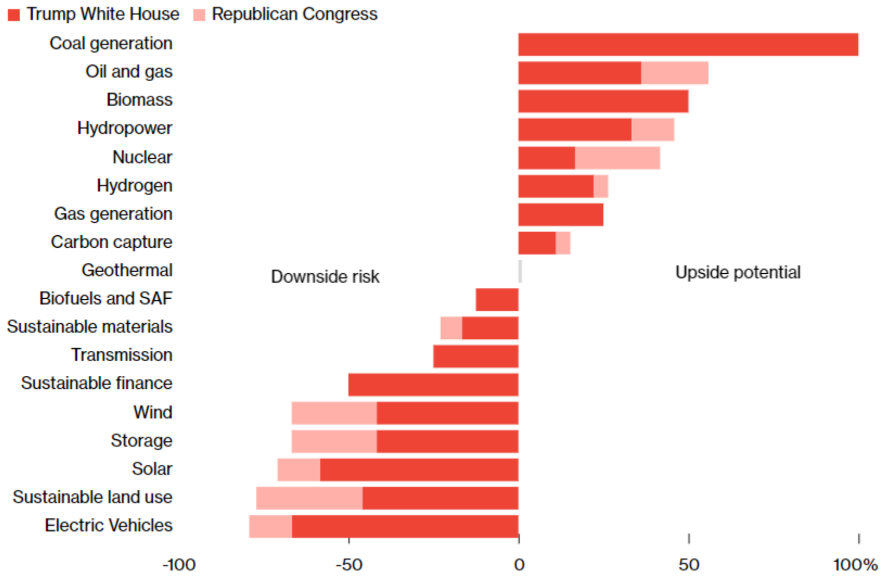
Source: *Clean Economy Works, via FloodLightNews,* [GOP gets 85% of the benefit of climate law. Some still hate it.]

Trump-administration unlikely to fully repeal IRA but may adjust program for the worse (II)

- Lower support for hydrogen production will undermine the business case and competitiveness of green hydrogen produced in the U.S. European industry, on the other hand, will benefit from less of a competitive pressure.
- Consulting firm Wood Mackenzie estimates that a full phase-out of the IRA could lead to a reduction of up to a third in the deployment of renewable energy, including wind and solar. The reason this figure is not higher is that these technologies are highly profitable under market conditions. However, scaling down would have direct implications for Power-to-X, as inexpensive renewable energy is crucial for the economically sustainable production of green hydrogen.
- Any new tariffs on imported equipment and materials could increase costs for technology used in Power-to-X projects. Europe and China are leaders in electrolyzer capacity, and importing these components would result in higher costs for U.S. projects, which would generally be detrimental to the development of the sector on a broader scale.
- A focus on fossil fuels, gas pipelines, and easier regulatory approvals for energy projects could have a positive effect on the production of blue hydrogen, although this is unlikely to be enough to offset potential changes in direct support. Rules regarding the definition of green hydrogen could also come into play. However, changes under a Trump administration are expected to relax requirements for temporal and geographical matching of electricity production and consumption, as well as additionality in electricity production. This could positively affect the production of green hydrogen. However, if the projects aim to sell to the EU, they must comply with European RFNBO regulations.

Energy Sectors Face Uneven Risk, Opportunity Under Republican Trifecta

Key energy transition sectors' exposure to US election outcome



Source: BNEF, *Republican Wins to Slow, Not Stop US Green Energy Growth: React*

Trump-administration unlikely to fully repeal IRA but may adjust program for the worse (III)

With majorities in both the Senate and House of Representatives, the Trump administration will be able to utilize both the Congressional Review Act and Budget Reconciliation

Budget Reconciliation

- Budget reconciliation allows the Senate to pass certain tax and spending changes with a simple majority vote, bypassing the typical 60 votes needed to avoid filibusters, and involves two main steps: passing a budget resolution and then a reconciliation bill.
- Step 1 requires the House and Senate to agree on a budget resolution with reconciliation instructions, which directs specific committees to create legislation affecting deficit levels. This resolution does not require presidential approval.
- Step 2 entails the Budget Committees crafting a reconciliation bill from committee submissions, which must comply with the Byrd Rule—ensuring budgetary effects and prohibiting deficit increases beyond ten years or changes to Social Security. Violations can be challenged with a 60-vote requirement to waive the Byrd Rule.

Congressional Review Act (CRA)

- Congress to disapprove federal agency rules via a joint resolution of disapproval within a defined introductory period of 60 legislative days after finalization, requiring presidential approval, though Congress can override a veto with a supermajority in both chambers.
- There are two processes under the CRA: a standard procedure needing a majority vote where filibusters can block action, and a fast-track procedure that limits debate time, enabling a simple majority to pass disapproval without filibuster interference.
- If a joint resolution disapproves a rule, similar rules cannot be issued without new legislation, preventing minor tweaks by the executive branch to reinstate overturned rules. The lookback period for the 119th Congress is anticipated for May 2024.

Potential Impact on 45V

- While the Trump administration would have the ability to overturn this tax credit, this is unlikely during budget reconciliation given its bi-partisan support and its potential to drive investment in Republican states
- However, guidance for the tax credit is vulnerable to change if it is finalized prior to inauguration. Draft guidance was criticized by both Democratic and Republican senators as being too stringent to the point of limiting hydrogen investment
- The Trump administration will have the ability to rescind and redraft the guidance for the credit (can be done with executive action), potentially making the rule less stringent. However, any actions taken by the administration would almost certainly result in delays in having final guidance available and may be followed by litigation

Source: *S&P Global Commodity Insights.*

Renewable Energy Directive III
A major driver for hydrogen demand

- The Renewable Energy Directive III (RED3) sets a collective target of 42.5% renewable energy across all sectors in Europe in the final energy consumption by 2030. RED3 is a directive and must be transposed into national laws by May 2025.
- A key driver in reaching the RED3 goal is the EU ETS, where sectors covered by the quota system must purchase allowances relative to their emissions. A decreasing supply of allowances gives companies (those that are included under EU ETS) an incentive to reduce their emissions through, for example, direct electrification, energy efficiency improvements, CCS (carbon capture and storage), and the replacement of fossil fuels with green fuels.
- The overall target is sometimes (but not always) complemented by sub-targets for different sectors for the use of renewable energy and RFNBOs (Renewable Fuels of Non-Biological Origin), including eFuels, as part of this.
- RED3 aims for the establishment of a system for "Certificates for Renewable Hydrogen" to track and validate the sustainability of hydrogen. The certification follows the EU definition of ‘green hydrogen’ in terms of additionality, temporal correlation, and geographical correlation, well the corresponding definitions for other types of low-carbon hydrogen.

- **Industry**
  - RED3 requires a 1.6% annual increase in renewable energy usage in the industrial sector.
  - Member States must ensure that at least 42% of hydrogen used for energy and non-energy purposes in the industry comes from RFNBOs by 2030, and 60% by 2035.
- **Road transport**
  - Member States must choose between A) a binding share of at least 29% renewables in the final energy consumption in the transport sector by 2030; or B) a binding target to reduce greenhouse gas intensity in transport by 14.5% by 2030.
  - The new rules also set a combined binding secondary target of 5.5% for advanced biofuels and RFNBOs in the share of renewable energy supplied to the transport sector, and at least 1% must be RFNBO.
- **Refineries**
  - Refineries must reduce the greenhouse gas intensity of fuels by at least 13% by 2030 under RED3. The use of low-carbon hydrogen is key to achieving this goal.
  - Underperformance means that the refinery must buy quotas in the EU ETS. National authorities are responsible for implementation and may impose fines or other regulatory restrictions.

ReFuelEU Aviation

› Aviation is not regulated by RED3 but has its own target.

› The minimum share of Sustainable Aviation Fuels (SAF) is set to increase significantly by 2050. By this date, at least 50% of SAF must come from eFuels, with the remainder permitted to be of biological origin. This division is based on the understanding that biological fuels are generally cheaper in the short term, while eFuels require current demand to mature and develop.

› SAF does not need to be produced within the EU. The ReFuelEU Aviation regulation emerged from the EU's 'Fit for 55' package, establishing a framework for sustainable aviation fuel usage.

› The regulation places shared responsibility on aviation fuel suppliers, EU airports, and aircraft operators. Non-compliance with these regulations will result in substantial fines.

› Airlines will be required to pay twice the price difference between SAF and conventional jet fuel for the missing volume of SAF. Additionally, any shortfall in SAF volume will be added to the procurement requirements for the following year.

Who will be affected by the obligations of ReFuelEU Aviation?

+ **Aviation Fuel Suppliers** must supply minimum shares of SAF according to mandatory quotas.
+ **EU Airports** with passenger traffic above 800,000 passengers or freight traffic above 100,000 tons per year must make the refueling of SAF possible (exceptions for small remote airports apply). Ideally, they should also establish alternative ground power supply (e.g., electricity, hydrogen).
+ **Aircraft Operators** departing from airports in the EU are obliged to refuel at least 90 percent of their yearly required aviation fuel within the EU. This requirement was introduced to prevent tankering (the practice of loading more fuel than needed in third countries).

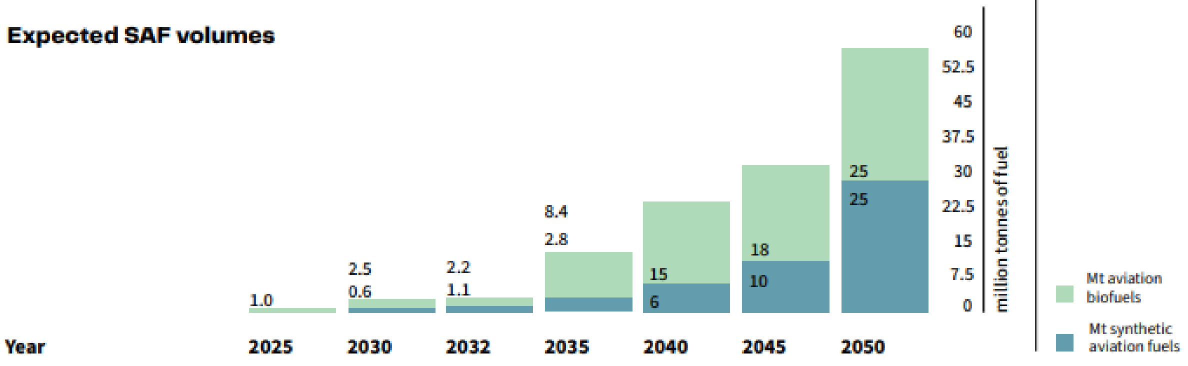
Achieving this EU target demands 100 GW of electrolysis capacity.

EU-wide quotas

Year	2025	2030	2032	2035	2040	2045	2050
Share of SAF	2%	6%	6%	20%	34%	42%	70%
Minimum share of synthetic aviation fuels	0%	1.2%*	2%*	5%	10%	15%	35%

* Average share of 1.2% for the period 2030 - 2031 and average share of 2% for the period 2032-2034

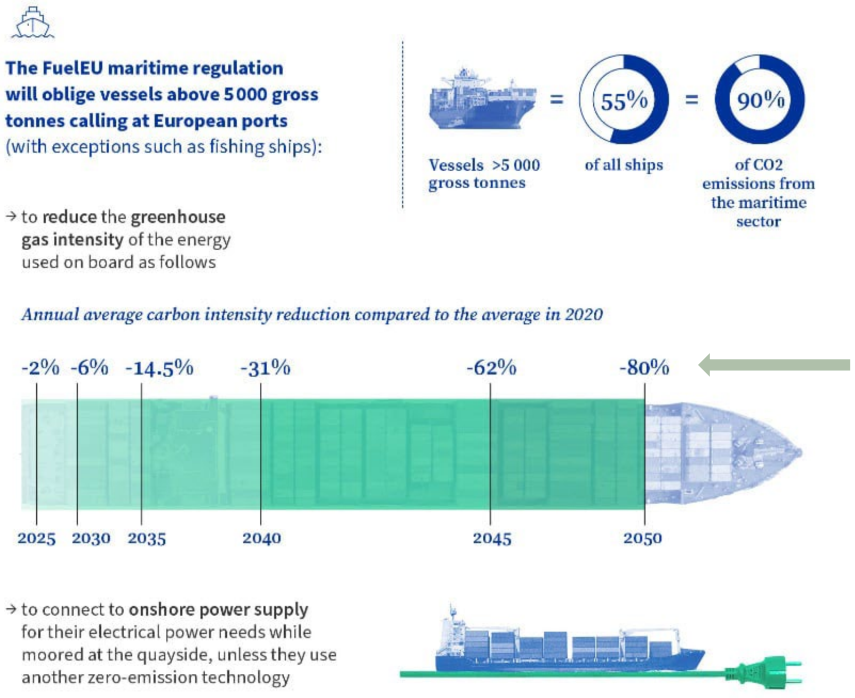
Expected SAF volumes



Source: NOW gmbh, NOW-Factsheet_ReFuelEU-Aviation-Regulation.pdf (now-gmbh.de)

FuelEU Maritime

- Shipping is not regulated by RED3 but has its own target.
- Blending requirements in the shipping industry are set to increase significantly by 2050, which will steadily drive up the demand for green fuels.
  - Applicability: These requirements apply to all ships with a gross tonnage greater than 5,000.
  - Within the EU: The regulations are mandatory for 100% of the energy used on voyages within the EU.
  - Entering or Leaving the EU: For voyages entering or leaving the EU, 50% of the energy used must comply with the blending requirements.
- Compliance Options:
  - Overcompliance: Ships that exceed the blending requirements can bank their excess compliance for future use. Overcompliance can also be pooled across different ships and companies to enhance flexibility.
  - Undercompliance: A limited allowance for undercompliance is accepted, allowing up to 2% of energy use to fall short of the requirements, but this is permissible for only one year.



Achieving this EU target demands 125 GW of electrolysis capacity.

Source: *NOW gmbh, NOW_Factsheet_FuelEuMaritime_Oktober-2023.pdf (now-gmbh.de)*

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