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ENERGY RESEARCH

Shades of green (hydrogen): optimising electrolyser business models

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Today's presenters and other key information

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

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Supply Chain

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丸紅株式会社 Marubeni, Kommunal Kredit, BlackRock, Barclays, BlueWaterEnergy, SEB, meridiam Investing for the community, low carbon powering tomorrow

Government & regulation

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

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

Source: Aurora Energy Research

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

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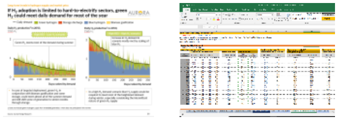
Hydrogen Market Attractiveness Report (HyMAR)

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

Strategic Insight Reports



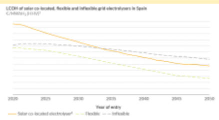
- Regular insight reports on topical issues in the evolving European hydrogen market covering country, policy and technology deep dives
- Upcoming reports on next slide

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, gas and carbon price forecasts
- Granular electrolyser business cases, including optimised grid-connected and renewables co-located models
- For use in strategy formulation, transactions and JV negotiations

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

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Source: Aurora Energy Research

We have identified four business models to produce hydrogen via electrolysers

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	Inflexible Electrolyser	Flexible Electrolyser	Co-located (Island)	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)	▪ Electrolyser connected to grid plus direct connection to RES asset
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
Markets modelled	▪ GB, IR, FR, ES, PT, IT, DE, NL, BE, PO, DK, NO, SE, FI	▪ GB, DE, ES	▪ GB, IR, FR, ES, PT, IT, DE, NL, BE, PO, DK, NO, SE, FI	▪ GB (offshore wind), DE (onshore wind), ES (solar)

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

Source: Aurora Energy Research

Agenda

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Source: Aurora Energy Research

In order to be cost competitive with blue hydrogen in Europe, green hydrogen needs to beat a target of ~2.5 EUR/kg H_2

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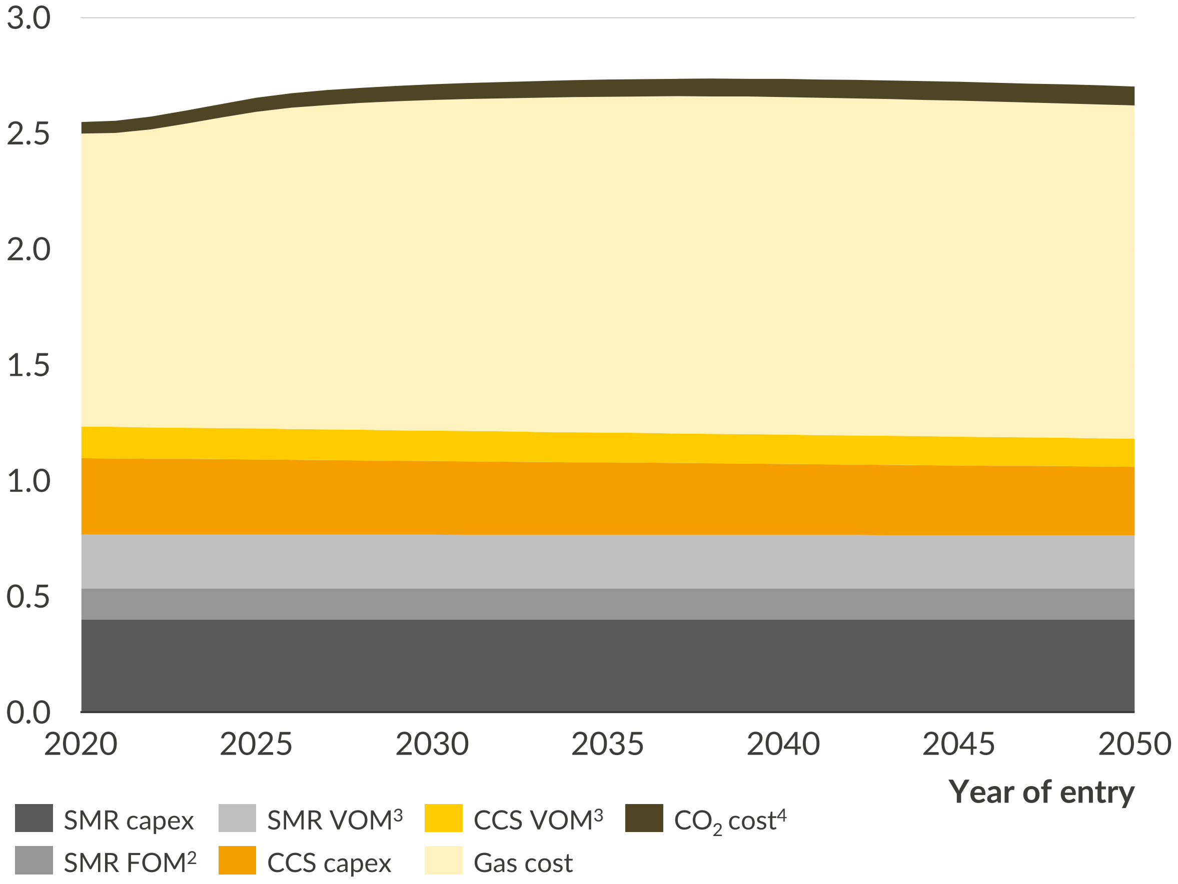
Blue Hydrogen

LCOH breakdown (large scale SMR+CCS[1] in Great Britain, 95% load factor)

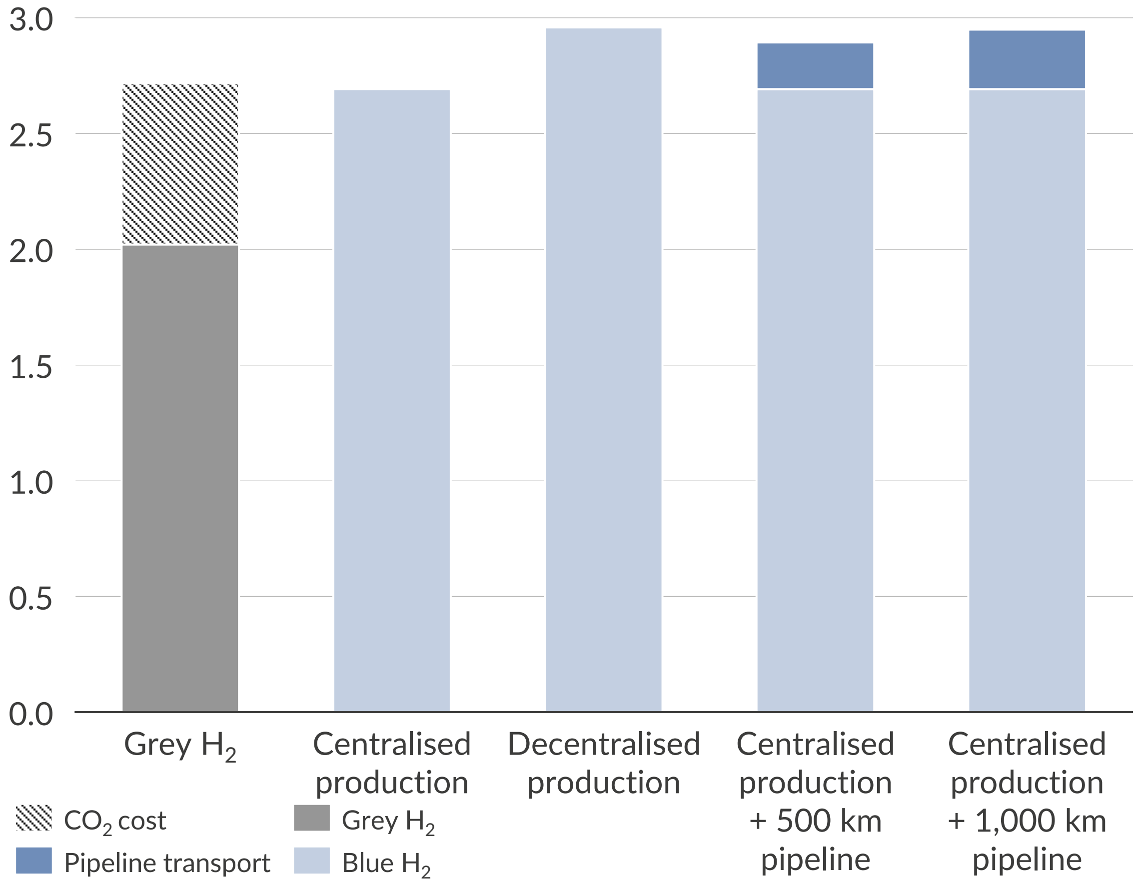
EUR/kg H_2



Decentralised blue hydrogen production has higher cost because of higher SMR capex, and centralised production requires hydrogen transport

LCOH grey and blue hydrogen (SMR+CCS) in Great Britain in 2030

EUR/kg H_2



1) Carbon capture & storage. 2) Fixed operation & maintenance costs (4% of CAPEX of SMR, 5% of CAPEX from CCS). 3) Variable operation & maintenance costs. 4) Cost arising from the taxation of residual emissions (currently ~5%)

Source: Aurora Energy Research

Appropriate carbon accounting and classification of low carbon hydrogen is important for developing a hydrogen economy

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Carbon intensity of hydrogen production

As well as cost, carbon intensity is a vital metric to evaluate

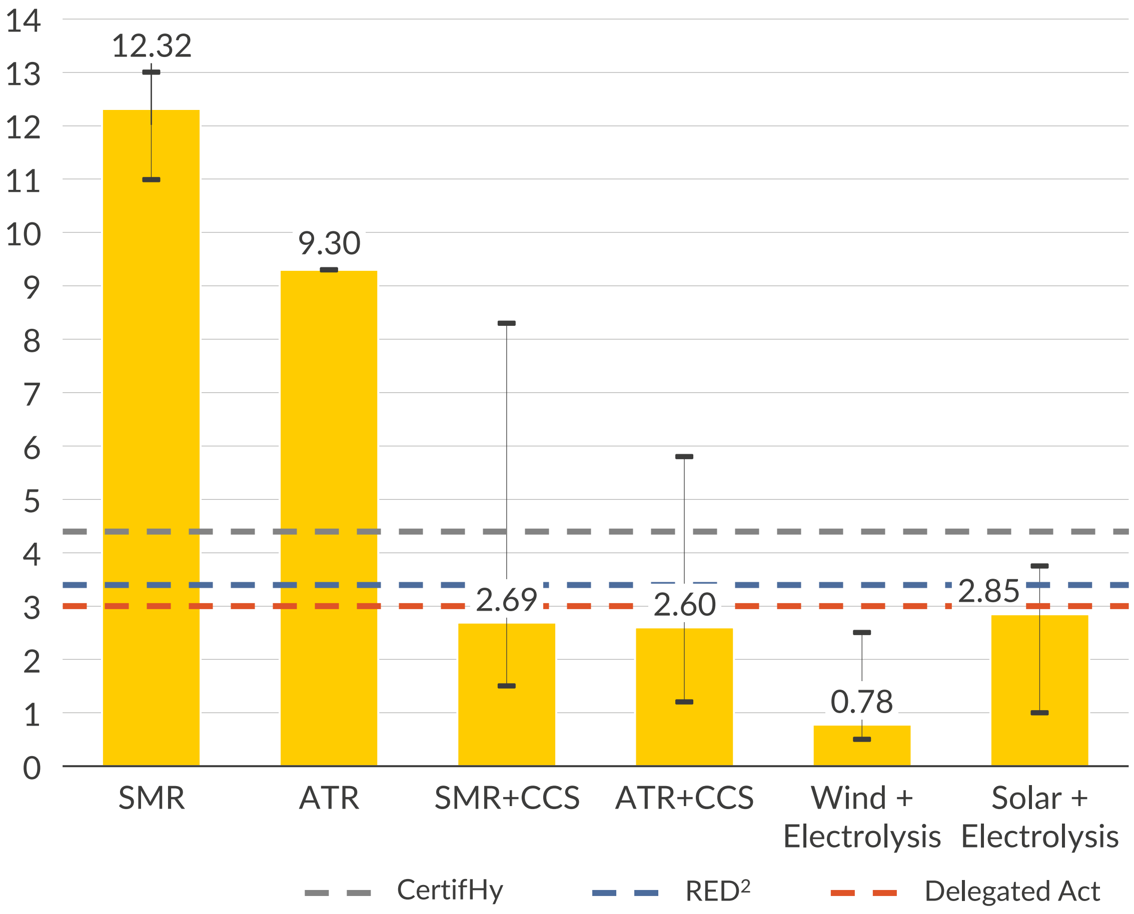
- Nearly all hydrogen produced globally today is made from methane via steam methane or autothermal reformation (SMR or ATR). While cost effective, these production methods have a high carbon intensity (see chart).
- There are several ways of making low carbon hydrogen, all with different lifetime carbon intensities[1]. Lifetime carbon emissions are important, since they account for both direct emissions (during hydrogen production) and indirect emissions (e.g. manufacture and transport of equipment), which can be significant for certain renewable technologies

The EU has recently published their first taxonomy of sustainable hydrogen

- In June 2021, the EU finalised the Delegated Act for Sustainable Finance Taxonomy, setting a carbon intensity limit of **3 tCO_2/tH_2** for sustainable hydrogen
- Importantly, this **limit includes lifecycle emissions**, which could exclude some blue hydrogen, and possibly even some green hydrogen from solar, from the definition
- The limit is lower than stipulated in the EU's Renewable Energy Directive for hydrogen used in transport, and lower than CertifHy's proposed limit of 4.37 tCO_2/tH_2 that would form the basis of a proposed trading system for low carbon Guarantees of Origin

Lifetime CO_2 intensity of hydrogen production methods

tCO_2/tH_2



1) When calculating lifetime emissions, all emissions are counted, including those during manufacturing, transportation and production; 2) EU Renewable Energy Directive

Sources: Aurora Energy Research

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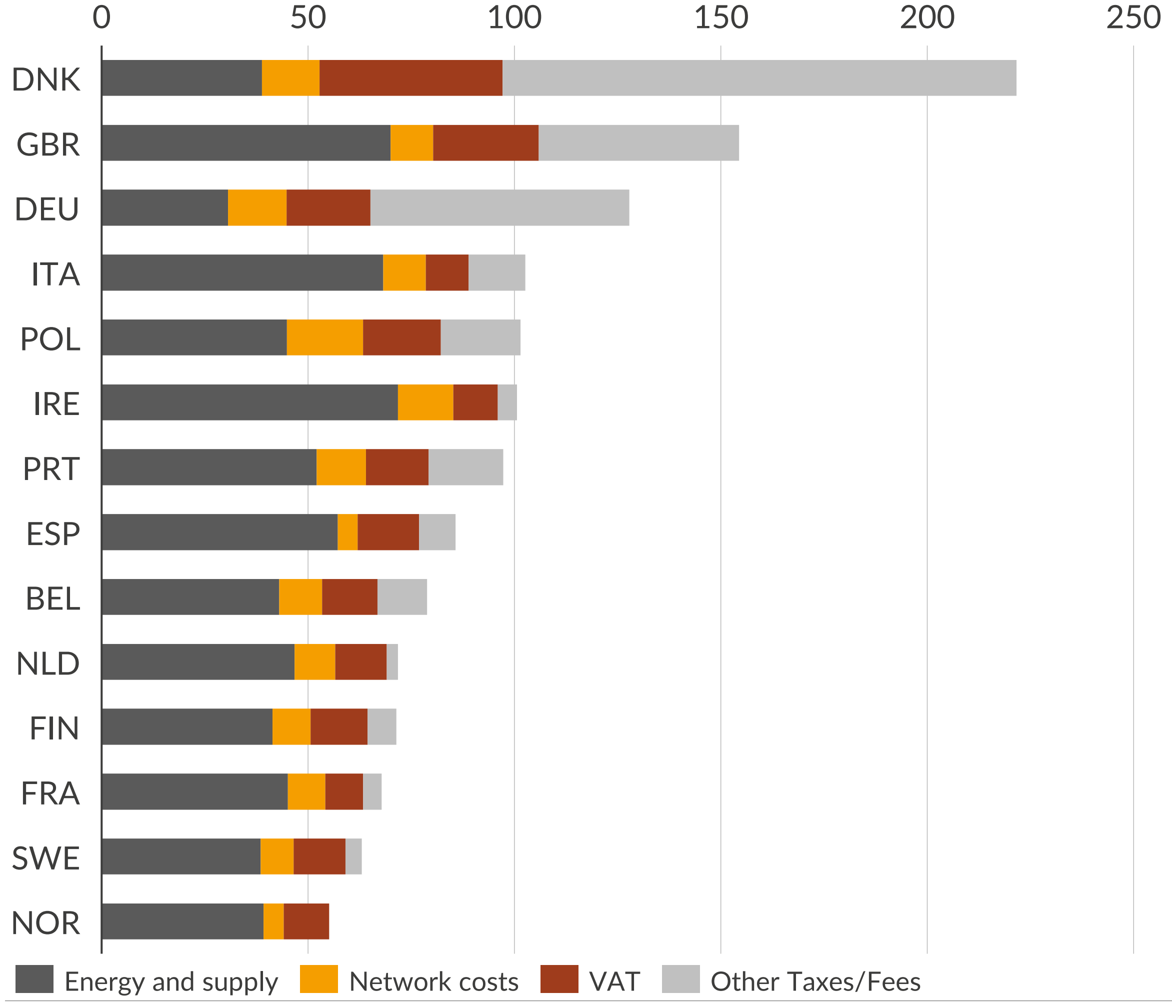
Source: Aurora Energy Research

Power costs for grid electrolysers include wholesale costs plus additional charges; exemptions apply in some countries

Electricity price components for non-household consumers in 2019[1]

EUR/MWh



Wholesale electricity prices do not reflect the full power costs of grid-connected electrolysers

- The chart data presents electricity price components for industrial (non-household) consumers, assuming that no exemptions are applied. In some countries there are specific exemptions in place or planned for electrolysers which reduce these costs
- Additional charges are aggregated at annual granularity. In reality they do vary with time (i.e. higher charges in peak periods) and in some cases location (i.e. higher charges in demand-dominated network areas)
- For our inflexible modelling we have assumed that additional charges remain constant year to year, and no exemptions to taxes or charges are applied
- Aurora has modelled flexible and inflexible electrolysers based on power market modelling for fourteen countries covered by Aurora's power market forecast

Four components make up the cost of power for an electrolyser in this model:

1. Energy and Supply – energy, customer service, and after sales management
2. Additional Charges
   a) Network Costs – grid connection fees and associated taxes, paid by anyone drawing from or feeding into the distribution grid
   b) VAT – Value added tax, or Goods and Services Tax, typically applied around 20% in the EU
   c) Other Taxes/Fees – includes renewable, capacity and environmental taxes

1) Consumers are filtered by their annual consumption between 70-150 GWh (Band IF), this corresponds to 8.5-18 MW electrolyser capacity working with 95% load factor.

Sources: Aurora Energy Research, Eurostat

The least carbon intensive electricity grids also produce the cheapest hydrogen, when electrolysers are operated inflexibly

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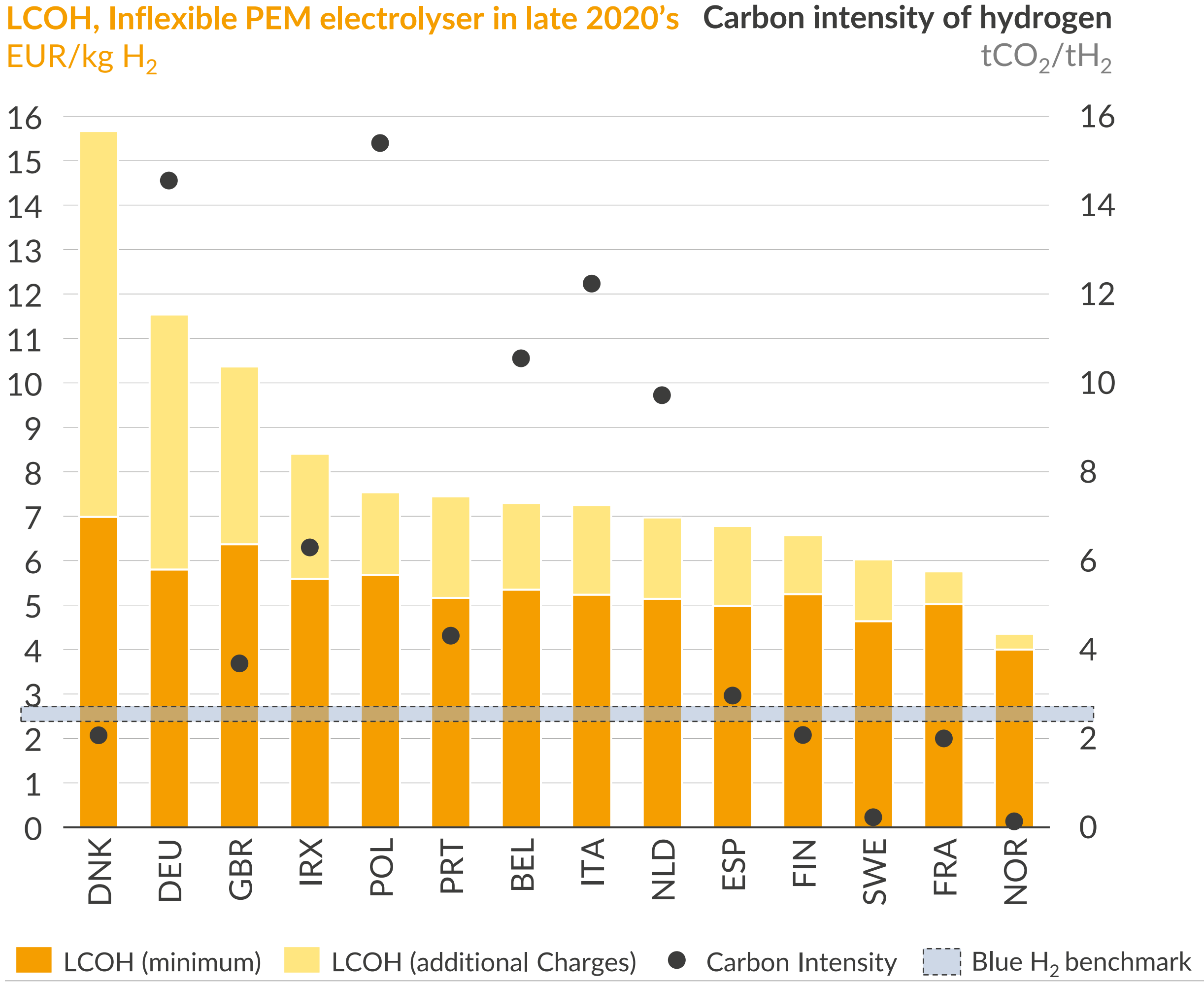
1 Inflexible



1) Minimum LCOH consists of electrolyser capex, opex and wholesale power prices 2) Additional charges include taxes, levies and fees

The lowest LCOH is driven by renewables or nuclear dominated grids

The lowest LCOH's found in this study are in the Nordic countries, and France. This is driven by low LCOE of renewables production and limited additional environmental or capacity charges.

The countries where it is cheapest to operate an electrolyser inflexibly have the secondary benefit of being able to produce the least carbon intensive hydrogen in Europe.

The highest LCOHs are a result of fees and taxes, and the carbon intensities vary

Additional charges added on top of wholesale power prices make it impractical to produce hydrogen inflexibly in certain countries such as Germany and Denmark.

Of the countries we looked at Denmark is the most expensive because of high taxes and levies applied to electricity – however the resultant hydrogen is extremely low in carbon intensity. Conversely, in Germany, the premium paid for electricity does not yield the benefit of low carbon hydrogen being produced.

Removing additional charges would level the playing field

Additional charges force Denmark and Germany into an uncompetitive position, if hydrogen producers were compensated for some or all of these additional charges, inflexible production would become more viable.

Source: Aurora Energy Research

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Source: Aurora Energy Research

We have investigated Germany, Spain and Great Britain in detail for the flexible electrolysers, because of their interest in hydrogen

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2 Flexible

Germany, Great Britain and Spain have different power price components, some of which also depend on location, time and capacity

- **Germany** is the best country to invest in according to our HyMAR report[1], and it has many compensations for electrolysers such as exemptions of EEG levy, CHP surcharge, offshore levy and grid charges. German grid charges are time-independent, yet they vary by location/DSO[2], total power consumption and peak power of the industrial consumer. Additional charges such as taxes and levies are consumption based flat rates
- **Great Britain** (especially Scotland) communicated its interest in exporting hydrogen produced via offshore wind energy. Grid charges vary by DNO[3] zone and peak power consumption, as well as being time-varying. Remaining charges are consumption based flat rate charges
- **Spain** expressed their interest in being a green hydrogen producer to export it to Europe. Spanish grid charges vary depending on peak power consumption and time of use, but do not vary between regions. Remaining charges are consumption based flat rate charges

Non wholesale power price components for industrial users

DEU	GBR	ESP
▪ Network fee (capacity, peak) ▪ Concession fee ▪ CHP surcharge ▪ StromNEV surcharge ▪ Offshore surcharge ▪ EEG surcharge ▪ abLAV surcharge ▪ Electricity tax	▪ Final Consumption Levies: FiT, CfD, RO, CCL ▪ Capacity Market Supplier Charge (CMSC) ▪ Grid charges: TNUoS (transmission only), BSUoS, DUoS and fixed grid charges (fixed meter charge and fixed capacity charge) ▪ Supplier operating cost	▪ Cost of adjustment services ▪ Capacity payments ▪ Cost of system operator ▪ Cost of market operator ▪ Transmission fee ▪ Distribution fee ▪ Removable remuneration ▪ Non-peninsular production surcharge ▪ Deficit annuities ▪ CNMC

1) Hydrogen Market Attractiveness Rating report is released in April 2021, available in EOS; 2) Distribution system operator; 3) Distribution Network Operator 4) The components are expressed in cost per unit consumption i.e. EUR/MWh

Sources: Aurora Energy Research, BNetzA, CNMC

Flexible electrolysers have significantly lower costs and carbon emissions than inflexible electrolysers in Great Britain

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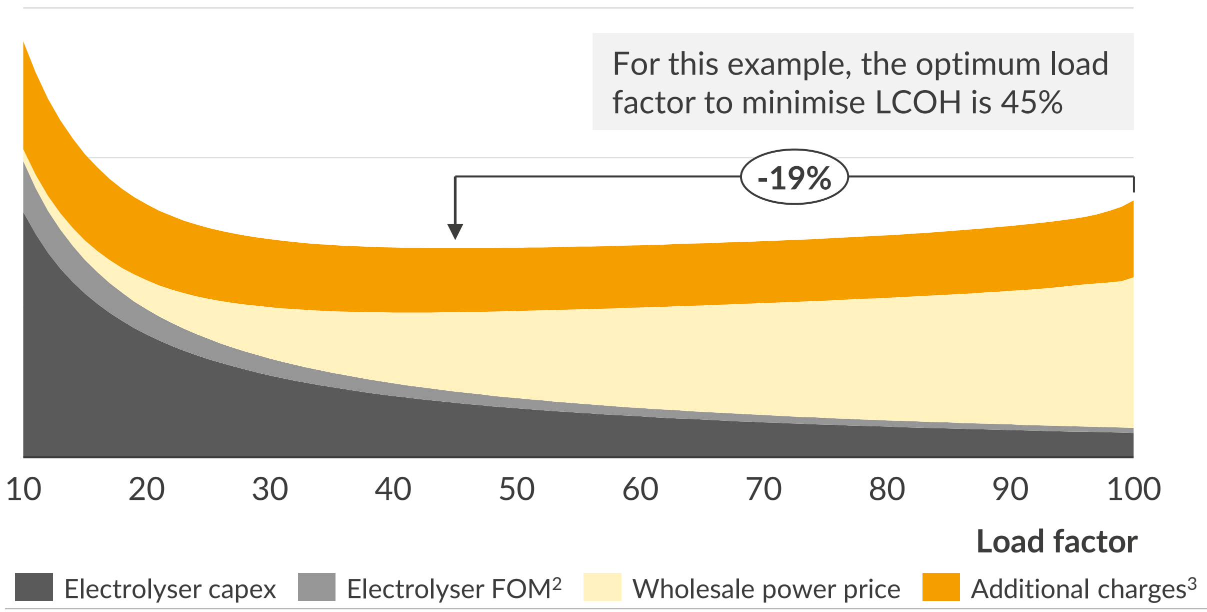
2 Flexible

- When the electrolyser responds to power price signals, it can reduce its running cost by reducing its wholesale power cost
- At very low load factors, the electrolyser capex becomes the most expensive component of its LCOH, as there are fewer units of hydrogen to levelise the cost over. At high load factors, the power cost makes up 85% of the LCOH. The additional charges make up 20-30%

LCOH[1] by electrolyser load factor in Scotland in 2030
EUR/kg H_2

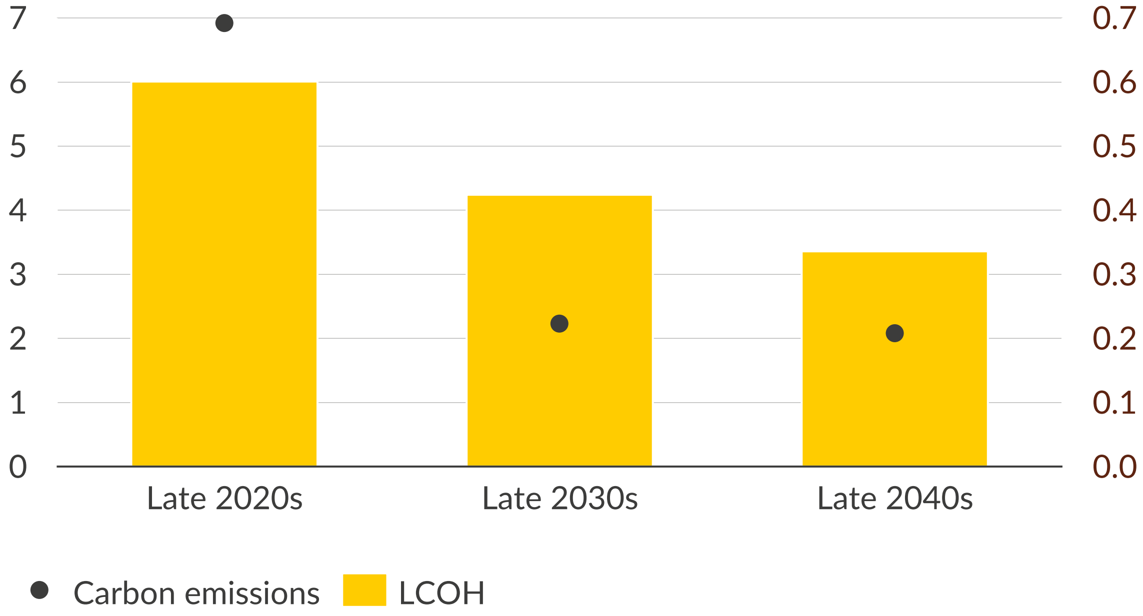


Flexible electrolysers in Great Britain have a falling LCOH through our time horizon, however it remains above the LCOH of both grey and blue H_2

- The levelised cost of hydrogen that is produced by flexible electrolysers halves from now until 2050, but in the 2030s and 2040s remains above blue
- The carbon intensity declines until 2035 as more renewable generation comes online. Flexible electrolysers have **~90% lower** carbon emissions compared to the inflexible operation in Great Britain

Average LCOH in Scotland (by year of entry)
EUR/kg H_2

Carbon emissions in Scotland
tCO_2/tH_2



1) LCOH figures are available to subscribers of our European Hydrogen Service
2) Fixed operation and maintenance costs 3) Additional charges consist of final consumption levies (FiT, CfD, RO, CCL), capacity market supplier charge (CMSC), grid charges and supplier operating cost
Source: Aurora Energy Research

Flexible production and exemptions from environmental levies will be key to keeping grid-powered hydrogen costs low

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2 Flexible

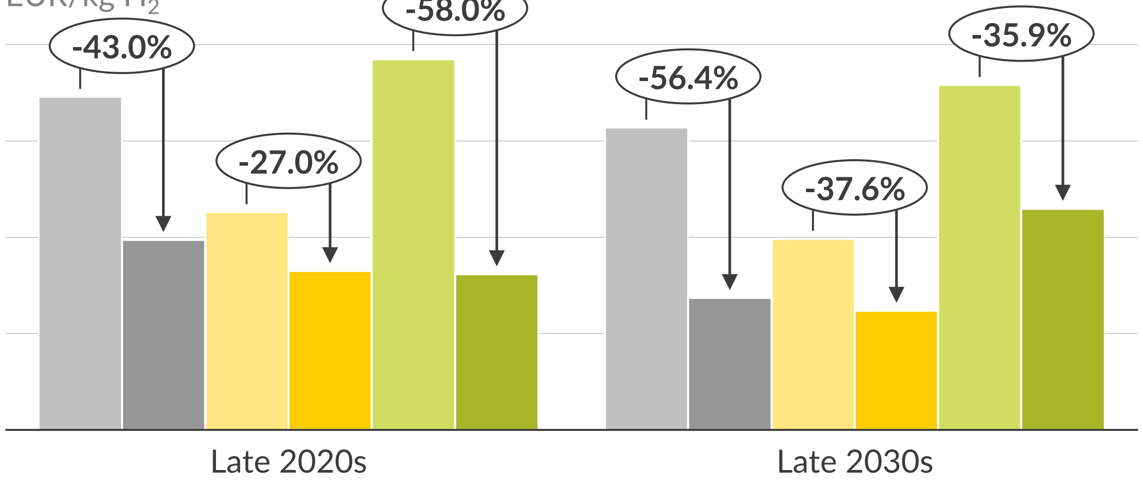
- In Great Britain and Germany, the LCOHs for flexible electrolysers in 2025 are significantly lower than for their non-compensated inflexible electrolyser counterparts. In Spain, the difference is much slighter as Spain already has low baseload power prices
- Of the three countries, Germany has the lowest LCOH until 2030, due to low priced bottom hours[1] and fee exemptions and compensations. After 2030 Great Britain and Spain become more competitive as Germany's exemption from EEG levy for electrolysers is due to end or be revised

As well as accessing a lower LCOH, operating an electrolyser flexibly drastically reduces the carbon intensity of hydrogen production

- This is unsurprising, since the most expensive hours of power are often related with the highest carbon intensity, therefore avoiding these hours reduces both operating cost and carbon intensity for flexible electrolysers
- Hydrogen produced by flexible electrolysis may be below the threshold to be considered sustainable by the EU. But it will almost certainly not meet additionality requirements for RED-II, which require special and temporal (at 15 minutes intervals) correlation with production and renewable generation

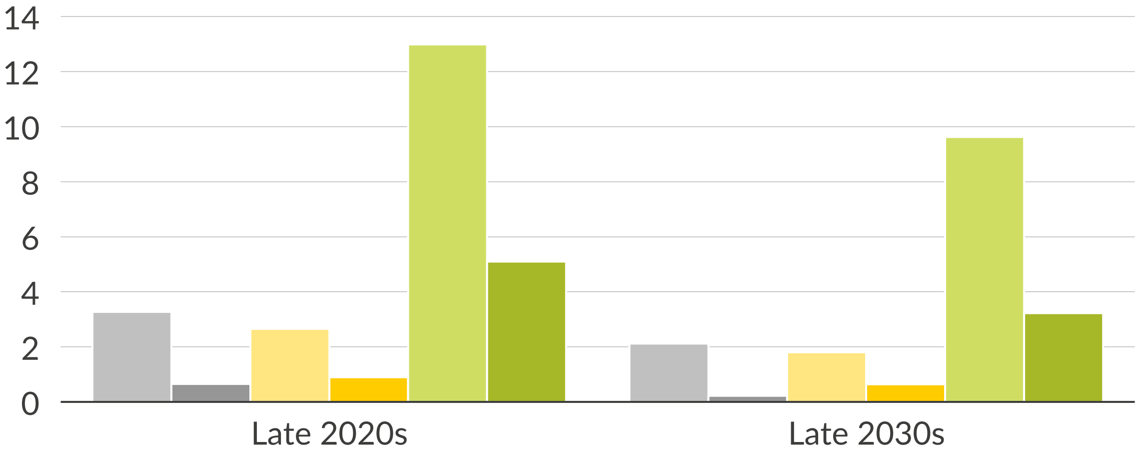
Average LCOH for flexible and inflexible operation[2]

EUR/kg H_2



Carbon intensity of hydrogen

tCO_2/tH_2 year of entry of electrolyser



GBR-Inflexible | GBR-Flexible | ESP-Inflexible | ESP-Flexible | DEU-Inflexible | DEU-Flexible

1) The hours at the lowest part of the retail price duration curve, in other words the cheapest hours during the year; 2) Flexible LCOH includes compensation and exemption from certain taxes, levies and fees. Inflexible LCOH does not include compensation or exemption 3) GoO: Guarantees of Origin, PPA: Power Purchase Agreement

Sources: Aurora Energy Research

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Source: Aurora Energy Research

Electrolysers can be co-located with renewables; reducing the relative size of the electrolyser increases its utilisation

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3 Co-located (island)

- "Co-located (island)" business model describes an PEM electrolyser co-located with a renewable asset. 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**: too large and the electrolyser is under-utilised. Too small and excess renewable generation is unused
- The questions that we investigated are as follows:
  1. What size of electrolyser relative to the renewable asset would result in the lowest LCOH?
  2. How would this relative sizing be influenced by renewable asset type and region?
  3. How the LCOH of the optimally sized co-located arrangement compared to the other business models?

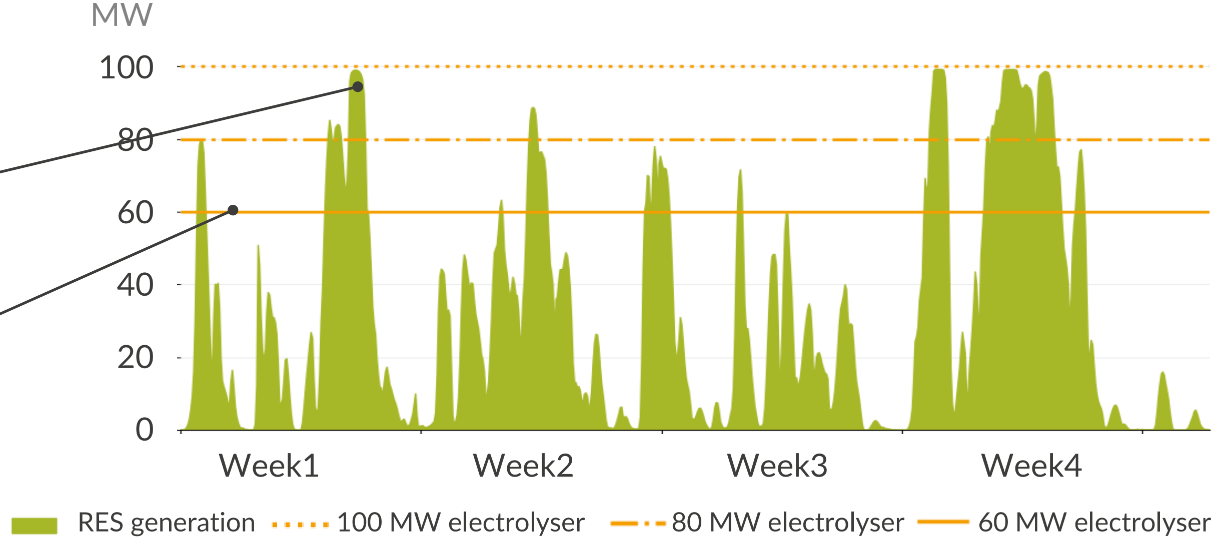
Decreasing electrolyser size results in more curtailed power (green area above orange line)

- An electrolyser size 1:1 to the onshore wind asset (100 MW) in GBR has a load factor of 39%
- A smaller electrolyser (60 MW) for the same wind park would have a higher load factor of 55% but spill 15% of the wind production

For this analysis we made the following assumptions

- We looked at solar, onshore wind and offshore wind
- The size of the electrolyser was optimised for minimum LCOH
- We assumed the electrolyser used all the power generated by the renewable asset up to its capacity, **any excess generation is curtailed**
- To account for curtailment, we assume the electrolyser bought the power from the renewable asset at its LCOE. We have assumed LCOE is proportional to the total RES power utilisation; hence, as renewable power is curtailed the effective LCOE of RES asset increases

Example electricity generation profile for a 100MW wind park



Source: Aurora Energy Research

Finding the optimum capacity ratio reduces the levelised cost of hydrogen; for GBR solar in 2030 the ideal ratio is 1:3

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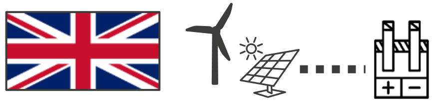
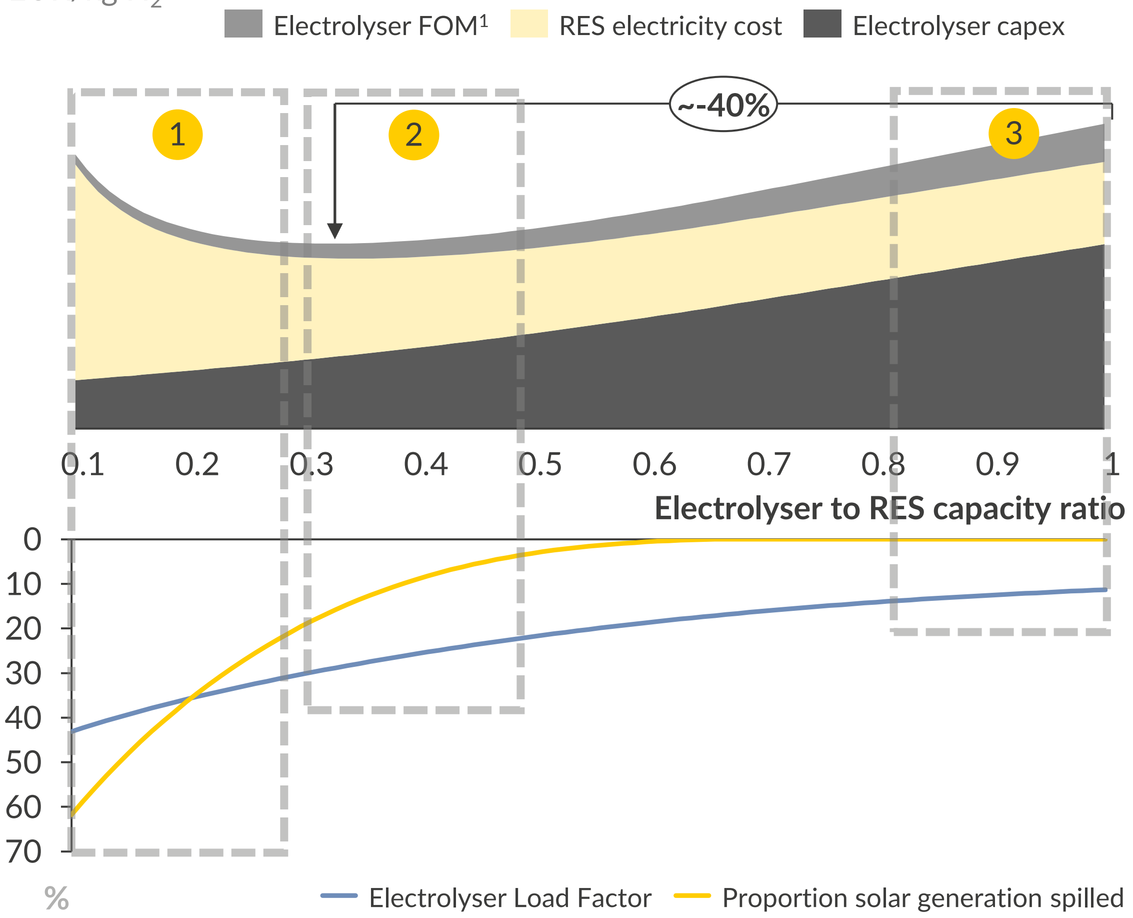
3 Co-located (island)



LCOH for electrolyser co-located with solar energy in GBR in 2030

EUR/kg H_2[1]



Optimising the size of the electrolyser relative to a solar asset can reduce the LCOH by ~40% compared to a 1:1 set-up

1. When the electrolyser size to RES size ratio is low, the electrolyser load factor is high but more solar production is curtailed. The high curtailment results a higher LCOE of the RES asset and therefore a higher 'RES electricity cost' contribution to the LCOH (i.e. cost per unit of solar increases as useful production declines) is high. In contrast, because of the high electrolyser load factor, the electrolyser capex's share in the LCOH is low because there are more units of hydrogen to average your costs over
2. The optimum ratio for co-located electrolyser with solar in Great Britain in 2030 is approximately a 0.3:1 (i.e. 30MW electrolyser to 100MW solar). This ratio represents the optimum trader off between solar generation spilled and a higher electrolyser load factor
3. When the electrolyser size to RES size ratio is high, the electrolyser load factor is also low but no solar production is curtailed. The LCOE is therefore low and the cost of power to the electrolyser is low. However, because of the low load factor, there are fewer units of hydrogen production to levelise the capex costs over, resulting in a large contribution to the LCOH from the capex

1) LCOH figures are available to subscribers of our European Hydrogen Service

Source: Aurora Energy Research

With optimally sized electrolysers, onshore wind energy gives the lowest LCOH at ~4 EUR/kg H_2 in 2030

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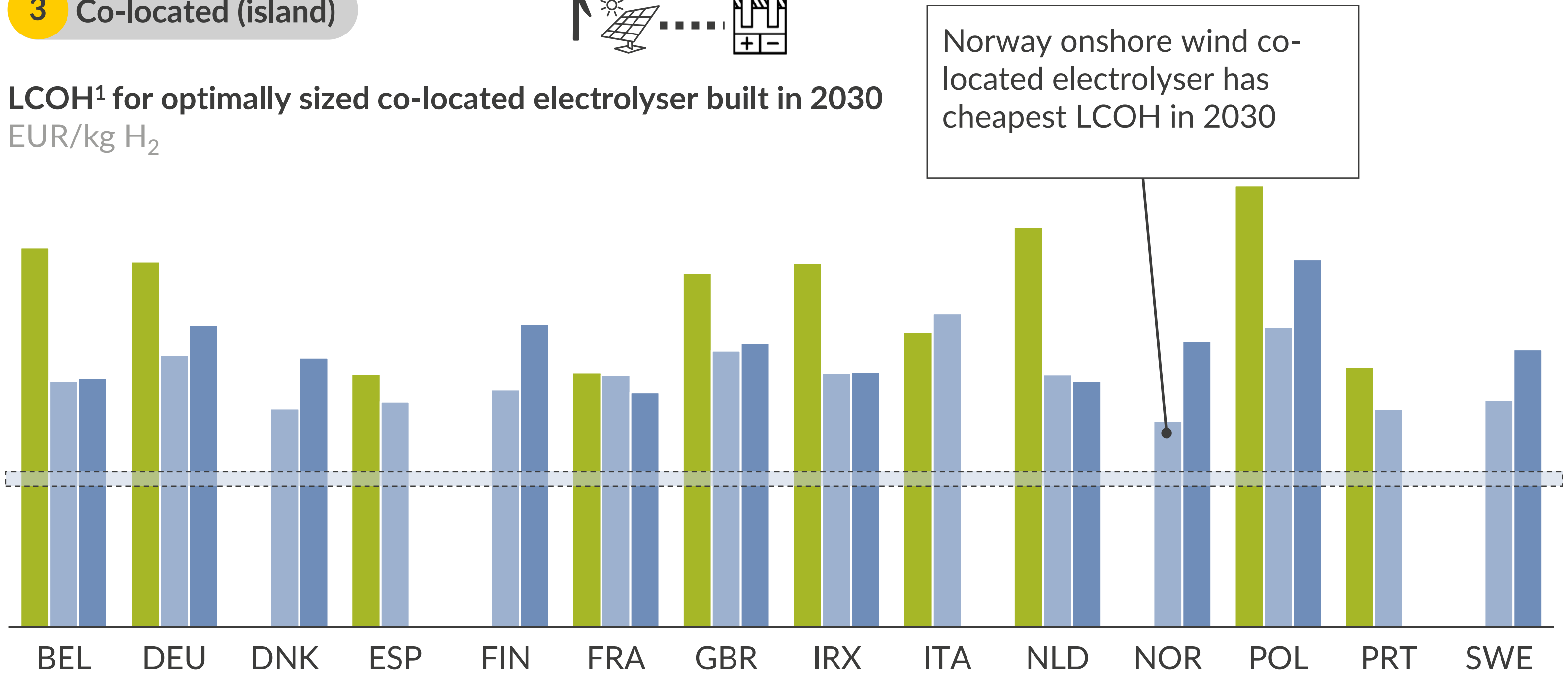
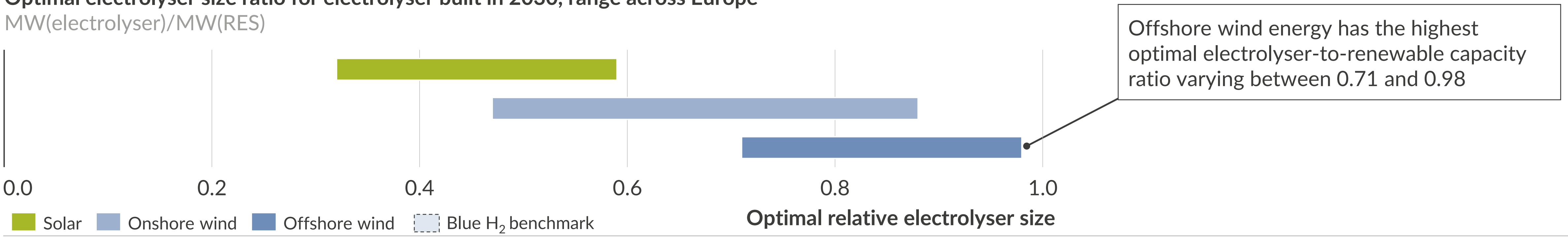
3 Co-located (island)

LCOH[1] for optimally sized co-located electrolyser built in 2030
EUR/kg H_2



Optimal electrolyser size ratio for electrolyser built in 2030, range across Europe
MW(electrolyser)/MW(RES)



Across Europe, onshore wind consistently gives the lowest LCOH, followed by offshore wind then solar

- Electrolysers co-located with onshore wind have the lowest LCOH for all regions except France and the Netherlands where offshore wind is marginally cheaper
- Electrolysers co-located with solar can compete with wind-based schemes in sunnier parts of Europe such as Spain, Portugal and France. In more northerly locations, the lower average load factor and greater seasonality result in more RES curtailment and lower electrolyser load factors, both increasing LCOH

1) LCOH figures are available to subscribers of our European Hydrogen Service

Source: Aurora Energy Research

Hydrogen produced by a 'right' sized electrolyser co-located with renewables is always cheaper than grid-connected electrolysers

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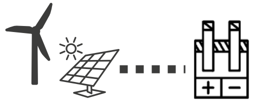
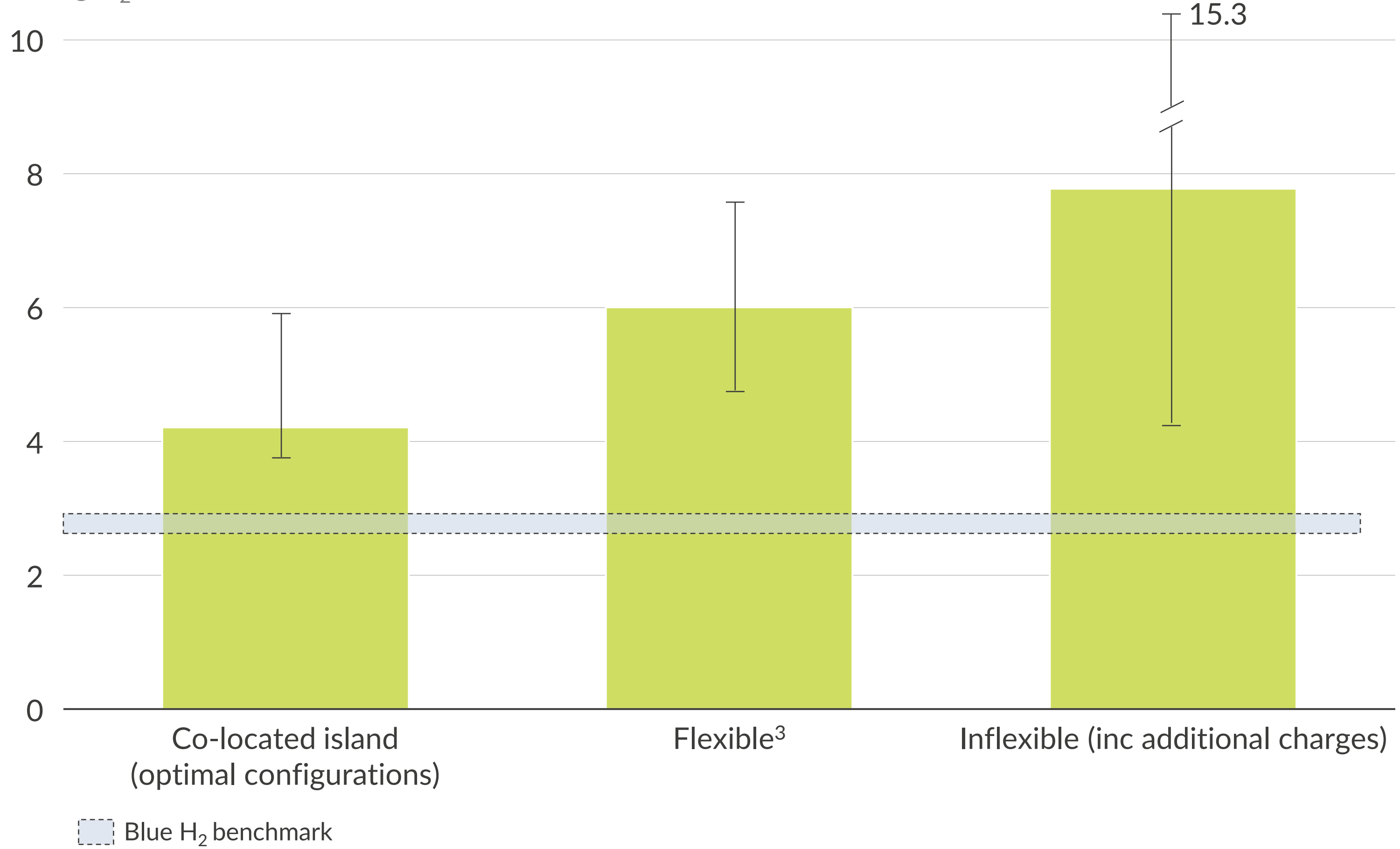
3 Co-located (island)



LCOH for optimally sized co-located electrolyser vs inflexible and flexible built in 2030, European average

EUR/kg H_2



Additional charges for grid electricity increase the levelised cost of hydrogen

- The average LCOH for co-located represents the average of the lowest LCOH in each region
- Co-located electrolysers have lower LCOH compared to the flexibly operating electrolysers when comparing between the same regions; however, the highest LCOH from co-located is higher than lowest LCOH from flexible or inflexible business model
- Inflexible operation can produce cheaper hydrogen if there were some compensation schemes on the additional charges

If governments apply compensations or exemptions for grid-connected electrolyser, costs would fall. However, it is important to keep in mind that grid connected electrolysers might have a considerable amount of carbon emissions, whereas hydrogen production via renewable co-location does not involve any direct emissions.

1) According to EEG 2021, electrolysers commissioned after 2030 have to pay the EEG surcharge. It is unclear if the exemption will end, or be reduced. 2) Minimim LCOH components of the inflexible electrolyser include electrolyser capex, opex and power price 3) Flexible business model only modelled for 3 regions: GBR, DEU and ESP

Source: Aurora Energy Research

Agenda

	Agenda	Research questions – model specific	Research Questions – General
	Hydrogen Production Introduction	What is Aurora's approach to comparing hydrogen production cost? What is the cost of producing blue hydrogen?	What is Aurora's approach to assessing carbon intensity of hydrogen?
Electrolyser Business Models	**Inflexible** *Electrolyser is grid-connected and operates constantly*	What is the minimum possible LCOH achievable in this scenario?	Can electrolyser produced hydrogen compete with blue hydrogen? - If so, when? What are the key sensitivities for each model? What are the carbon intensities of each model? - Does this meet the EU's taxonomy requirements?
Electrolyser Business Models	**Flexible** *Electrolyser is grid-connected and operates according to power price signals*	What is the optimal load factor for each country/year?	
Electrolyser Business Models	**Co-located (island)** *Electrolyser is connected only to a renewable generator and takes electricity directly*	What is the optimal ratio of electrolyser size to renewable generator?	
Electrolyser Business Models	**Co-located (grid)** *Electrolyser is connected to both a renewable generator and the grid, and can operate based on price signals from both*	What is the optimal ratio of electrolyser size to renewable generator? Does adding a grid connection make economic sense?	

Source: Aurora Energy Research

Adding a grid connection to a co-located electrolyser allows it to increase its load factor during times of low RES output

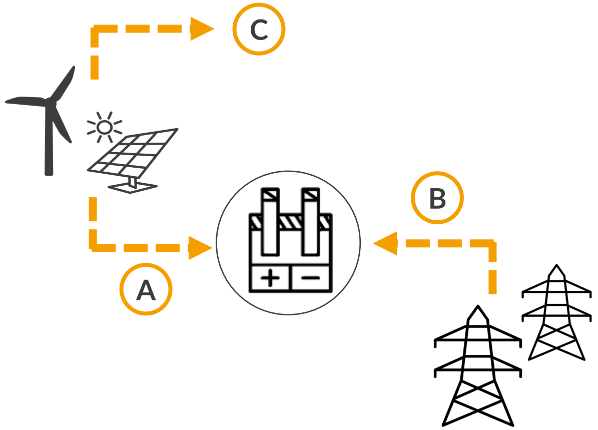
4 Co-located (grid)

- This section explores a fourth electrolyser business model: co-location with renewables and a grid connection. For this business model, the only grid connection is for the electrolyser (and not the RES asset)
- This business model complements a purely co-located electrolyser, allowing for greater flexibility in hydrogen production, however there are additional complexities to consider, such as grid charges and carbon intensity of imported grid electricity
- According to Aurora's global electrolyser database, most electrolyser projects state the source of power as being wind, solar or grid, but not a combination of RES and grid. It is unclear how popular this business model will be

Schematic of co-located electrolyser with grid connection to electrolyser

Key:

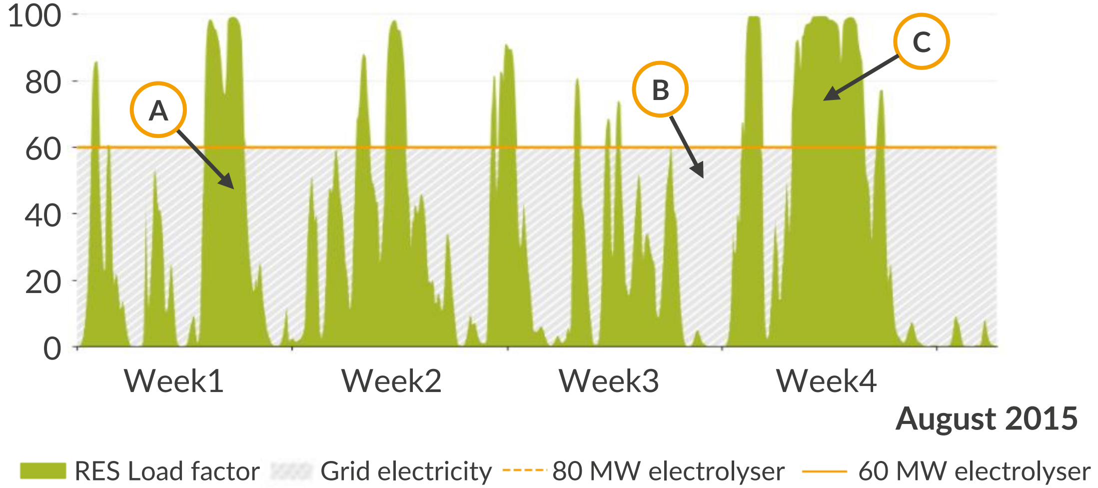
- (A) Electrolyser imports power from RES
- (B) Electrolyser imports power from grid
- (C) RES spills power



The grid connection allows the electrolyser to purchase grid electricity

- With a grid connection, the electrolyser can choose to purchase grid electricity to top up its production when the renewables asset is not generating enough to 'fill up' the electrolyser
- However, any power purchased from the grid will have associated grid charges, which vary by capacity, time of use and region, as well as an associated carbon intensity

Example electricity generation profile for a wind park
MW



Source: Aurora Energy Research

Our modelling examines how an electrolyser behaves when it can take power from RES and the grid; we look at GB, DE and ES

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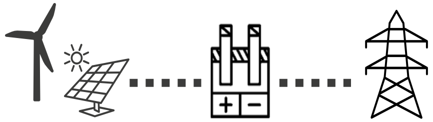
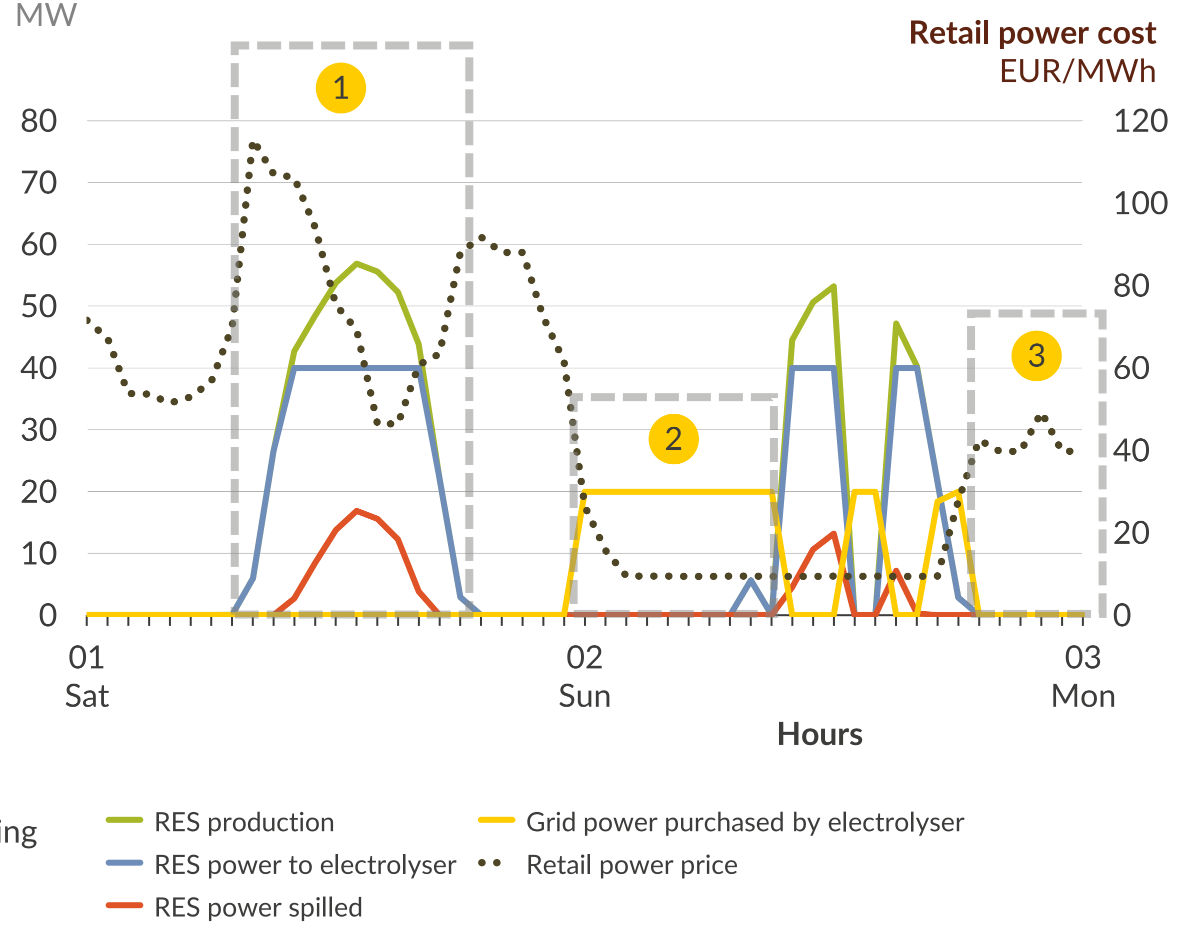
4 Co-located (grid)



- In order to capture the behaviour of different renewable technologies, we model three different combinations of location and RES technology: offshore wind in Great Britain; onshore wind in Germany; and solar in Spain
- In each case, we model an optimal renewable location, and include all relevant non-wholesale power components (grid charges, taxes, supplier margin etc.)
- For each country, we fix the RES capacity at 100 MW and vary the electrolyser capacity between 0-100 MW. At the same time, we vary the grid connection capacity between 0-100 MW
- We model the this three-way system using a bespoke electrolyser dispatch model which interacts with Aurora's power market model
- In the model, the electrolyser decides when to produce hydrogen, how much hydrogen to produce, and whether to take power from the RES or from the grid. It makes these decisions based on the interplay of the power price (plus any additional costs, e.g. grid charges), the marginal cost of hydrogen production and any potential revenue from hydrogen production

1. RES is generating, hydrogen is being produced, some RES power is spilled
2. Electrolyser imports grid electricity when power is cheap and RES is not generating
3. No power imported when price is high

Example operation for 100 MW solar with 40 MW electrolyser and 20 MW grid connection



Source: Aurora Energy Research

Adding a grid connection to a RES + electrolyser model can offers a slight reduction in LCOH compared to island mode

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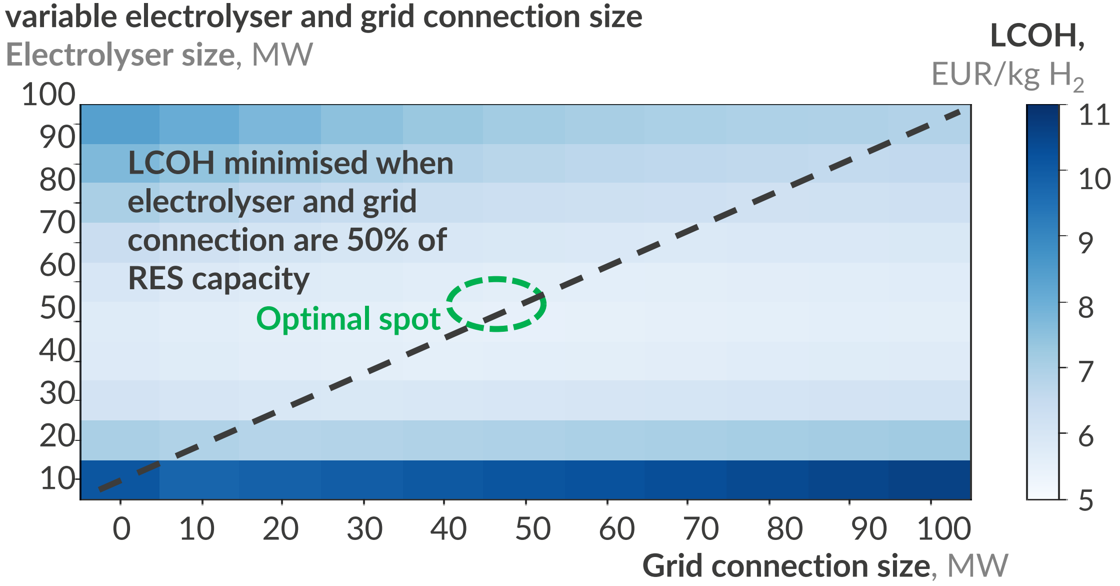
Adding a grid connection marginally reduces the LCOH for solar co-located electrolyser with grid connection in Spain

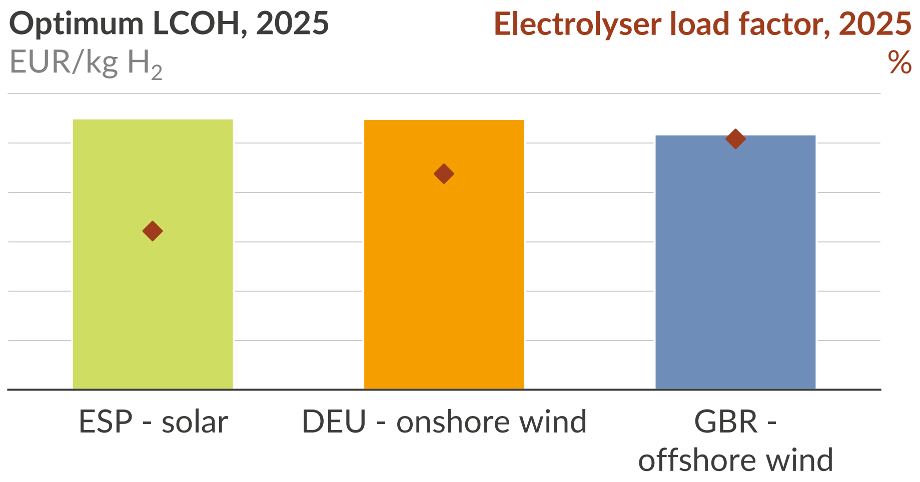
- Adding a grid connection enables the electrolyser to produce hydrogen using grid electricity when the renewable asset is not generating. However, it will only do so if the retail power price is cheap
- Adding a grid connection also adds additional capex to project which scales with the grid connection size
- These counterbalancing factors result in the LCOH being reduced as the grid connection is increased only for solar in Spain, and not for onshore wind in Germany or offshore wind in Great Britain

Representative LCOH of solar co-located electrolyser in Spain with variable electrolyser and grid connection size



When in their optimum configuration, higher electrolyser load factors are correlated with lower LCOH values

- In the optimum configuration for the three co-located grid connected arrangements we modelled, GBR-offshore wind resulted in the highest electrlyser load factor, follwed by DEU-onshore wind, then ESP-solar
- A higher electrolyser load factor resulted in the RES asset and electrolyser capex being levelised over more units of hydrogen, leading to a lower overall LCOH
- The GB and DEU case both had zero direct emissions as they did not choose to take power from the grid. The ESP-solar case had very low CO_2 emissions because it only imported grid electricity during low price hours: a time when grid CO_2 intensity is typically at its lowest



Source: Aurora Energy Research

Takeaways

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Grid connected, inflexibly operated electrolysers typically have the highest LCOH out of all the business models tested because of capturing high average power prices and high non-wholesale costs, such as grid connections and environmental levies. Hydrogen cost could be halved if electrolysers were exempted from these additional charges. The cheapest region is Norway where both the average power price and the non-wholesale costs are low. This business model also has the highest CO_2 intensity, reaching up to 15 tCO_2/tH_2 in Poland and Germany.

Grid connected, flexibly operated electrolysers achieve a ~50% reduction in LCOH (vs. inflexible), since high power price periods are avoided. In some countries flexible electrolysers decrease the carbon intensity by 90% vs. inflexible operation because the avoided high power price periods are also the most carbon intensive.

Co-located electrolysers without grid connection (island) become cost competitive with blue hydrogen in late 2030s. If electrolysers become cheaper and more efficient and RES assets attain lower LCOEs, this could be substantial brought forward to roughly year 2030. Hydrogen produced in an island mode co-location is cheaper than grid connected electrolysers after 2025, and would have zero direct emissions

Co-located electrolysers with RES and grid connection can purchase grid electricity to top-up their load factors when there is no RES production and power prices are low. In Spain, a solar co-located electrolyser can reduce its LCOH by adding a grid connection and taking advantage of low power price periods caused by wind power. However, electrolysers co-located with wind energy in Great Britain and Germany do not see a reduction in their LCOH by adding a grid connection due to the additional cost of the grid connection and few low power price hours to take advantage of when the wind asset is not generating.

Source: Aurora Energy Research

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