Aurora keynote:

Scaling up the hydrogen economy - Opportunities for renewables

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Hydrogen will play a key role in decarbonising industry: by 2050, we expect industry demand for hydrogen of 125-307 TWh

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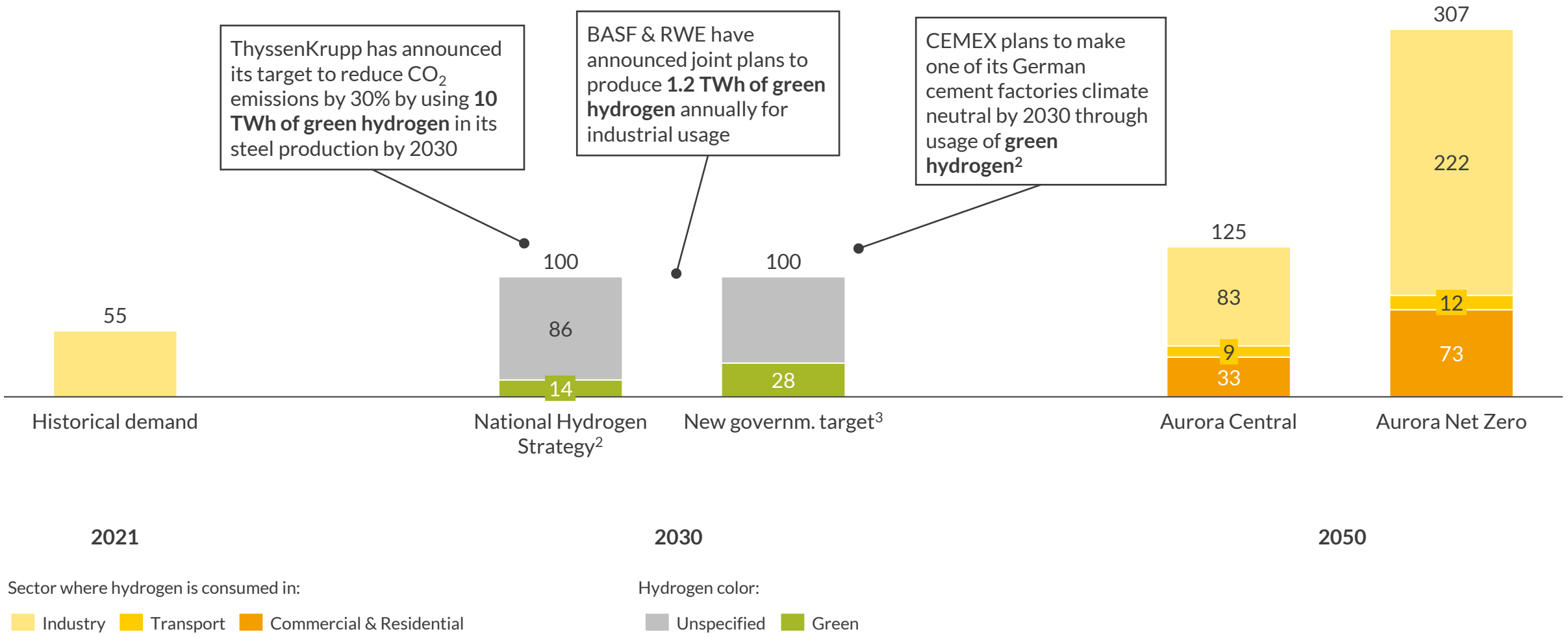
Final energy hydrogen demand[1]
TWh



1) H2 demand from the power sector does not fall in this category. 2) As of June 2020. 3) Economic minister announced electrolyser targets of 10 GW for 2030 on January 11, 2022. To calculate green hydrogen production from 10 GW electrolysers, we assume here the same full load hours as mentioned in the national hydrogen strategy.
Sources: BMWi, BMWK, Thyssenkrupp, BASF, CEMEX, Aurora Energy Research

Announced electrolyser projects of 21 GW for 2030 would be enough to reach targets but few projects have been realised yet

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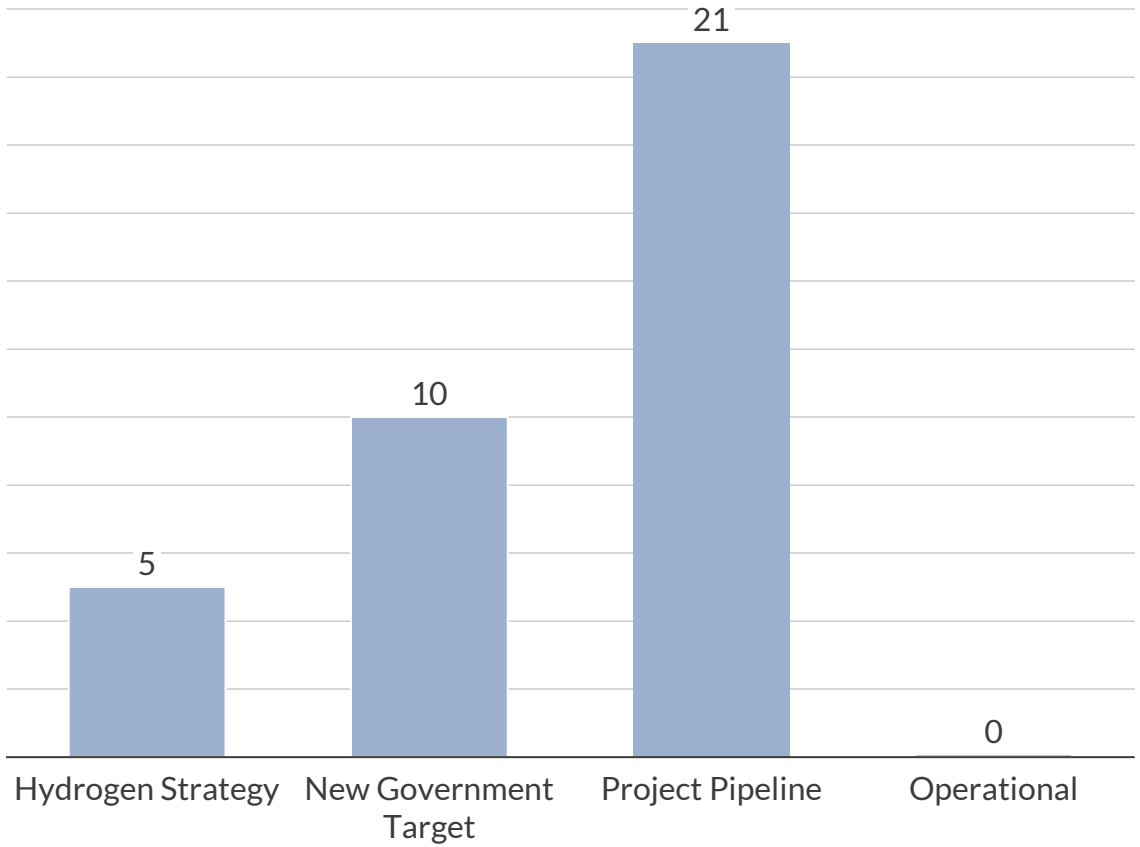
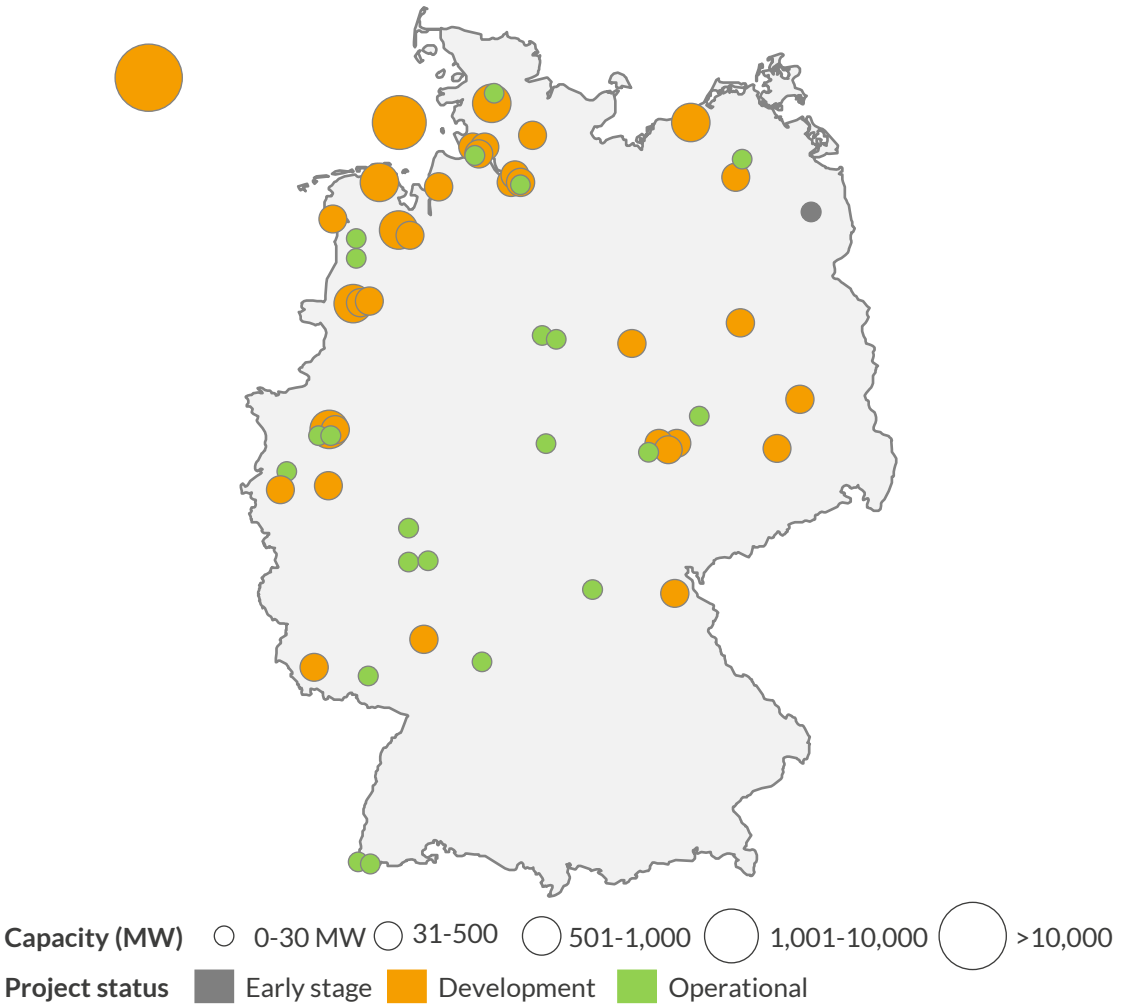
Announced electrolyser capacity in Germany by 2030
GW



Locations of electrolyser projects in Germany (all commissioning years)



1) Depending on electrolyser full load hours and availability of green power.

Source: Aurora Energy Research

For grid-based electrolysis with PPAs, RED II Delegated Act requires monthly correlation until 2026; hourly correlation starting in 2027

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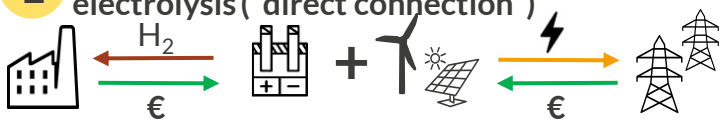
Renewable hydrogen production[1]

1 Physical Co-location of renewables and electrolysis ("direct connection")



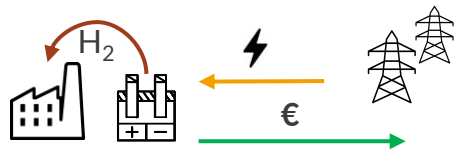
- Generation from RES asset is considered renewable under the requirements (Art. 3 DA):
- **New RES asset**: The RES asset must come into operation after, or at the same time as, the electrolyser producing hydrogen.
  - RES asset comes into operation max. 36 months before or after electrolyser
  - Repowered RES assets can be used[2]
- **No grid consumption**: The asset must not be connected to the grid or it must provide evidence that no electricity is taken from the grid to produce hydrogen.
  - Smart meter is necessary for grid-connection

Focus of today

2 Grid-based electrolysis with greening via PPA

- Electricity consumed from grid with one ore more PPAs satisfy requirements if (Art. 4 (2) DA):
- **Additionality:** Green H_2 production has to add to the overall renewable capacity by adding capacity
  - RES asset comes into operation max. 36 months before or after electrolyser[3], it has not received subsidies before repowering; Subsequent PPAs allowed[4]
- **Geographic correlation:** The RES asset and the electrolyser should be geographically correlated.
  - RES asset and electrolyser should be within same bidding zone or neighbouring ones
- **Temporal correlation:** RES generation and electrolyser electricity consumption need to coincide timely.
  - Hourly correlation or used of battery storage is required (monthly correlation until 2027)

Grid-based electrolysis with average grid power



- Electricity from grid is considered renewable under the following requirements (Art. 4 (1) DA):
- **RES share:** Grid-electricity mix must be low carbon
  - Electrolyser is located in a bidding zone where average RES share in electricity mix exceeds 90% & capacity factor of electrolyser (fully load hours divided by 8760) is not higher than bidding zone's RES share

New specification under Delegated Act

- *Directly applicable once Act is adopted*
- *Only applicable starting in 2027*

1) RED II differentiates between co-location (art. 27 (3) RED II) and grid-based electrolysis (recital 90 RED II). 2) If investments exceeding 30% of the investment that would be needed to build new installation. 3) If electrolyser capacity is added to a project site within 36 months, it's commissioning date is considered to be the original installation's one. 4) If the PPA of a formerly "new" RES asset ends, a new PPA can be established with this asset, satisfying the requirements of additionality.

Sources: European Commission, Ref. Ares(2022)3836651 - 20/05/2022 and Directive (EU) 2018/2001, Aurora Energy Research

1 For fully merchant assets, average LCOH between 5 and 6 EUR/kg H_2 can be reached in 2025; In the long run, we expect 3 EUR/kg H_2

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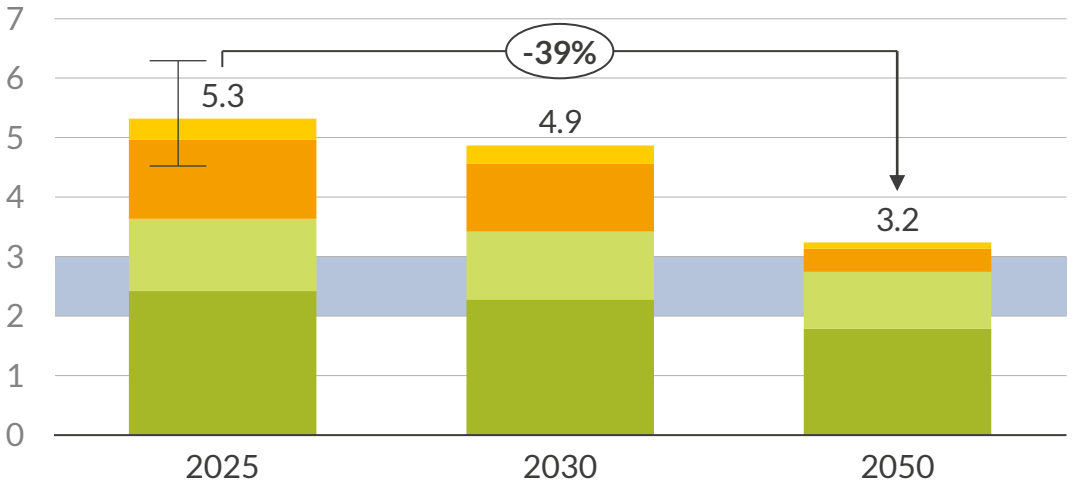
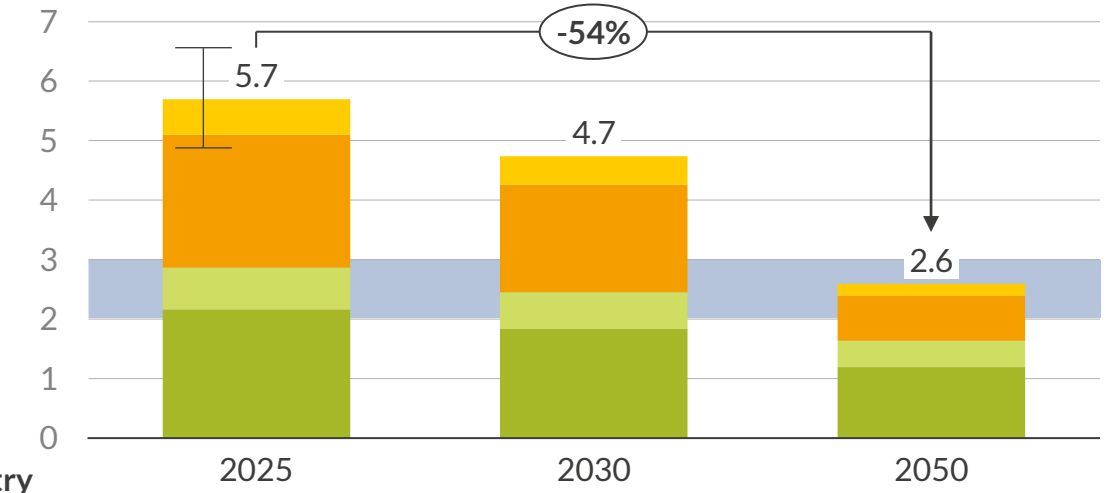
LCOH breakdown for onshore wind and electrolysers
EUR/kg H_2

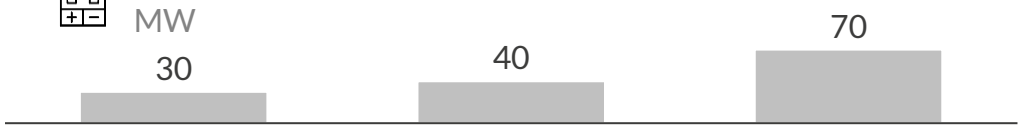


LCOH breakdown for solar PV and electrolysers
EUR/kg H_2

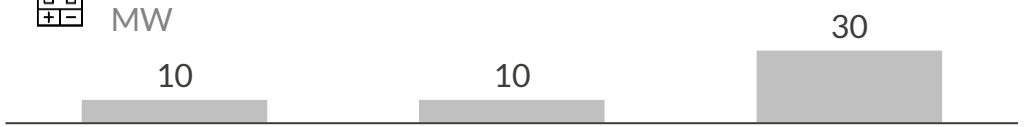


Year of entry

Optimal electrolyser size for 100 MW onshore wind
MW



Optimal electrolyser size for 100 MW solar PV
MW



RES CAPEX | RES OPEX | Electrolyser CAPEX | Electrolyser OPEX | Electrolyser size | Blue H_2 benchmark

- Strong declines in electrolyser CAPEX lead to larger electrolysers and more H_2 production at declining LCOH
- Solar PV CAPEX decline faster than onshore wind CAPEX causing LCOH to decrease even quicker, below 3 EUR/kg H_2 in 2050

Source: Aurora Energy Research

1 High green H_2 prices in Germany can be expected before large import volumes from pipelines are available and drive down prices

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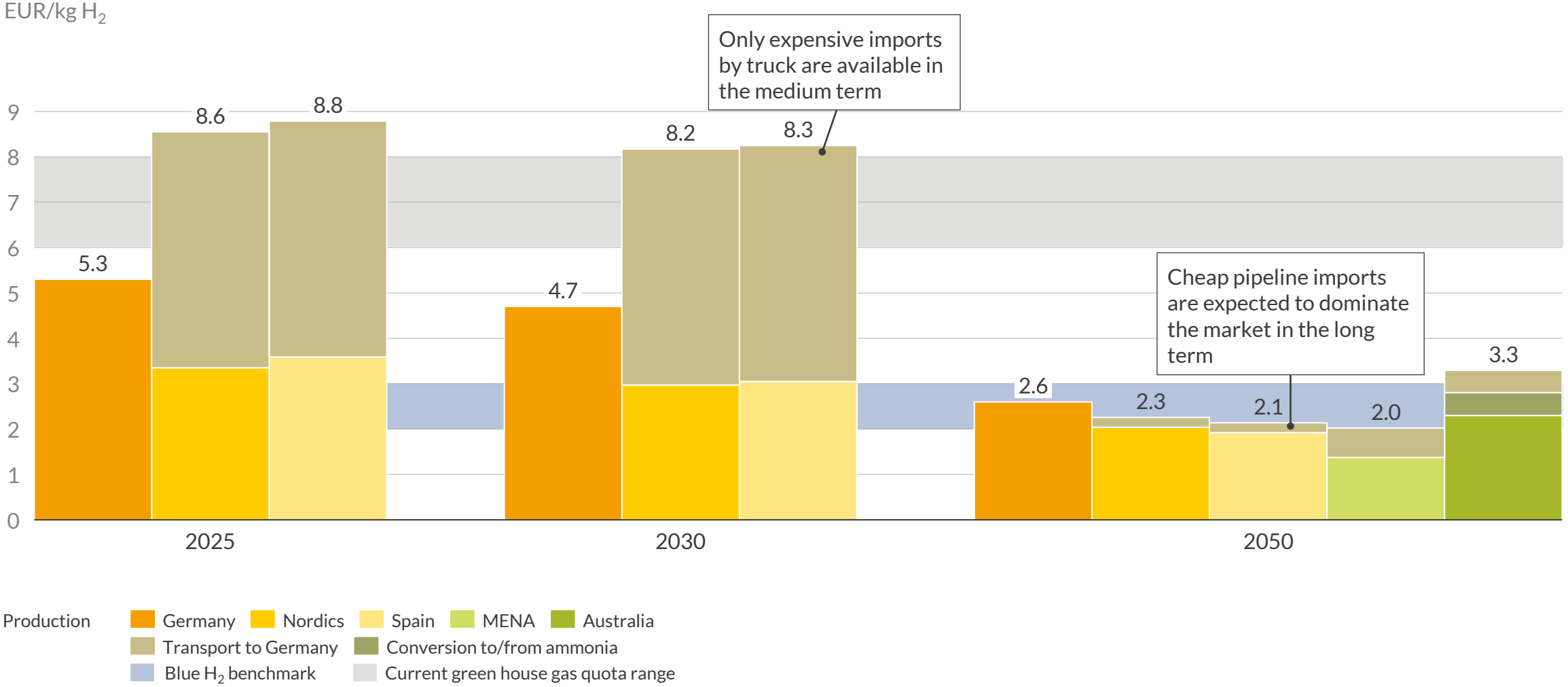
LCOH for optimally sized co-located electrolyser & transport cost to Germany
EUR/kg H_2



Source: Aurora Energy Research, BMWK, BMUV

1 For onshore wind, co-location with H_2 is more profitable than stand-alone merchant RES at hydrogen off-taker price of 5 EUR/kg

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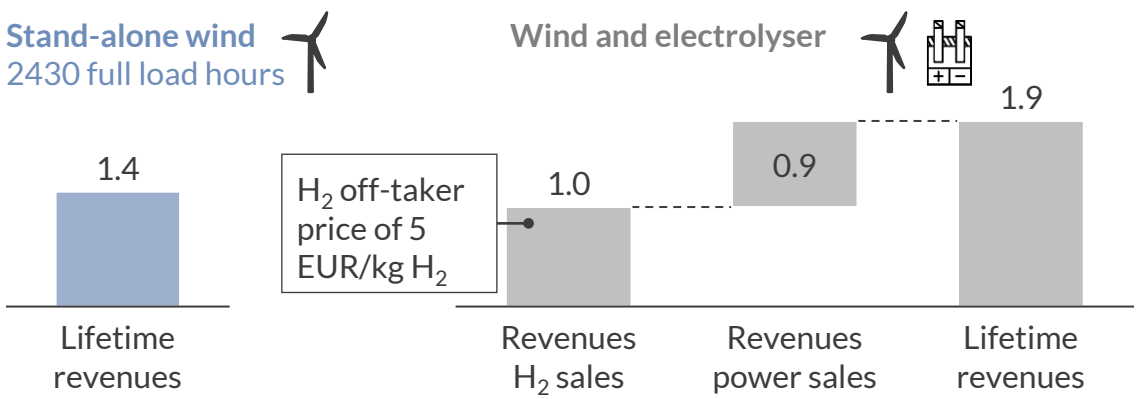
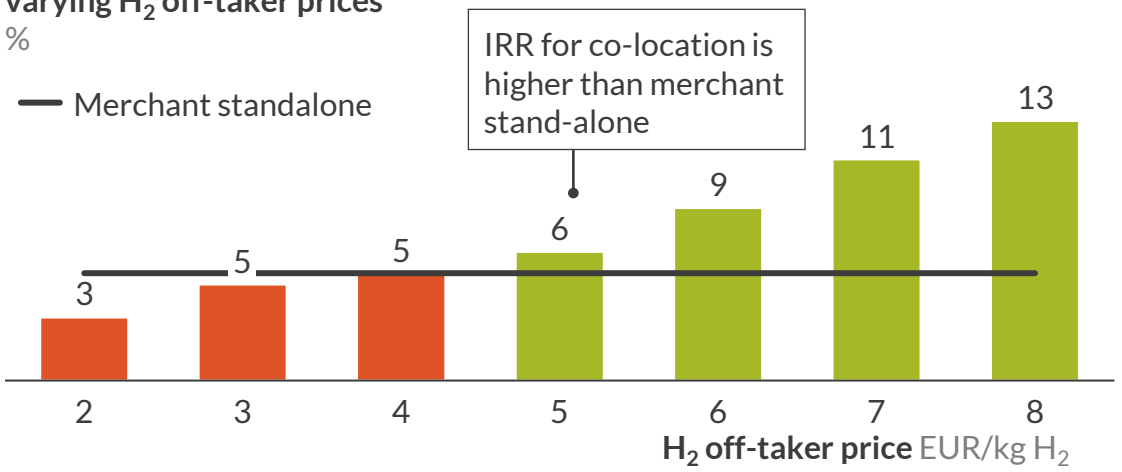
Lifetime revenues of co-located onshore wind and electrolyser and stand-alone wind asset commissioned in 2025[1]

mEUR/$MW_{onshore}$



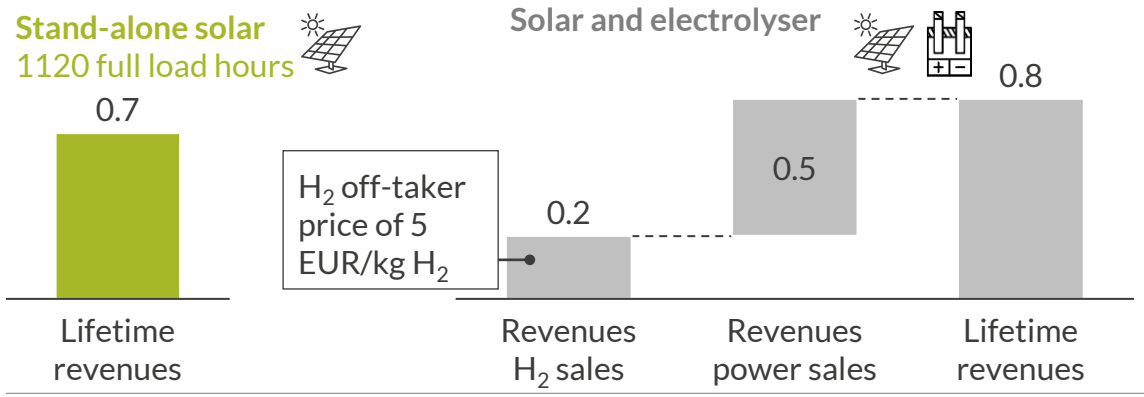
IRR of onshore wind with co-located electrolyser commissioned in 2025 at varying H_2 off-taker prices

%



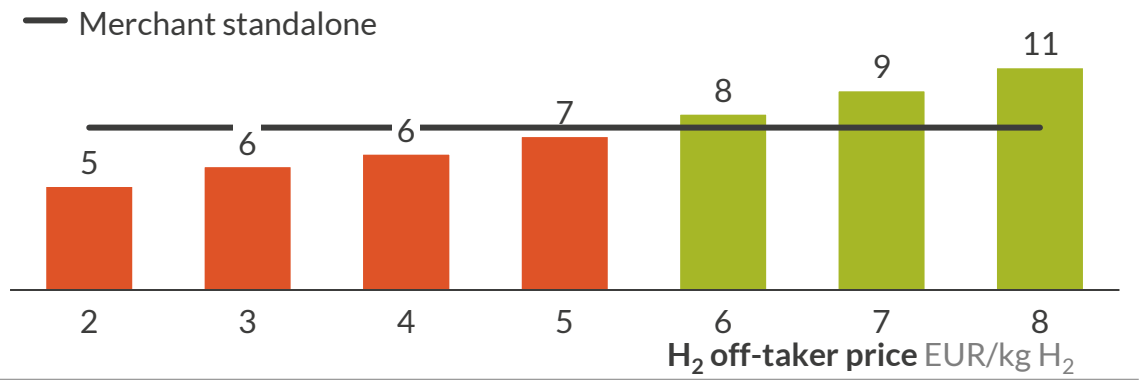
Lifetime revenues of standalone and co-located solar and electrolyser and stand-alone solar asset commissioned in 2025[2]

mEUR/MW_{solar}



IRR of solar asset with co-located electrolyser commissioned in 2025 at varying H_2 off-taker prices

%

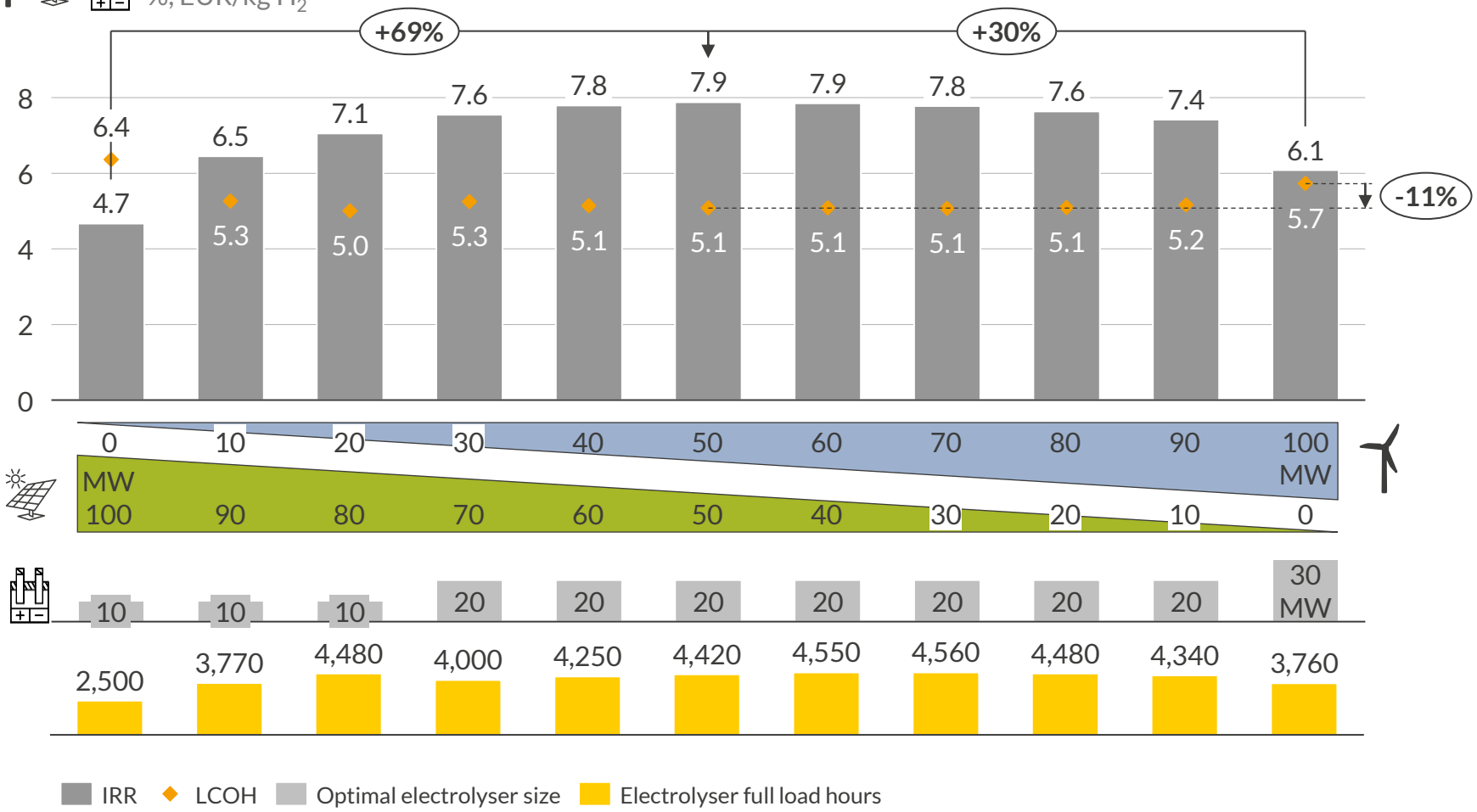


1) For electrolyser sizes of 40 MW co-located with 100 MW onshore wind 2) For electrolyser sizes of 10 MW co-located with 100 MW solar.

Source: Aurora Energy Research

1 A combination of wind and solar helps improving IRR and lowering LCOH to ~5 EUR/kg H_2

IRR and LCOH of a co-located electrolyser with a combined solar and wind asset commissioned in 2025
%, EUR/kg H_2



Combining solar PV and onshore wind at an exemplary site

- Complementary production profiles of solar PV and onshore wind help increasing utilisation of the electrolyser, thereby reducing the cost of the project
- Here, we assess combinations of a solar PV asset (970 full load hours) and onshore wind (2340 full load hours) at a site in northern Brandenburg
- The IRR of a project realised in 2025 is maximised at a 50 MW : 50 MW solar to wind ratio, combined with a 20 MW electrolyser
- The economic optimal asset sizing can reduce the LCOH to 5.0 EUR/kg H_2
- ➢ Combining RES technologies significantly improves the business case compared to co-location with a single RES technology

Source: Aurora Energy Research

2 Grid-based electrolysers save on transport cost and allow combining favourable sites, but several levies must be paid

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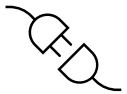
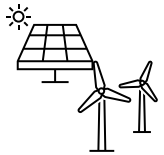
Advantages of grid-based electrolysis (industry perspective)

- No transport cost for H_2



- Easier integration with industrial processes

- Usage of electrolysis waste heat



- Combination of favourable renewable sites

Disadvantages of grid-based electrolysis (industry perspective)

- Levies must be paid[1]

- Greenness will presumably be even more difficult to prove

1) However, there is no obligation to pay network charges and no electricity tax for grid-based electrolysis, § 118 VI s. 1EnWG , § 9a I StromSG. 2) StromNEV surcharge is 4.37 EUR/MWh for first GWh consumed, afterwards it is reduced to 0.25 EUR/MWh. 3) If it is green hydrogen according to § 12i EEV there is an exception from theses surcharges.

Sources: Aurora Energy Research, EEG, KWKG, StromSG, EnWG, AbLAV

2 PPA-based hydrogen production can be 21 % cheaper than production from co-location if the fair PPA price is determined fundamentally

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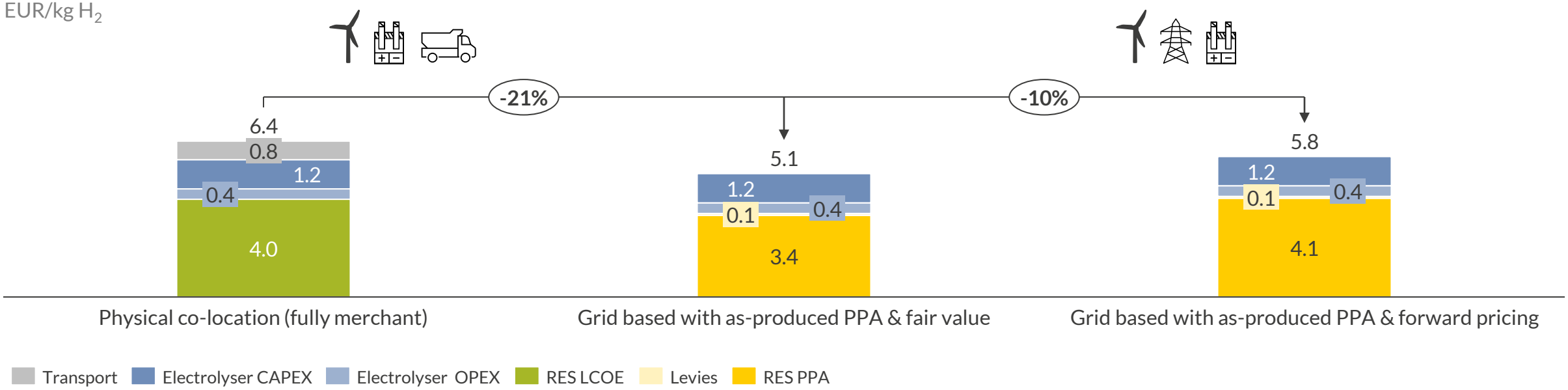
LCOE for 100 MW onshore wind in 2025
EUR/MWh

Long-term PPA price[1]
EUR/MWh

LCOH & transport costs of 100 MW onshore wind and 30 MW electrolyser in 2025[2]
EUR/kg H_2



1) As-produced volume clause is assumed; PPA fair value is fundamentally modelled based on capture price forecasts; Future-based pricing is based on extrapolating futures and historic capture price discounts, thus leading to higher PPA prices. 2) Electrolyser commissioning date and PPA start is 2025; Transport costs assuming 100 km truck transport of pressurised H_2.

Source: Aurora Energy Research

Key takeaways

1. Average green hydrogen production in Germany from co-location could achieve LCOH of ~5 EUR/kg by 2025.

2. Given current policies in place (GHG quota, CCfDs), German willingness to pay green hydrogen prices above 5 EUR/kg seems likely in the next 10 years. Starting in the 2030s, cost decline and green hydrogen imports (e.g. from MENA region) could gradually push down green hydrogen prices once transport infrastructure is in place (e.g. ports, pipelines).

3. At hydrogen prices above 5 EUR/kg, adding an electrolyser to an onshore wind farm can increase overall project IRR, making it more attractive than fully merchant stand-alone RES. For solar, the benefit is smaller.

4. To maximise project IRR of co-located RES and electrolyser and push down LCOH, a combination of wind and solar and oversized RES asset relative to electrolyser capacity is optimal.

5. PPA-based green hydrogen production allows to save on hydrogen transport cost, make use of favourable RES sites and potentially reduce hydrogen storage cost. With an as-produced PPA, LCOH of ~5 EUR/kg by 2025 can be achieved. Given the savings in transport cost, grid-based H_2 production is currently cheaper for industrials.

Source: Aurora Energy Research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