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ENERGY RESEARCH

Shades of green (hydrogen) – part 2: in pursuit of 2 EUR/kg

23 February 2022

Aurora provides data-driven intelligence for the global energy transformation

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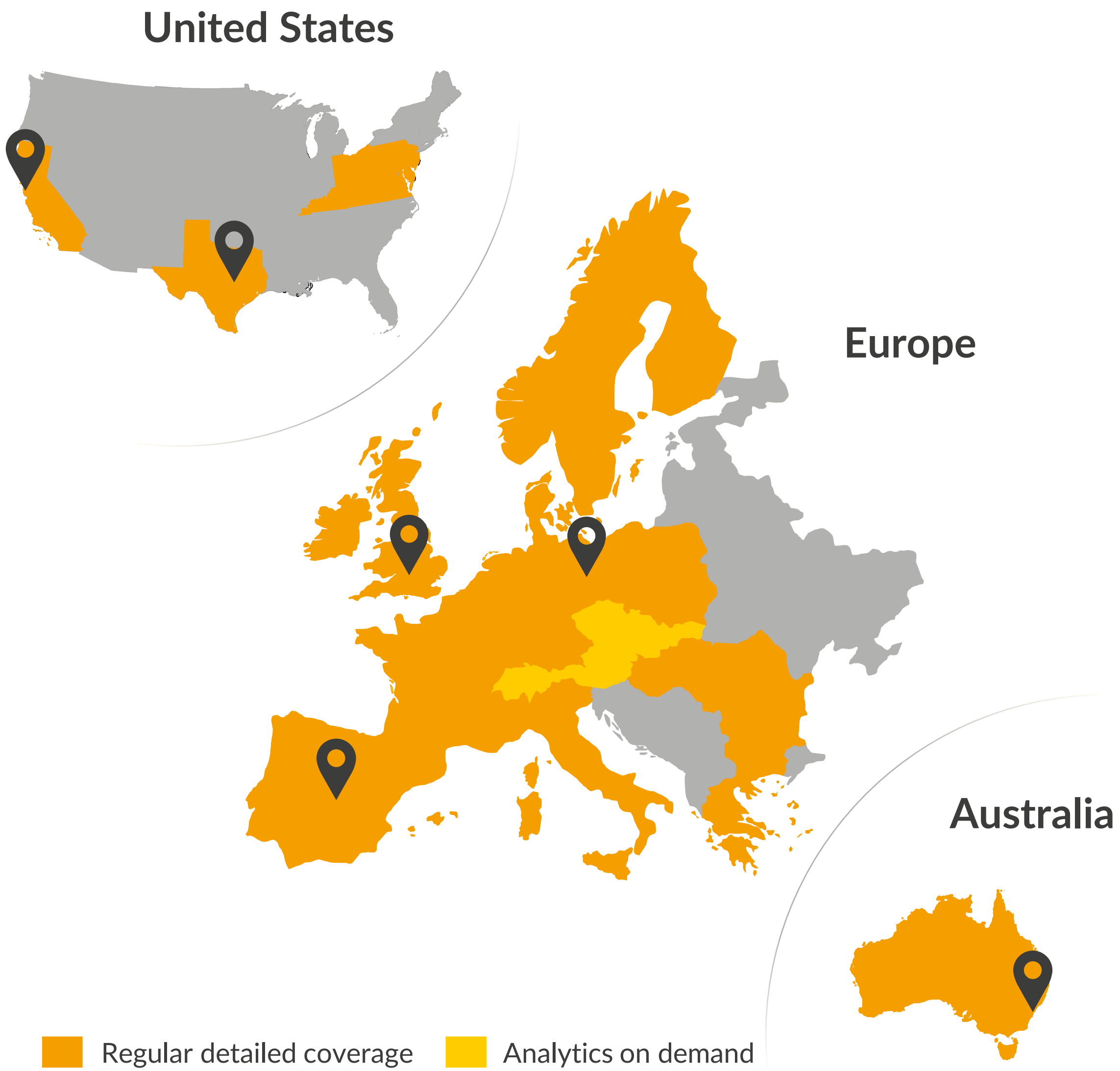
- Power markets
- Renewables
- Storage
- Electric vehicles
- Hydrogen (H_2)
- Carbon (CO_2)
- Natural gas



6 Offices
Oxford | Berlin | Madrid
Sydney | Austin | SF Bay Area

225+
market experts

550+
subscribing companies

100+
transactions supported in 2021

Source: Aurora Energy Research

Our European Hydrogen Market service offers regular insights, policy/market updates & roundtable discussions

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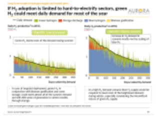
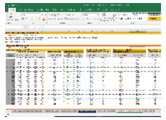
Hydrogen Market Attractiveness Report (HyMAR)

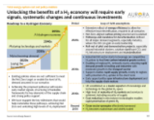

- Hydrogen market sizing: demand scenarios by country and sector
- Summary of policy developments and incentives across Europe
- Analysis of demand and supply drivers
- Global electrolyser project database

Strategic Insight Reports

- Regular insight reports on topical issues in the evolving European hydrogen market covering country, policy and technology deep dives
- Upcoming reports on next slide

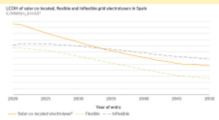
Policy updates & thought leadership




- Regular updates on European Hydrogen policies and incentives across power, heat, transport and industry
- Thought leadership on required policies and incentives to grow hydrogen sector

Access anytime via EOS online platform

Investment case analysis



- Hydrogen production economics based on Aurora's in-house power, natural gas and carbon price forecasts
- Granular electrolyser business cases, including grid-connected inflexible and optimised production models, and co-location with renewables

Group Meetings

- Presentation of Market Attractiveness reports and Strategic Insight reports
- Networking opportunity with developers, investors and Governments – the 'go-to' roundtable to discuss hydrogen developments in Europe

Workshops and analyst support


- Bilateral workshops to discuss Aurora's analysis and specific implications
- Ongoing analyst support to answer questions about our research

For more information, please contact
Alan Jabbour, Commercial Associate - Hydrogen & Global Commodities

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☎ **+44 (0) 07425 647505**

Source: Aurora Energy Research

Timeline of strategic insight reports and policy updates

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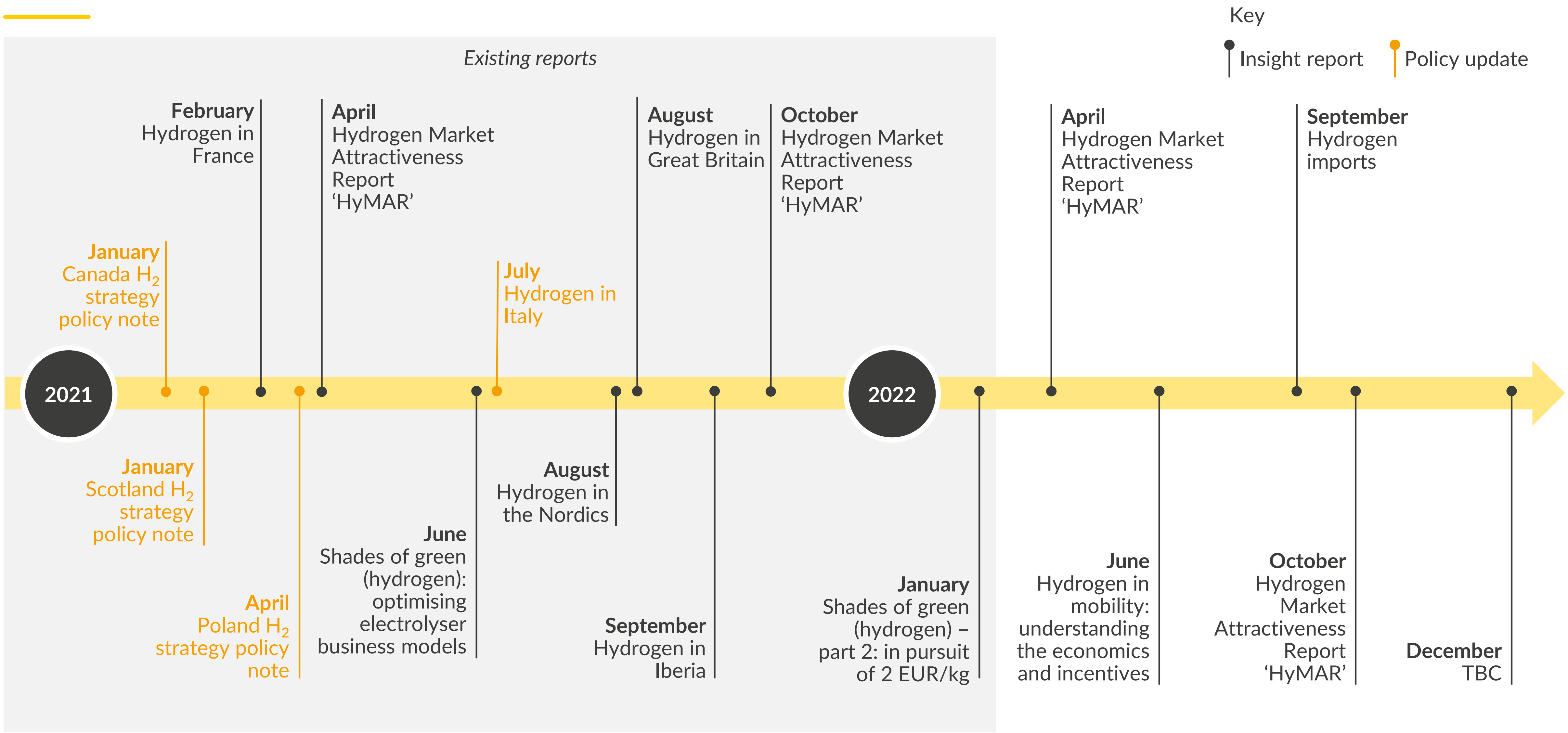

All reports are available to subscribers of Aurora's European Hydrogen Service

Source: Aurora Energy Research

Aurora is already providing hydrogen market analysis to major players across the value chain

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Utilities & Renewables

- EDF Energy
- RWE
- e.on
- uniper
- CEZ Group
- SSE
- steag
- Wärme Hamburg
- Trianel
- eew Energy from Waste
- ONYX POWER
- TRITON POWER
- VIRIDI
- NICE Solar Energy
- eregio
- axpo
- Ørsted
- BSR Energy
- amp
- rhenag EnergieBündel. Seit 1872.
- fortum
- edp
- octopus energy
- SWH. Stadtwerke Halle
- ScottishPower
- centrica

Supply Chain

- BASF We create chemistry
- BOC Member of The Linde Group
- urenco The Energy to Succeed
- ITM POWER Energy Storage | Clean Fuel
- SIEMENS
- SALZGITTER AG Stahl und Technologie
- Mitsubishi Power
- Port of Rotterdam

Financiers

- The Crown Estate
- SEB
- PJT Partners
- 丸紅株式会社 Marubeni
- BlackRock
- BlueWaterEnergy
- Kommunal Kredit
- Barclays
- meridiam Investing for the community
- low carbon powering tomorrow

Government & regulation

- Schweizerische Eidgenossenschaft / Confédération suisse / Confederazione Svizzera / Confederaziun svizra
- Ministerie van Economische Zaken en Klimaat
- JETRO Japan External Trade Organization
- Department for Business, Energy & Industrial Strategy
- Bundesnetzagentur
- CREG
- Committee on Climate Change
- Department for Transport
- National Infrastructure Commission

Upstream gas and networks

- Repsol
- Shell
- equinor
- Naturgy
- OGE
- nationalgrid
- Thyssengas
- Vitol
- fluxys

Source: Aurora Energy Research

Agenda

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I. Electrolyser business models

II. Hydrogen production

III. Stand-alone grid connected electrolysers

IV. Co-located (island) electrolysers

V. Co-located (grid) electrolysers

Research questions for all business models

- What is the LCOH for each country/year?
- Which countries have the lowest cost?
- Is it possible to beat the 2 EUR/kg H_2 target?

We have identified four business models to produce hydrogen via electrolysers, enhanced the co-located grid connected model

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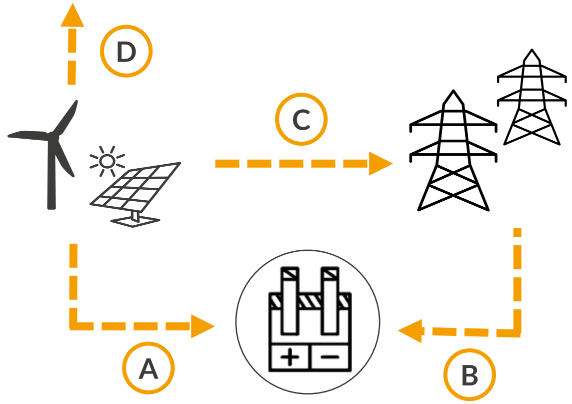
Overview of connections we considered in our business models

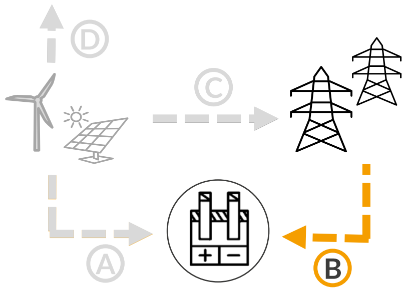


- (A) Electrolyser imports power from RES[1]
- (B) Electrolyser imports power from grid
- (C) RES exports power to grid
- (D) RES spills power

Stand-alone grid connected electrolysers

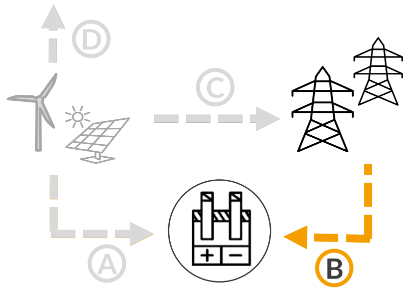
1 Inflexible

- Grid electricity **only** and runs at **95%** load factor



2 Flexible

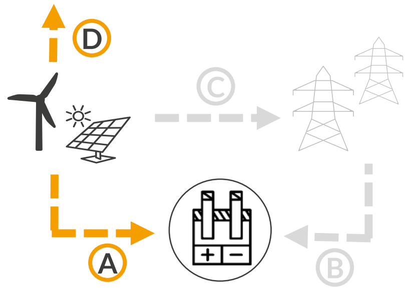
- Grid electricity **only** and ability to choose operating hours to minimise LCOH[2]



Co-located electrolysers

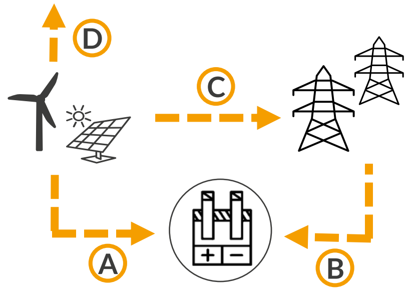
3 Co-located (island)

- Electrolyser connected to renewable asset only (no grid connection)



4 Co-located (grid)

- Direct connection between electrolyser and RES asset, and both connected to grid



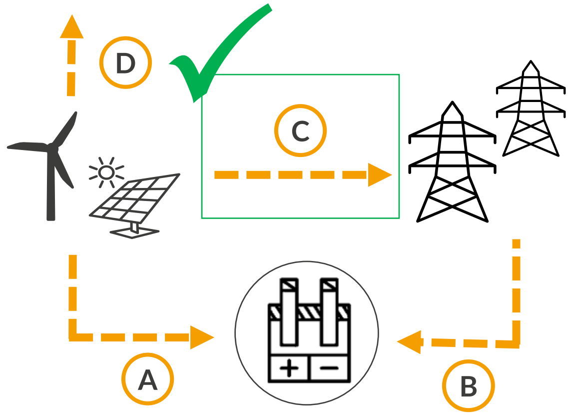
1) RES: Renewable energy asset 2) LCOH: Levelised cost of hydrogen

Source: Aurora Energy Research

We have updated our business models, combined wind and solar for co-location, and added 5 new countries with detailed retail market costs

Updated business model – both RES asset and electrolyser connected to grid in the co-located (grid) model

- We added a connection between the renewable asset and the grid to allow renewable asset to sell its electricity

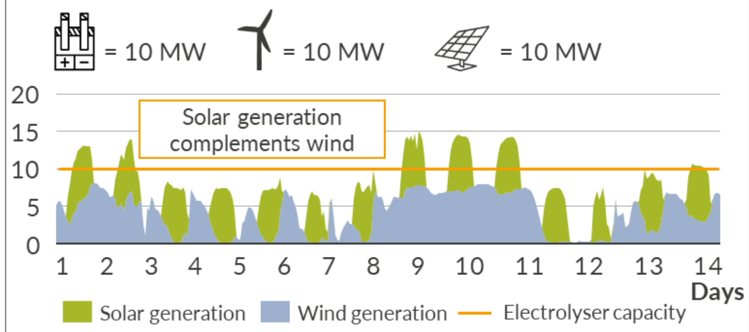


- A Electrolyser imports power from RES
- B Electrolyser imports power from grid
- C RES exports power to grid
- D RES spills power

We assess combined wind and solar assets for co-located business models, and optimised the size of both assets with an objective of minimising LCOH

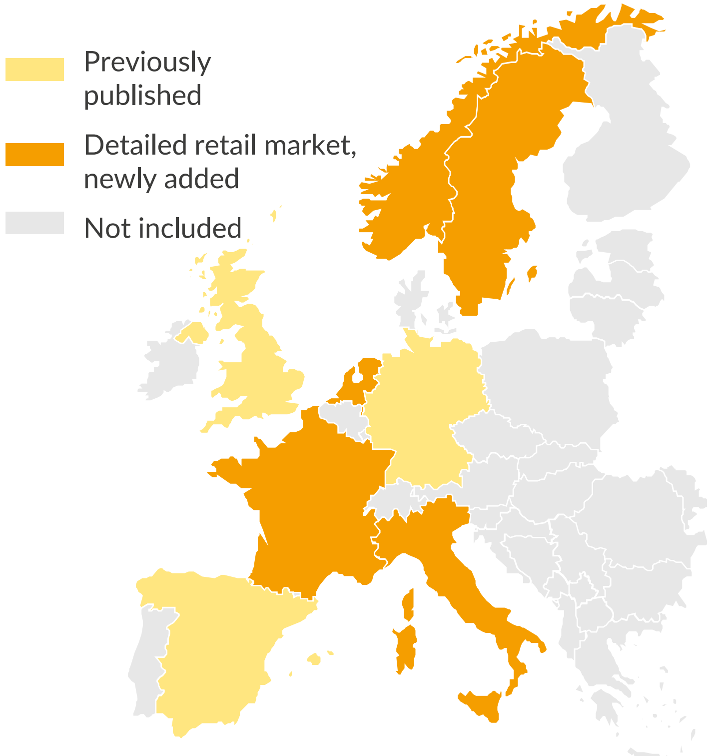
- Previously, in "*Shades of green (hydrogen): optimising electrolyser business models*" – June 2021, we looked at the optimal size of co-location with wind **or** solar assets
- In this report, we combine onshore wind and solar assets and optimise their sizes
- The below chart shows how wind and solar generation can complement each other

Example electricity generation profiles for onshore wind and solar
MW



More countries with detailed retail prices; hence, more countries for flexible and co-located (grid) business models

- We have added five new countries (NOR, SWE, NLD, FRA, ITA)
- Country deep-dives in policy/subsidy schemes



Source: Aurora Energy Research

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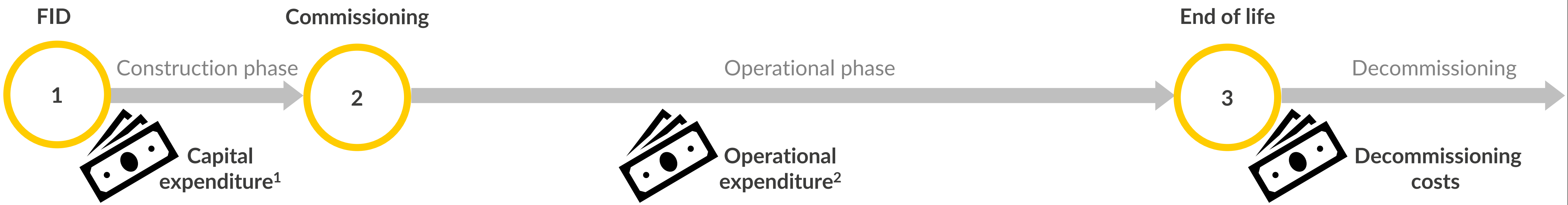
Research questions for all business models

- What is the LCOH for each country/year?
- Which countries have the lowest cost?
- Is it possible to beat the 2 EUR/kg H_2 target?

Using the levelised cost of hydrogen production allows us to compare hydrogen with other forms of energy on a cost basis

Levelised Cost of Hydrogen (LCOH)



$$LCOH = \frac{Capital\ expenditure + Operational\ expenditure + Decommissioning\ costs}{Produced\ hydrogen}$$

✘ Revenues i.e. subsidies or hydrogen sales are not included in LCOH calculation

Why do we use LCOH?

- The levelised cost of hydrogen (LCOH) production allows us to compare different modes of hydrogen production with other forms of energy production, by considering the production costs over the whole lifetime

How is it calculated?

- LCOH is calculated by dividing the net present value (NPV) of the total lifetime costs of the asset by the NPV of the total hydrogen production over the lifetime. While this analysis does not account for revenue components (i.e. subsidies or hydrogen sales), we include some country-specific cost exemptions
- This gives one value of LCOH for the lifetime of the asset e.g. an LCOH of 5 EUR/kg H_2 in 2025 represents the lifetime average production costs for that plant which becomes operational in 2025
- The actual production costs within a year can vary significantly e.g. an electrolyser connected to the grid without hedging is exposed to the hourly power prices

1) Includes construction costs, planning and permitting costs, development costs, etc. 2) Includes fuel costs, maintenance, grid connection costs, land rent, debt servicing (if applicable), repairs; 3) This varies heavily by country depending, for instance, on the available support schemes.

Source: Aurora Energy Research

Reference cost for blue hydrogen in Europe is 2.5-2.7 EUR/kg; or up to 3 EUR/kg if delivery costs are included

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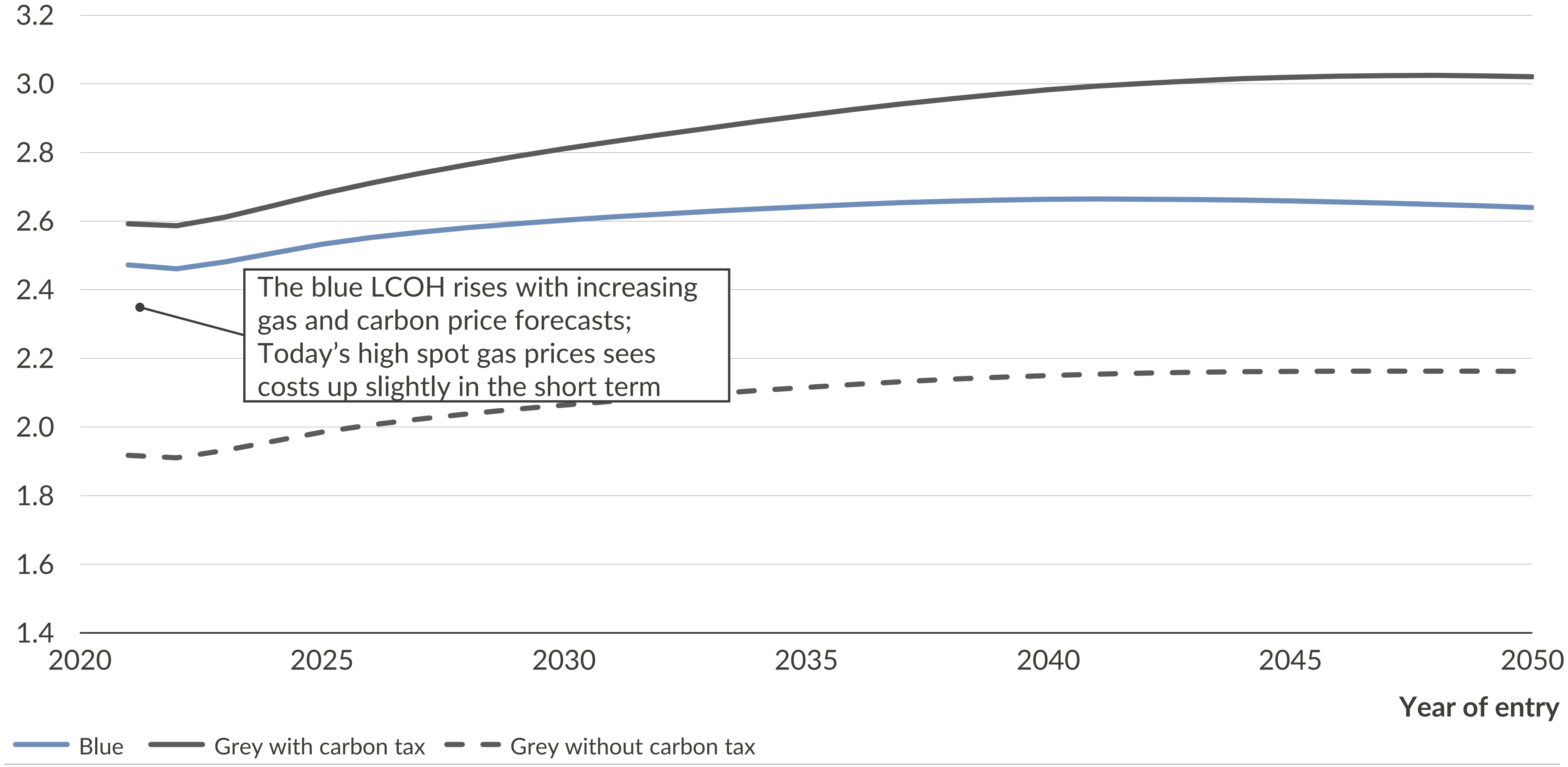
Blue Hydrogen

LCOH of large scale blue and grey hydrogen produced by steam methane reforming in Great Britain (95% load factor)
EUR/kg H_2



- We assume 8% WACC for the blue and grey hydrogen production systems
- We use Aurora's gas price forecasts from October 2021- Central scenario
- Using a smaller scale SMR would increase the capex by 50%, resulting in a ~30% increase in the blue hydrogen cost
- For a large-scale SMR facility, hydrogen transport might be necessary. A newly built pipeline with a length of 500 km would add ~10% to the cost of blue hydrogen

Source: Aurora Energy Research

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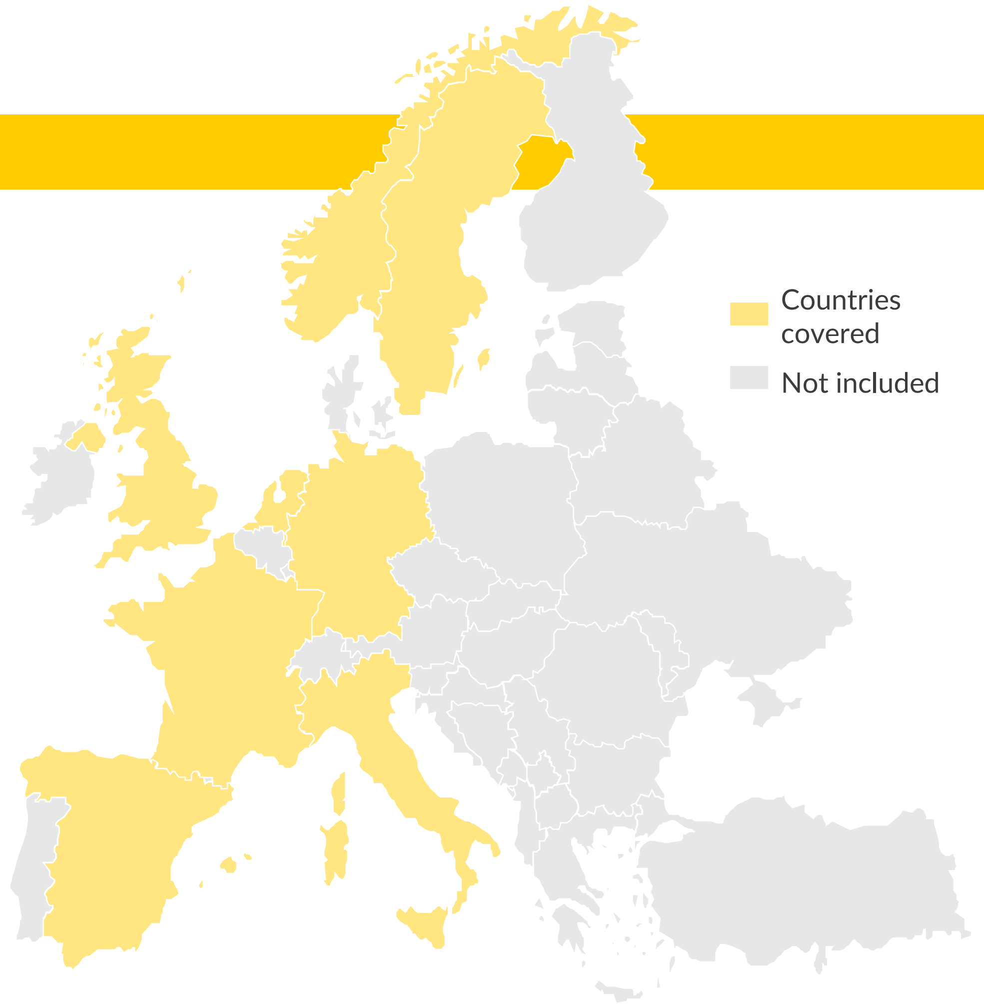


Research questions for all business models

- What is the LCOH for each country/year?
- Which countries have the lowest cost?
- Is it possible to beat the 2 EUR/kg H_2 target?

Flexible electrolysers can avoid producing in high price periods; the lowest LCOH is achieved at lower annual load factors

2 Flexible

- A "flexible" business model describes an electrolyser connected to the grid that can avoid producing in high-priced hours to minimise its LCOH
- The flexible electrolyser will operate in those hours where the total variable costs are lower, which is a combination of:
  1. **Wholesale energy costs –** based on Aurora's long-term projections on the market prices
  2. **Additional charges –** industrial consumers are subject to additional costs, some of which change on an hourly basis depending on the period in the day and year i.e. the energy component of the retail tariff

Cost optimisation

To achieve the lowest LCOH, our methodology considers:

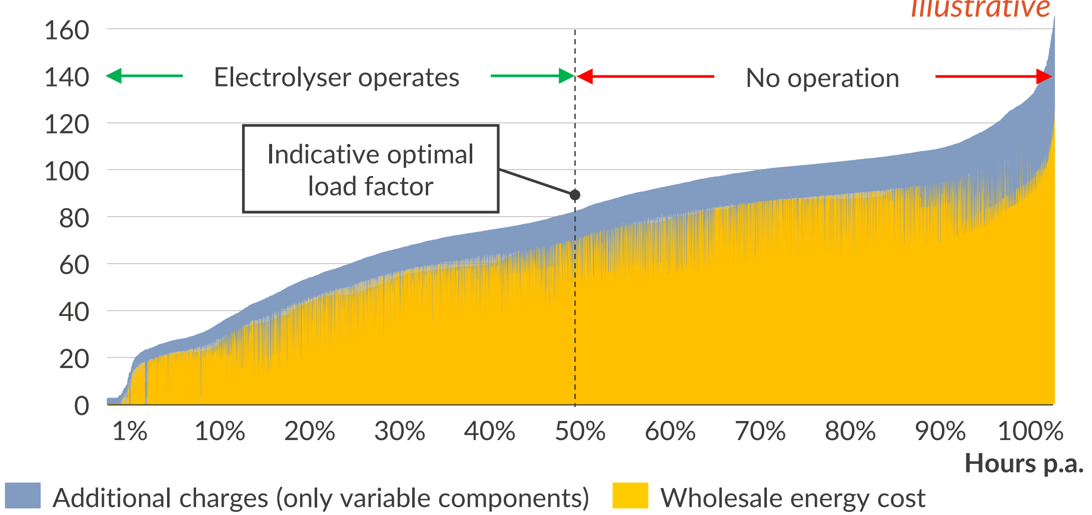
i. **Hourly granularity –** The optimisation occurs with hourly granularity using Aurora's Central forecast of power prices for each region together with our view on the evolution of additional variable cost components e.g. retail tariff costs

ii. **Lifetime operations –** The model decides which operations are optimal considering the full lifetime of the electrolyser, typically 25 years

iii. **Perfect foresight –** The model optimises the operations of the electrolyser having full visibility on the evolution of energy costs

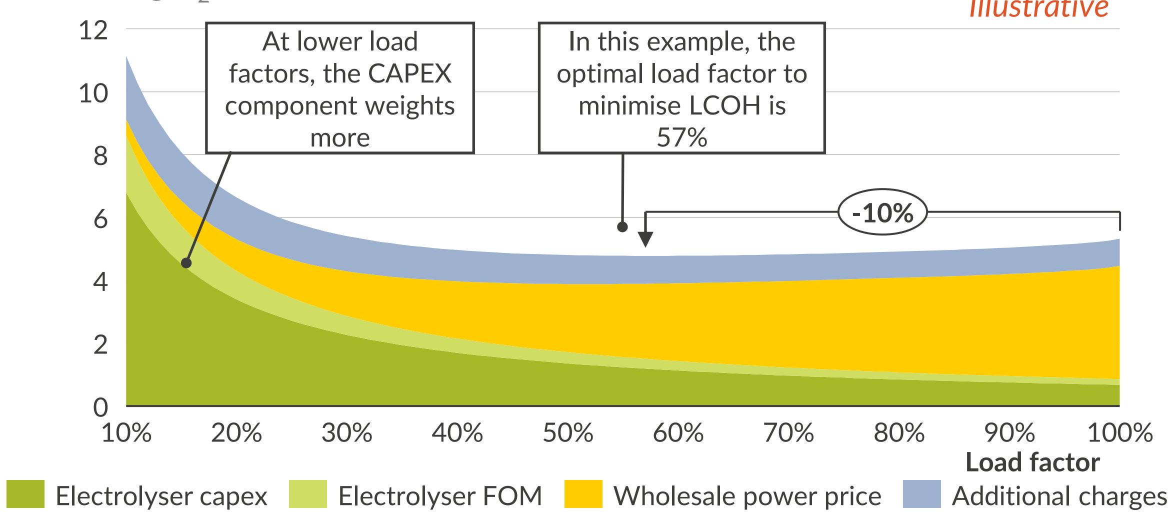
Example price duration curve

EUR/MWh



LCOH breakdown by component

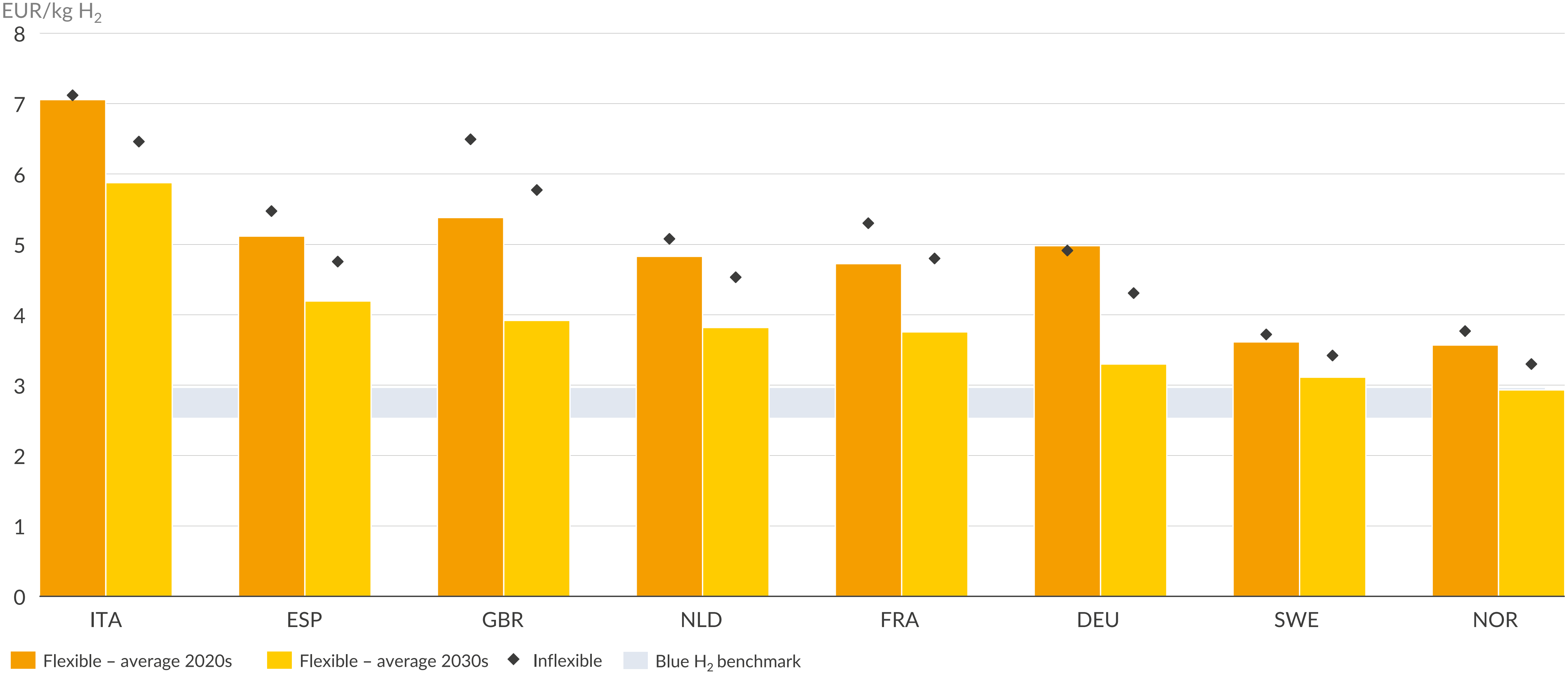
EUR/kg H_2



Source: Aurora Energy Research

Grid connected electrolysers can't compete with blue hydrogen until the 2030s; more public support needed

Inflexible and flexible LCOH for different countries by decade of entry – PEM electrolyser



1) Carbon intensity of hydrogen only shows the direct emissions 2) LCOH from price zone Sud in ITA, N in GBR, SE1 in SWE and NO1 in NOR 3) EU Taxonomy's definition of low-carbon hydrogen has a lifecycle emissions less than 3 tCO_2/tH_2

Source: Aurora Energy Research

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IV. **Co-located (island) electrolysers**

V. Co-located (grid) electrolysers

Research questions for all business models

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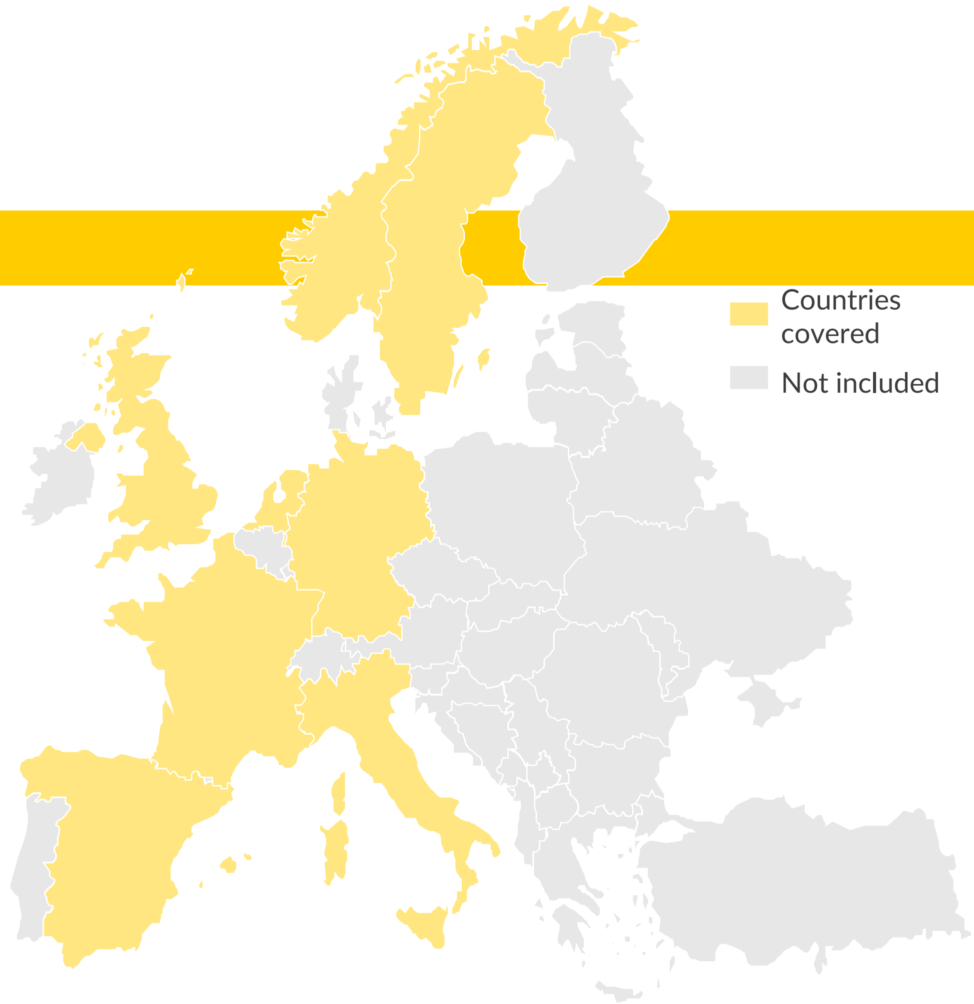
- Which countries have the lowest cost?
- Is it possible to beat the 2 EUR/kg H_2 target?



Electrolysers can be co-located with renewables; an optimal sizing of the renewable assets is crucial to deliver cheap hydrogen

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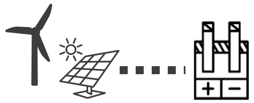
3 Co-located (island)

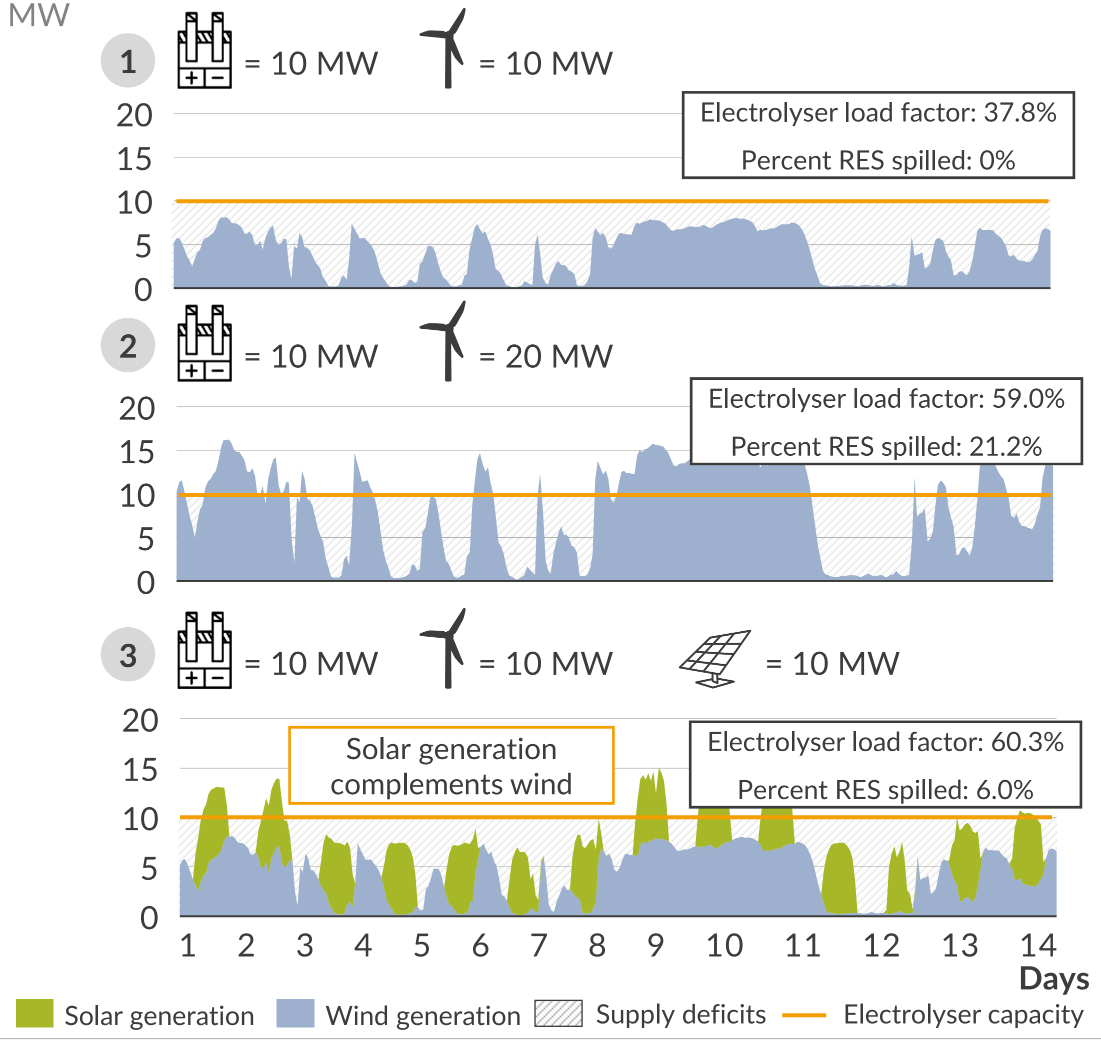


- A “co-located (island)” business model describes a electrolyser co-located with one or more renewable assets. It has **no grid connection** and thus operates as an ‘island’
- **The key consideration for this business model is the size of the electrolyser relative to the renewable asset**:
  1. **Under-utilised electrolyser** – Given the intermittency of renewables, if the renewable asset is not sized optimally, the hydrogen costs can be high due to a low utilisation of the electrolyser
  2. **Over-sized renewable asset** – If the renewable asset is too oversized relative to the electrolyser capacity, this can lead to significant energy spillage and a high LCOH as the renewable costs are also taken into account
  3. **Optimal size -** The optimal sizing can be analysed for each location to deliver the cheapest hydrogen possible. Wind and solar co-location can help to achieve the optimal solution

For this analysis we made the following assumptions:

- We explored different capacity combinations of onshore wind and solar PV to find the lowest LCOH
- We assume the electrolyser uses all the power generated by the renewable asset up to its capacity, **any excess generation is curtailed,** increasing the LCOH[1]
- A polymer electrolyser membrane (PEM) electrolyser was used due to its suitability for operating at variable load factors

Example electricity generation profiles for various renewable sizing



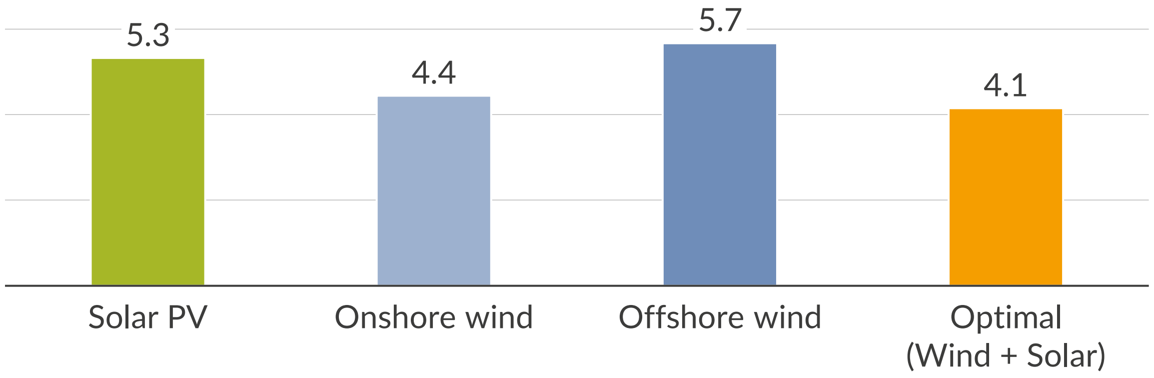
1) Curtailment is reflected in the LCOH, as energy spillage leads to a higher average cost of energy, increasing green hydrogen production costs.

Source: Aurora Energy Research

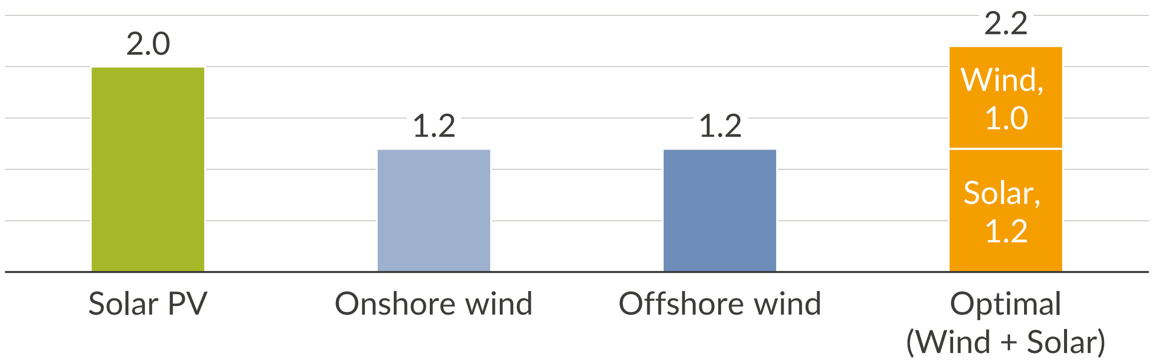
Hybrid co-location models with onshore wind and solar PV offer the lowest hydrogen production costs compared to individual technologies

Analysis of a co-located (island) PEM electrolyser in France commissioned in 2025. Assumes that the electrolyser is co-located with the optimal amount of renewable capacity.

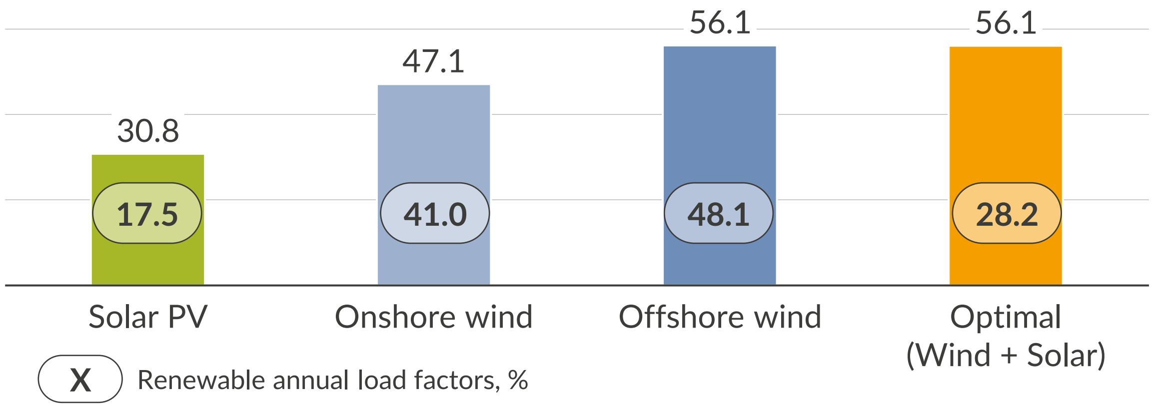
1 LCOH by energy source in 2025
EUR/kg H_2



2 Optimal RES size for 1 MW electrolyser in 2025
MW



3 Electrolyser annual load factor in 2025
%



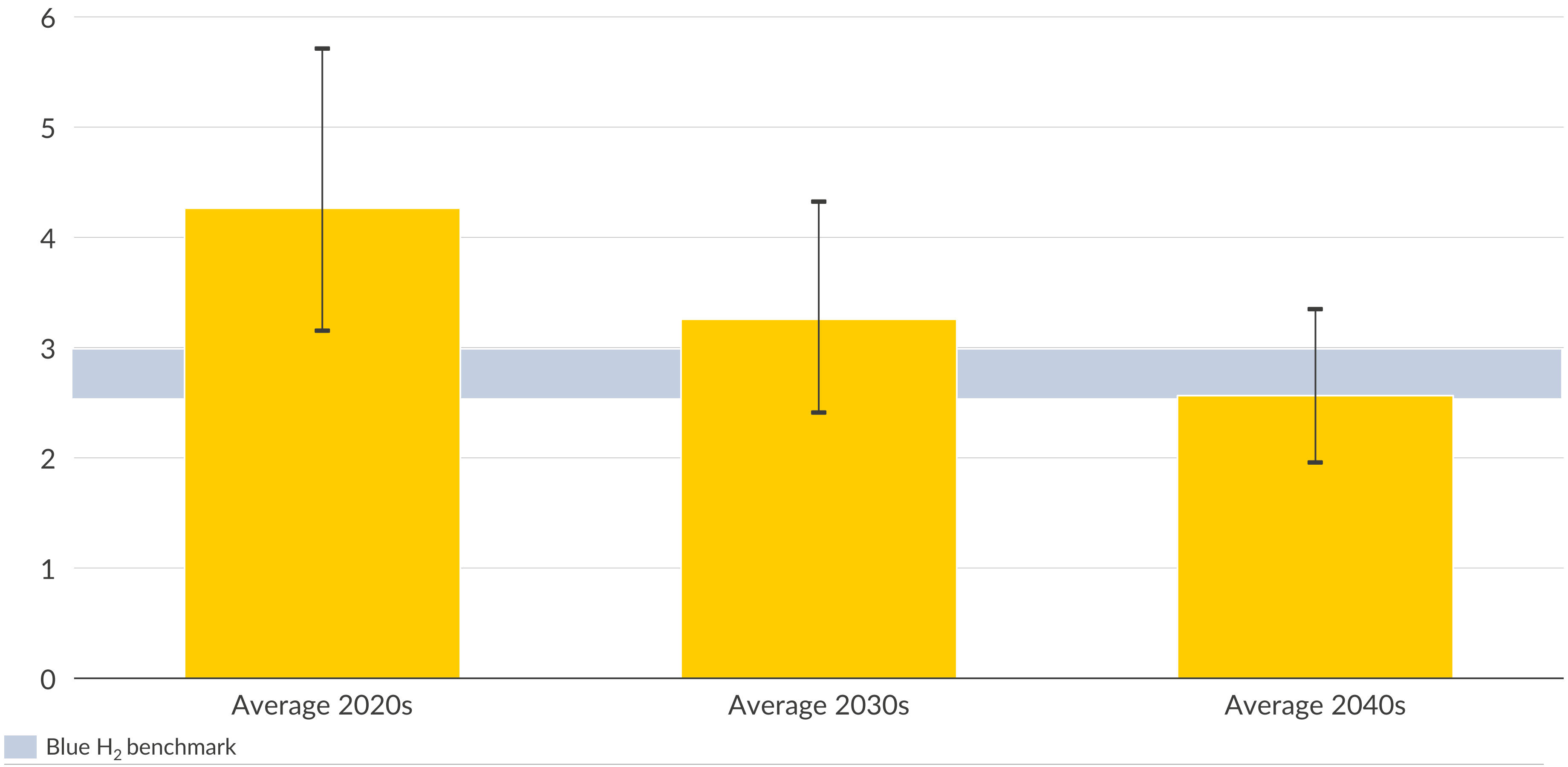
- Hybrid co-location models with onshore wind and solar PV offer the lowest LCOH compared to individual technologies, reaching 4.1 EUR/kg H_2 by 2025
- For individual technologies, the optimal sizing relative to the electrolyser capacity varies significantly. Whilst for wind technologies the optimal oversizing is ~20%, a solar system can double the electrolyser capacity
- Hybrid systems with wind and solar can be oversized further given the complementarity of their generation profile. This allows to achieve a higher annual load factor (>50%) while minimising energy spillage, leading to lower H_2 production costs
- In addition, the hybrid systems with wind and solar can also benefit from cost savings in certain OPEX components e.g. from optimising plant maintenance

Source: Aurora Energy Research

Hybrid co-location models reach cost parity with blue hydrogen in 2030s; and reach 2 EUR/kg H_2 by 2050 in several countries

3 Co-located (island)

LCOH for optimally sized co-located island electrolyser built in 2020s, 2030s and 2040s, European average
EUR/kg H_2



- We optimised the size of onshore wind and solar asset with to minimise the cost of production, the LCOH values shown in the graph represent the lowest cost that can be achieved in each country by combining onshore wind and solar assets
- We expect a decrease in the electrolyser costs as well as the cost of renewables; however, despite these cost reductions green hydrogen is not competitive with blue hydrogen until 2030s

Source: Aurora Energy Research

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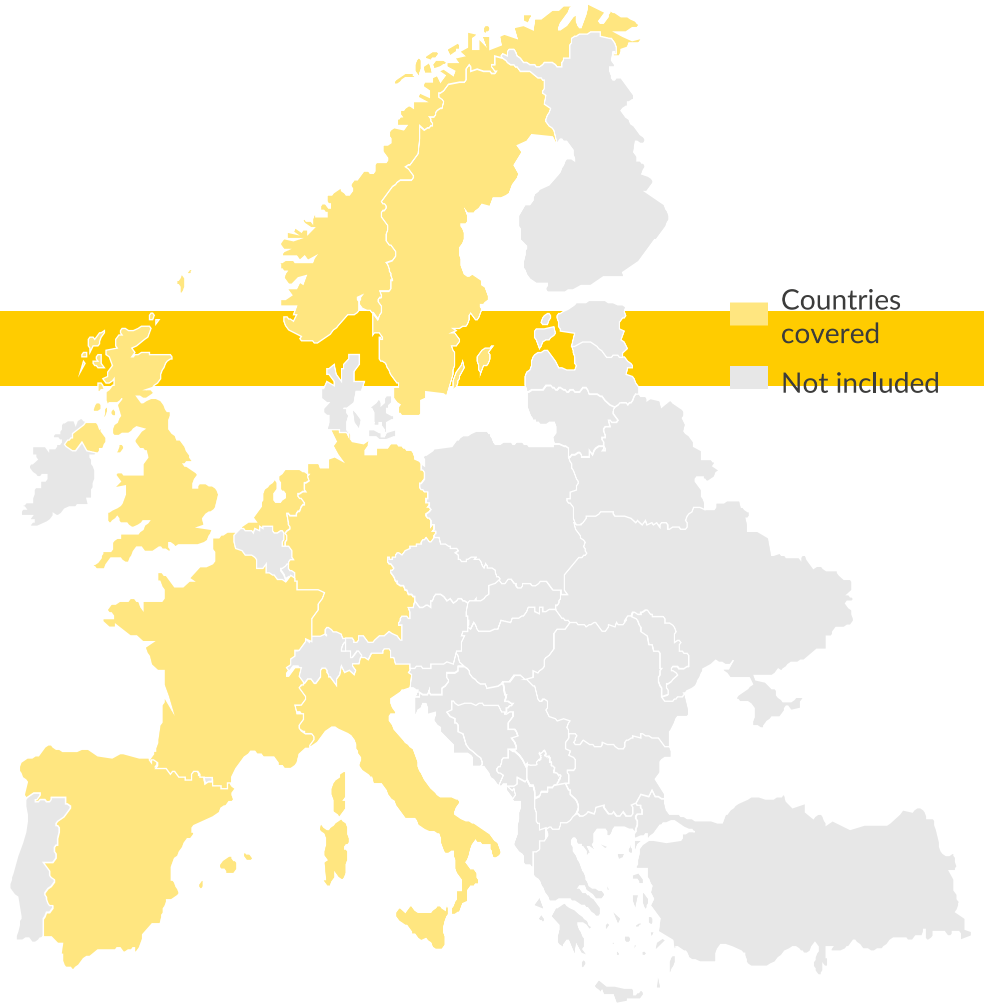

Research questions for all business models

- What is the LCOH for each country/year?
- Which countries have the lowest cost?
- Is it possible to beat the 2 EUR/kg H_2 target?

Adding a grid connection to a co-located electrolyser can increase its load factor in periods of low RES output and increase revenues

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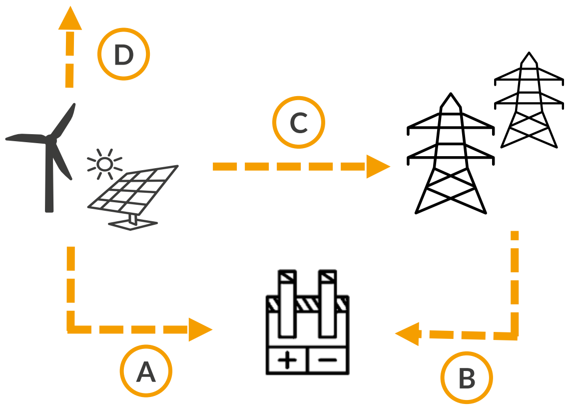
4 Co-located (Grid)

Schematic of co-located electrolyser and renewables with grid connection

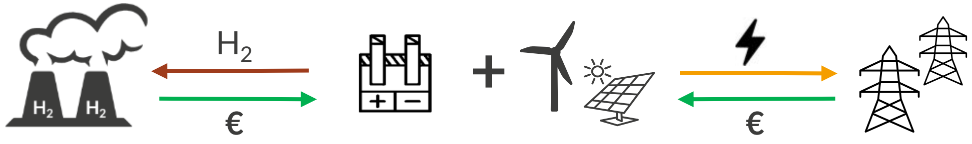


Key:

- (A) Electrolyser imports power from RES
- (B) Electrolyser imports power from grid
- (C) RES exports power to grid
- (D) RES spills power

- A “co-located (grid)” business model expands on the island co-located electrolyser model, providing an additional grid connection which allows for greater flexibility in hydrogen production
- With a grid connection, the electrolyser can choose to purchase grid electricity to top up its production when the renewables generation is insufficient and it is still profitable to produce hydrogen. The system can also sell any excess renewable generation, minimising spill
- However, any power purchased from the grid will have associated grid charges, which vary by time of use, voltage level, and carries an associated carbon intensity

Under this business model, revenues come from two sources:



1 Hydrogen exports

- The electrolyser produces hydrogen with power from the RES assets or the grid
- Produced hydrogen is sold to offtakers e.g. in industry

2 Electricity exports

- The RES assets generate electricity and sell to the grid at wholesale prices
- Or it supplies power to the electrolyser if hydrogen is more valuable

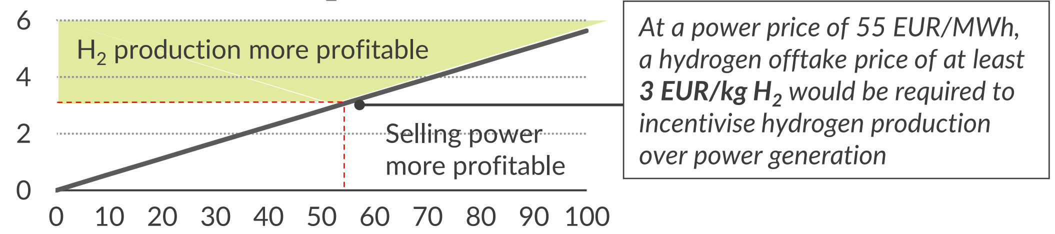
Revenue optimisation

To maximise its revenues, the asset will need to optimise its operations based on the profits from both sources, which is dictated by:

i. Hourly power prices – we use Aurora Central scenario for the analysis

ii. Hydrogen price – we assume a fixed purchase price by industrial offtakers

Hydrogen price, EUR/kg H_2



Power price, EUR/MWh

Source: Aurora Energy Research

Grid connected co-located projects decrease costs by 15-20% in Norway and Sweden, and 2% in Germany and France; rest don't decrease

4 Co-located (Grid)

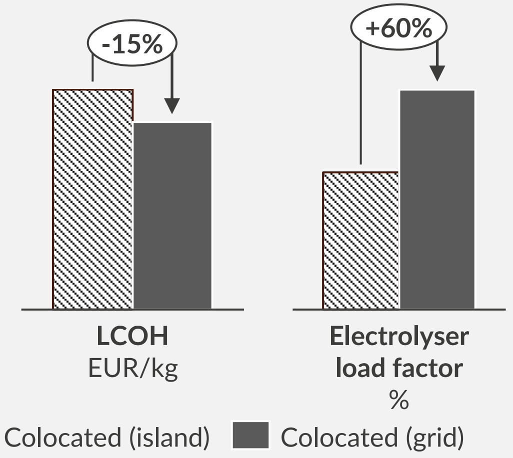
Adding grid connection reduces LCOH, increases IRR and electrolyser load factor for Norway in 2025

- Adding 70MW and 80MW of grid connection decreases LCOH by 15% and 16% respectively in Norway and Sweden
- Added revenue stream and power source lead to increased IRR and electrolyser load factor in Norway

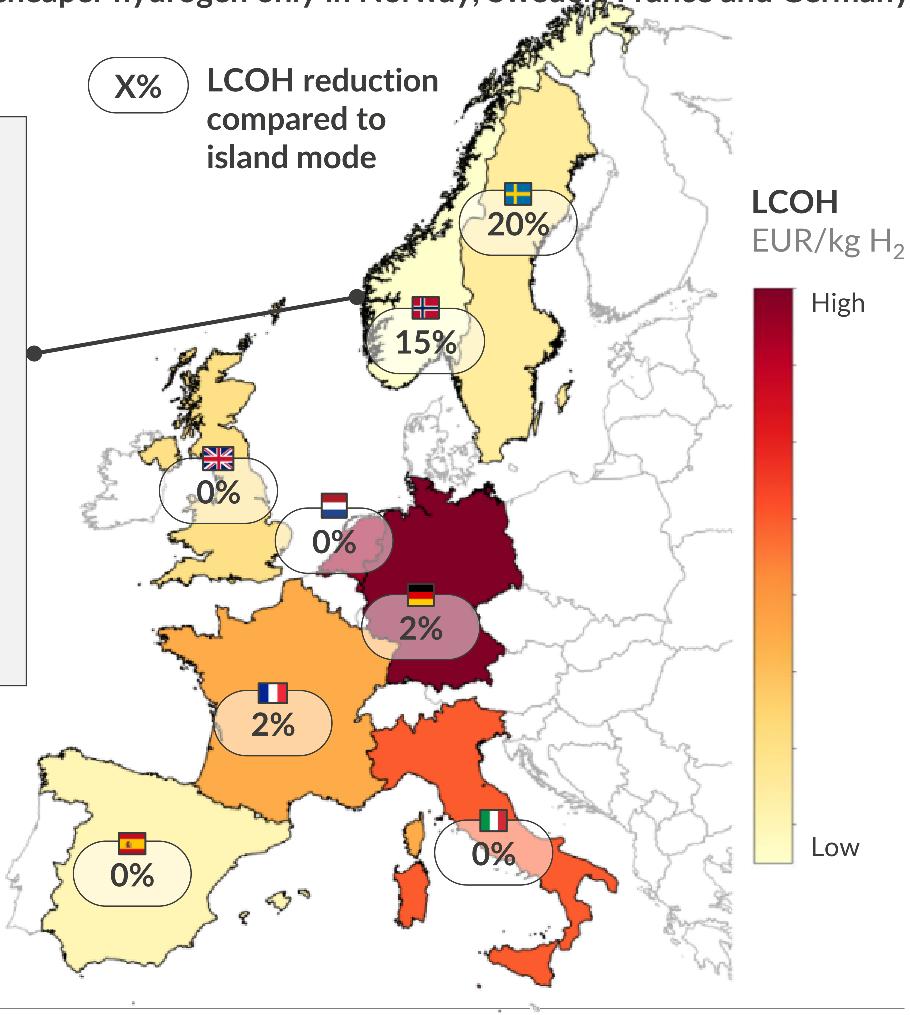
Adding grid connection de-risks the electrolyser project and increases optionality

- The availability of two different sources of revenue mitigates the risk of the business model and provides higher optionality due to exposure to both hydrogen and electricity markets
- Exposure to multiple markets reduces counterparty and regulatory risks

Comparison of co-located island and co-located grid models in Norway for 2025



Optimally sized[1] co-located and grid connected electrolyser built in 2025 produce cheaper hydrogen only in Norway, Sweden, France and Germany



1) See appendix for details of how this business model is modelled

Source: Aurora Energy Research

Takeaways

AURORA

Aurora has expanded its analysis on electrolyser business models. According to our analysis, 2 EUR/kg H_2 cost in 2030 can only be achieved with significant additional cost reduction in the electricity and electrolyser costs. Aurora suggests ~3 EUR/kg H_2 is a more realistic value

Electrolysers are exempt from electricity tax in Sweden, Norway, and Germany. Germany offers further exemptions from EEG, CHP and offshore surcharges for “green hydrogen” production. Italy and Great Britain have significant cost reduction potential if taxes and network charges are waived

1. Inflexibly operating electrolysers in Norway and Sweden produce the lowest cost hydrogen of the countries analysed, but even they don’t achieve cost parity with blue H_2 until the 2040s

2. Operating electrolysers flexibly can reduce costs drastically; however, strong inter-seasonal variability in hydrogen supply calls for seasonal hydrogen storage. Similar to inflexible, the cheapest production is in Norway and Sweden

3. Combination of onshore wind and solar results in the lowest production cost for all the countries in the co-located (island) business model. Spain produces the cheapest hydrogen in all years, and achieves the cost parity with blue hydrogen in early-2030s

4. Connecting the renewable assets and electrolyser to the grid is beneficial for Norway, Sweden, Germany and France due to their lower power prices and additional charges. In other countries, paying additional money for building a grid connection does not improve the system economics

Source: Aurora Energy Research

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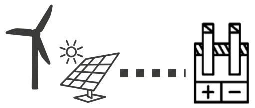
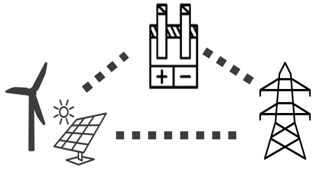
ENERGY RESEARCH

We have identified four business models to produce hydrogen via electrolysers, enhanced the co-located grid connected model





	1 Inflexible	2 Flexible	3 Co-located (Island)	4 Co-located (Grid)
Description	▪ Grid electricity **only** and runs at **95%** load factor	▪ Grid electricity **only** and ability to choose operating hours to minimise LCOH[2]	▪ Electrolyser connected to renewable asset only (no grid connection)	▪ Direct connection between electrolyser and RES asset, and both connected to grid
Key drivers	▪ Can **decouple electrolyser location from RES location** to be closer to demand ▪ Possible to 'green' power via GoOs/PPAs[1] ▪ High load factor achievable ▪ Produces regular output of hydrogen	▪ **'Smart' operation** avoids periods of high power prices and high grid charges, accessing lower LCOH ▪ Can **decouple electrolyser location from RES[3] location** to be closer to demand ▪ Possible to 'green' power via GoOs/PPAs	▪ Availability of **zero carbon, low marginal cost renewable energy** ▪ Benefits from decreasing renewable LCOEs ▪ Can optimise capacity ratio of electrolyser:RES in order to minimise LCOH	▪ Combines the benefits of grid connected and co-located business models ▪ Availability of **zero-carbon, low marginal cost renewable energy** ▪ Option to 'top up' electrolyser with grid electricity, or to sell renewable energy to the grid to increase revenues
Constraints	▪ Access to power grid ▪ Capital cost of grid connection ▪ Electrolyser subject to costly **grid charges** ▪ Uncertain **carbon intensity** of hydrogen output	▪ Lower average load factor results in less hydrogen production ▪ Due to smart operation, hydrogen production is less regular	▪ **Intermittency of RES** results in inconsistent hydrogen production ▪ **Lower average electrolyser load factors** ▪ Often located away from demand ▪ Optimal electrolyser:RES size can result in significant spilled power	▪ Electrolyser subject to grid charges ▪ Carbon intensity of grid electricity ▪ Capital cost of grid connection ▪ Must be located near to RES - often far from demand

1) GoO: Guarantees of origin, PPA: Power purchase agreement 2) LCOH: Levelised cost of hydrogen 3) RES: Renewable energy systems

Source: Aurora Energy Research

Lowest cost configuration differs by country and deployment year; co-location with/without grid connection is the most popular setup

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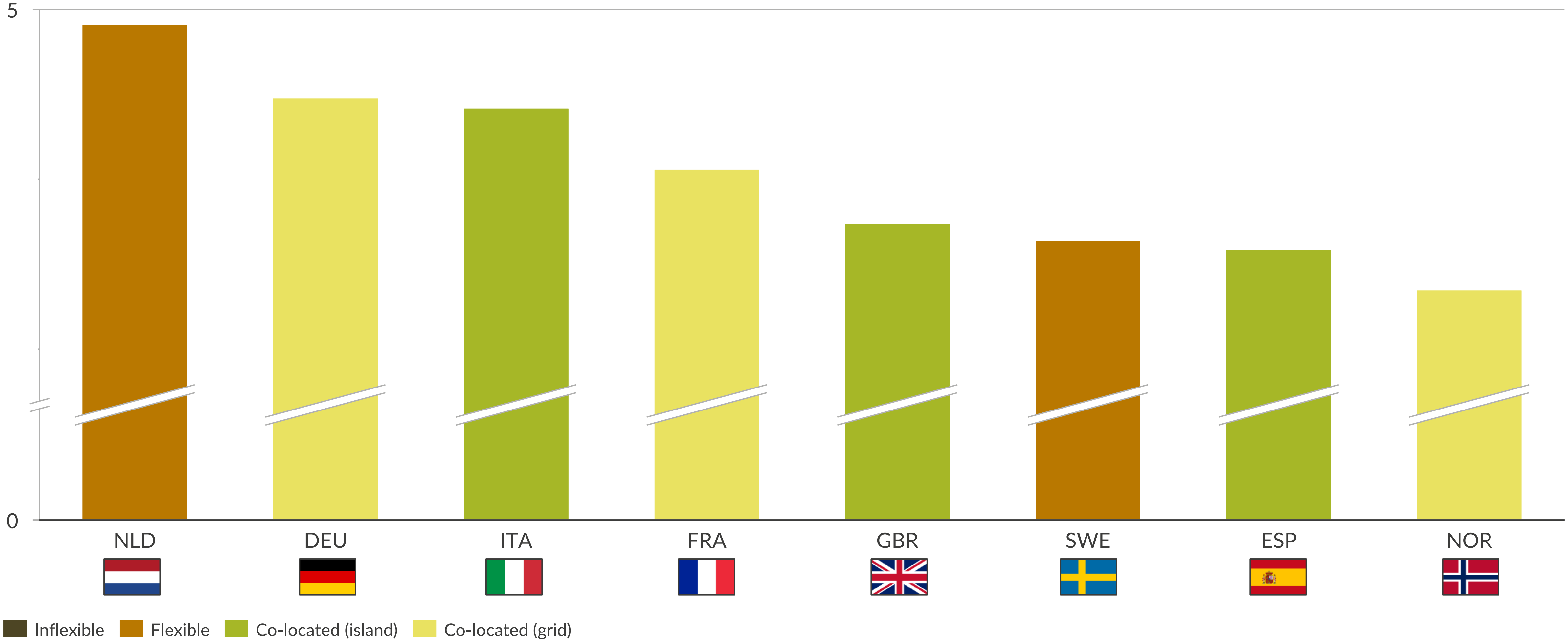
LCOH[1] of lowest cost configuration for an electrolysers commissioned in 2025
EUR/kg H_2



1) LCOHs are available to the subscribers

Source: Aurora Energy Research