The role of green hydrogen in the I-SEM

This is a redacted report. To access the full report, please contact

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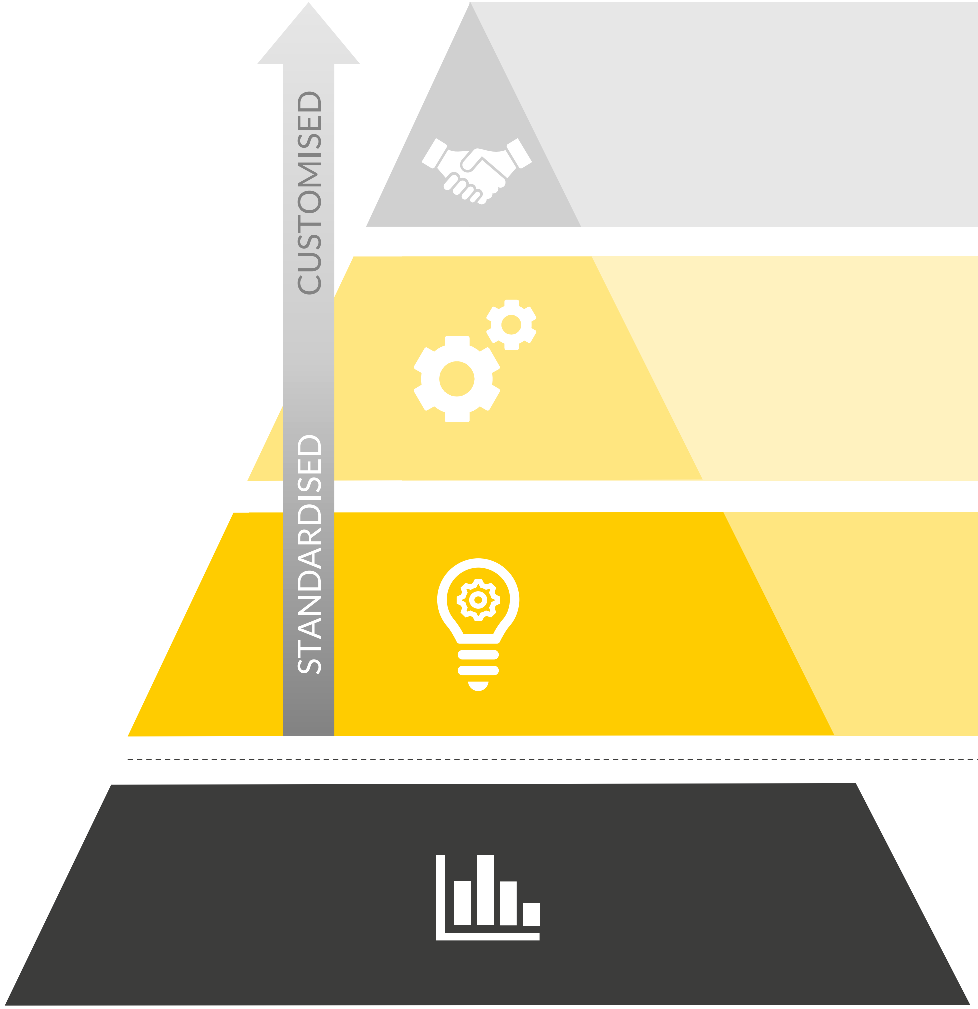

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Source: Aurora Energy Research

Aurora provides market leading forecasts & data-driven intelligence for the global energy transition

Power markets

Renewables

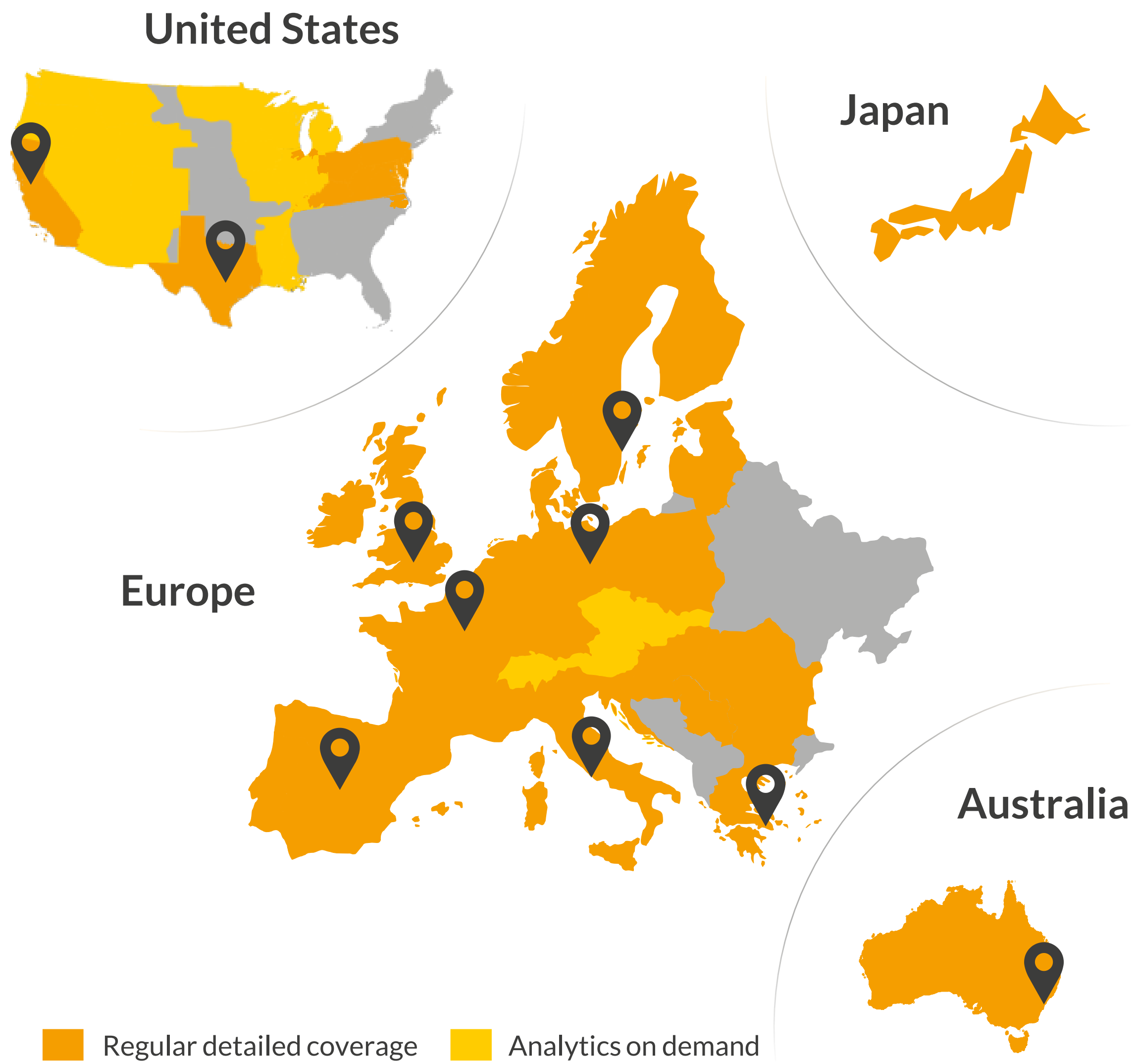
Storage

Electric vehicles

Hydrogen H_2

Carbon CO_2

Natural gas



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transactions supported in 2021

Source: Aurora Energy Research

Meet the Irish Research Team

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Analyst, UK and Ireland

Aurora's bespoke offerings

For more information on scenario analysis, site-specific asset economics including comparison of revenue models, bespoke forecasting, competitor analysis and auction bidding support, please contact our commissioned projects team or Ireland Senior Commercial Associate, Cara Valentine (details below).

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Hydrogen can play a key role in energy systems due to the versatility of its applications

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The role of hydrogen in energy systems

- Hydrogen can be burnt using a similar process to natural gas, or converted to electricity using hydrogen fuel cells, making it a highly versatile commodity for storing, transporting and consuming low-carbon energy.
- Outside the power sector, hydrogen has significant potential to be used in hard-to-abate sectors (e.g. steel, cement, plastic and heavy transport) where electrification may not be technically or economically feasible.
- Within the power sector, hydrogen can provide a reliable source of long-term energy storage, which is critical for maintaining security of supply in a predominantly wind and solar based power system.

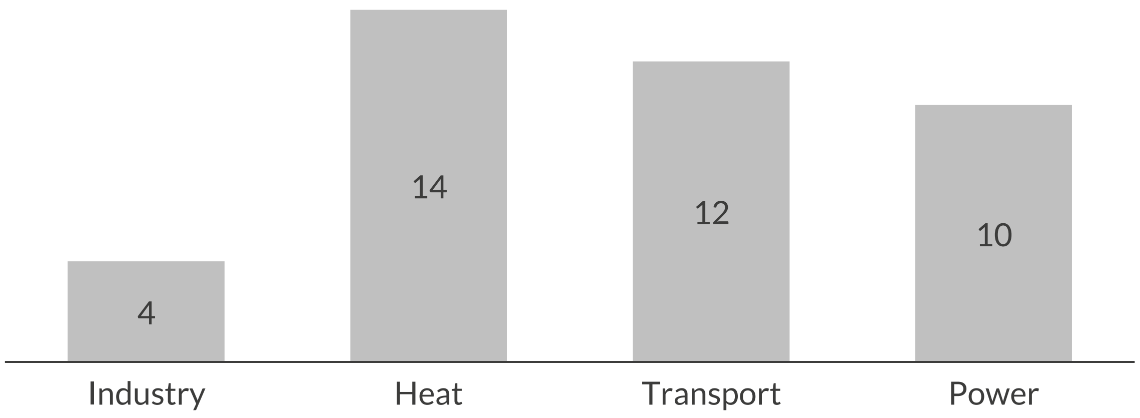
Industry	Transport	Heat	Power
Fertiliser	H_2 vehicle	High-temp.[3]	CCGTs
Metal refining	Synthetic fuels	H_2 boilers	Peakers
Other end use	Upgrading fuels	Hybrid heat	Storage

Near-term → Long-term

Core challenges for a developed hydrogen economy

1. **Carbon intensity:** hydrogen must be produced through low-carbon methods to enable decarbonisation
2. **Commercial readiness:** hydrogen-ready technologies are still nascent and the economics of commercial-scale rollout are still unclear
3. **Efficiency:** low efficiencies are typical of production processes[1] and of consumption[2]
4. **Infrastructure:** a fully fledged transport and storage network is required to tap the full potential of hydrogen

All-island energy-related CO_2 emissions by sector in 2021[4]
$MtCO_2$



Some data has been redacted. 1) Due to conversion losses, losses resulting from further compression or cooling. 2) I.e. hydrogen boilers are less efficient than electric alternatives. 3) I.e. high-temperature industrial process heat. 4) Source: Sustainable Energy Authority of Ireland. Total emissions, including non-energy emissions in Ireland were 59.3 Mt in 2021. There may be some double counting of emissions in industry and heat numbers.
Source: Aurora Energy Research

Aurora expects all-island hydrogen demand to significantly increase from just 11kt of demand today

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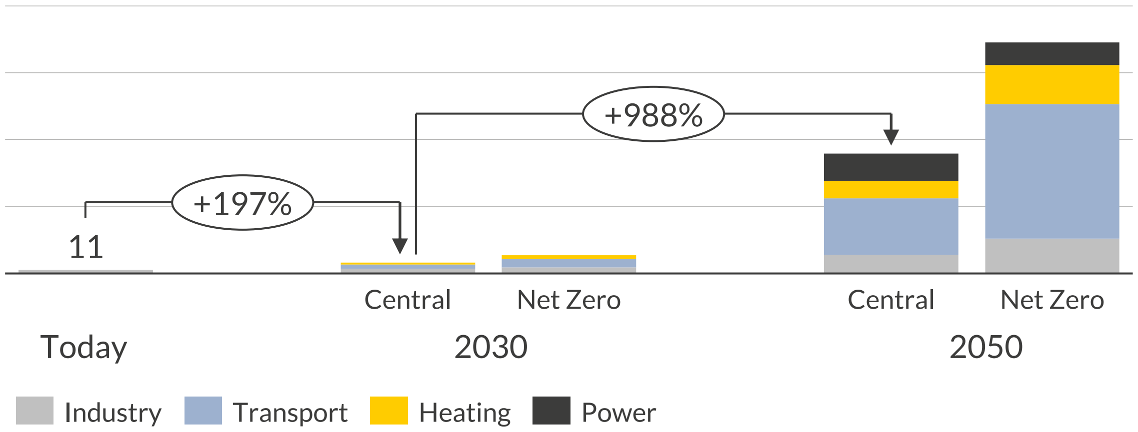
H_2 demand in Ireland by sector, including H_2 derivatives and imports[1]

kt



Hydrogen quantities in perspective

- One tonne of hydrogen equates to 39.4MWh of thermal energy at the higher heating value (HHV)[2]
- One kilo-tonne of hydrogen can be used to:
  - Heat 3100 houses for one year using hydrogen boilers
  - Fuel 240 hydrogen buses for one year
  - Produce 22.5GWh of electricity using hydrogen CCGTs[3]
  - Produce 20kt of steel (Germany consumes ~3Mt of steel per year)

Current demand for hydrogen is limited in Ireland — 2023

- The only industrial hydrogen demand source currently operational in Ireland is the Whitegate oil refinery, located near Cork. The facility consumes hydrogen for the hydrogenation of oils and the production of biofuels
- Low domestic demand has been a significant inhibitor of Irish hydrogen production capacity and infrastructure development

Hydrogen demand will likely increase in transport and industry — 2024-30

- Coaches and heavy-duty vehicles powered by hydrogen fuel cells are expected to account for ~30% of the hydrogen demand increase in Ireland to 2030[4]
- Early adopters of hydrogen in industrial processes will emerge in efforts to decarbonise

Beyond 2030, significant growth in demand will come from the aviation, power and heating sectors — 2031-50

- The aviation sector will significantly increase the use of hydrogen and its derivatives in the late timeline
- Ireland's relatively modern gas network can transport natural gas blended with up to 20% hydrogen, or pure hydrogen with some adjustments[6]. However, there is significant uncertainty around the use of hydrogen in domestic heating due to competition from heat pumps

Some data has been redacted. 1) Includes hydrogen required to produce derivatives such as ammonia or synthetic fuels. 2) HHV is defined as the amount of heat released upon combustion, taking into account the latent heat of vaporisation of water. 3) Hydrogen CCGTs can operate with an efficiency of 50-57% HHV (compared to 57% for gas CCGTs), meaning 1TWh of electricity can be produced using 45kt of H_2. 4) the Hydrogen Mobility Ireland initiative is already trialing H_2 buses in Dublin.

Source: Aurora Energy Research, FCHO

Green hydrogen production typically requires electrolysis; blue hydrogen requires gas and CCS and is expected to cost [redacted]/kg in 2030

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Hydrogen is categorised by colours based on the source and production process

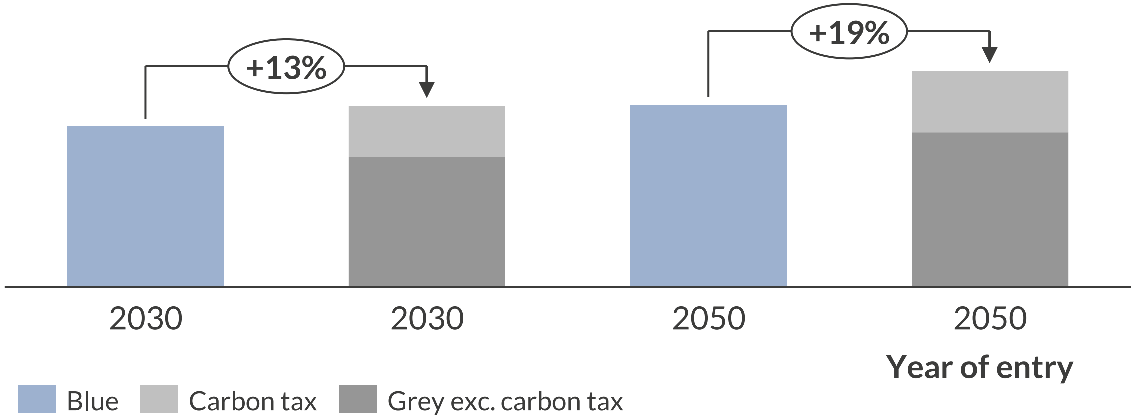
H_2 type	Green[1]	Yellow[1]	Blue	Grey
Source	RES/clean grid and water	Grid (non-zero carbon intensity) and water	Gas	Gas
Production process	Electrolysis: The use of electricity to decompose water into oxygen and hydrogen		Steam methane reforming (SMR) + carbon capture and storage	Steam methane reforming (SMR)
CO_2 intensity in 2030[2] $kgCO_2$/ kgH_2	0	[redacted]	[redacted]	[redacted]

Report focus

The production cost of blue and grey hydrogen are useful benchmarks when analysing green hydrogen prices

- Grey hydrogen is the dominant production method currently, although a high CO_2 intensity makes it unsuitable in a Net-Zero world
- Green and blue will likely compete to be the preferred clean hydrogen production method, however, blue requires both natural gas and carbon capture and storage (CCS)
- In 2030, the blue hydrogen price is expected to be more cost competitive than grey hydrogen, with the additional CCS CAPEX more than offset by the additional carbon cost
- Further increases in both carbon and gas prices will cause the cost of production of blue hydrogen to increase by 13% by 2050

LCOH of blue and grey hydrogen[3]
EUR/kg H_2 (real 2021)



Some data has been redacted. 1) The EU has now finalised its definition of renewable hydrogen. For the full set of conditions under which hydrogen can be classed as 'renewable' in the EU, please see the Delegated Act to Renewable Energy Directive II, published for on 13th February 2023. 2) Excluding processing and transport. 3) Based on Aurora Central January 2023 forecast.
Source: Aurora Energy Research

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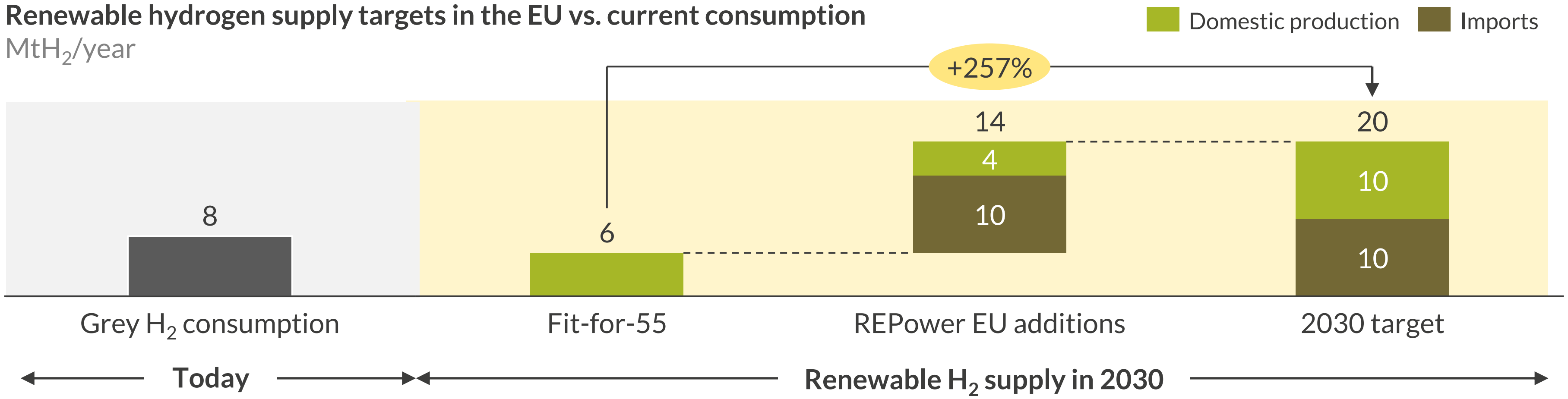
The REPowerEU more than doubles the ambition of the European Union to produce and import renewable hydrogen by 2030

Within the strategies to diversify the gas supply included in the 'REPowerEU strategy', the 'Hydrogen Accelerator' measure was published in May 2022

Renewable hydrogen supply targets in the EU vs. current consumption

MtH_2/year



- The plan is targeting a total of $20MtH_2$/year of renewable hydrogen consumption by 2030
- The new target could make all current consumption 'green' and still help to further decarbonise key industrial sectors providing an additional ~12Mt/year of renewable hydrogen
- Aurora estimates that electrolyser capacity would need to reach at least 75GW (in line with the REPowerEU target of 65-80GW) by 2030 to provide enough domestic production to supply ~10Mt of green hydrogen per year[2]

Additional measures included in the strategy relate to regulation, support for infrastructure, and the development of cross-country partnerships

- Further develop the regulatory framework to promote a European hydrogen market
- Accelerate the timelines for State aid notification approvals. The Commission will assess the first IPCEI[1] projects (IPCEI Hy2Tech awarded 41 projects from 35 companies) on hydrogen within 6 weeks
- Support the development of an integrated gas and hydrogen infrastructure, hydrogen storage and port infrastructure. Here, the Commission states that all new cross-border infrastructure should be hydrogen compatible
- Finally, the Commission will support a 'Mediterranean Green Hydrogen Partnership', conclude the 'Green Hydrogen Partnerships', and work with the industry to establish a 'Global European Hydrogen Facility'

Some data has been redacted. 1) Important Projects of Common European Interest. 2) Assumes a fleet-wide average electrolyser load factor of 63%.

Sources: Aurora Energy Research, European Commission

A number of ambitious hydrogen targets have been set, but both of the I-SEM jurisdictions lack national strategies

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Republic of Ireland

The Republic of Ireland remains one of the only EU countries without a national hydrogen strategy

- Green hydrogen production from surplus renewable electricity by 2030[1]
- Zero emission gas-fired generation from hydrogen commencing by 2030[1]
- 2GW of offshore wind capacity for green hydrogen production by 2035[1]

- Hydrogen Strategy for Ireland to be published by DECC in 2023
- Climate Action Plan pledged further measures to develop hydrogen policy
- Department of Transport to set out plans for the use of renewable fuels in transport by 2025

Northern Ireland

Northern Ireland's hydrogen policy is mainly inherited from the UK Government's Hydrogen Strategy[2], but tailored policy is lacking

- Establish a hydrogen Centre of Excellence in research and innovation by 2025[3]
- Research and development projects on hydrogen eligible for funding[3]

- Independent report commissioned by Department for the Economy recommends Northern Ireland-specific, road-mapping and local policy coordination
- However, there is no indication of a Northern Ireland-specific strategy

Joint initiatives

Cross-border cooperation will be important for the development of an all-island hydrogen economy

- The Irish Department of Transport is in co-operation with the Department for Economy in Northern Ireland over a joint hydrogen research project
- The research explores safety regulation and the interoperability of green hydrogen refueling on the island of Ireland; outputs are expected in 2023

- Joint research efforts will be extended to understanding the feasibility of green hydrogen transport refueling on a cross-border basis

Existing policy | Future policy

Some data has been redacted. 1) Source: Republic of Ireland Climate Action Plan 2023. 2) UK Hydrogen Strategy. 3) Northern Ireland Energy Strategy. 4) Hydrogen Opportunities in Northern Ireland Report.

Source: Aurora Energy Research

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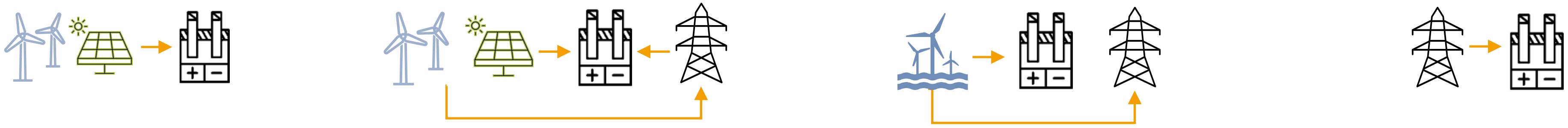
Aurora has analysed four key business models to produce hydrogen using electrolysers

Power flow



Deep dive markers for following slides

	I Co-located off-grid	II Onshore co-located grid	III Offshore co-located grid	IV Standalone
Hydrogen is 'green'	✓	✗	✓	✗
Avoids electrolyser grid charges and connection costs	✓	✗	✓	✗
Access to electricity markets	✗	✓	✓	✗
Constant H_2 production possible	✗	✓	✗	✓
Location-flexible	✗	✗	✗	✓
Modelling assumptions	▪ Electrolyser uses all the power generated by the renewables asset ▪ Entry in 2025 and 2030	▪ Distribution connected asset[1] ▪ Import costs considered include PSO levy, DUoS, TUoS, capacity and imperfections charges ▪ Entry in 2025 and 2030	▪ Offshore wind can either prioritise lowest LCOH, or maximum hydrogen production ▪ Entry in 2030	▪ Distribution connected asset[1] ▪ Import costs considered include PSO levy, DUoS, TUoS, capacity and imperfections charges ▪ Entry in 2030

Some data has been redacted. 1) Grid charges calculated based on a 10MW asset with a 38kV connection voltage.

Source: Aurora Energy Research

Connacht delivers the lowest LCOH for a co-located off grid business model due to higher average wind speeds

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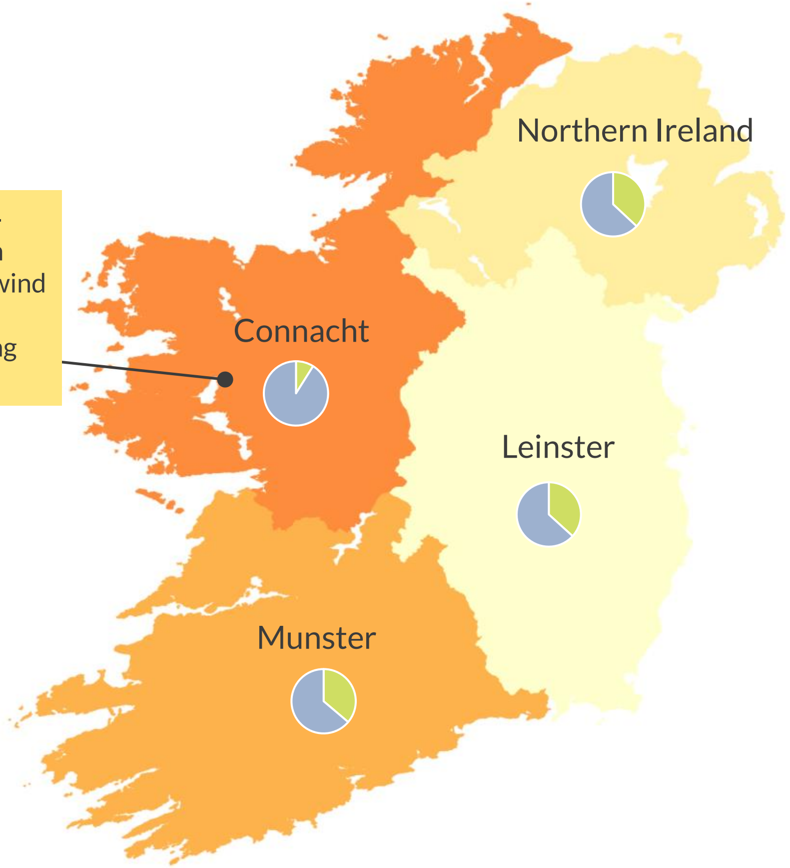
I Co-located off-grid

Optimal co-located renewables capacity shares[1]



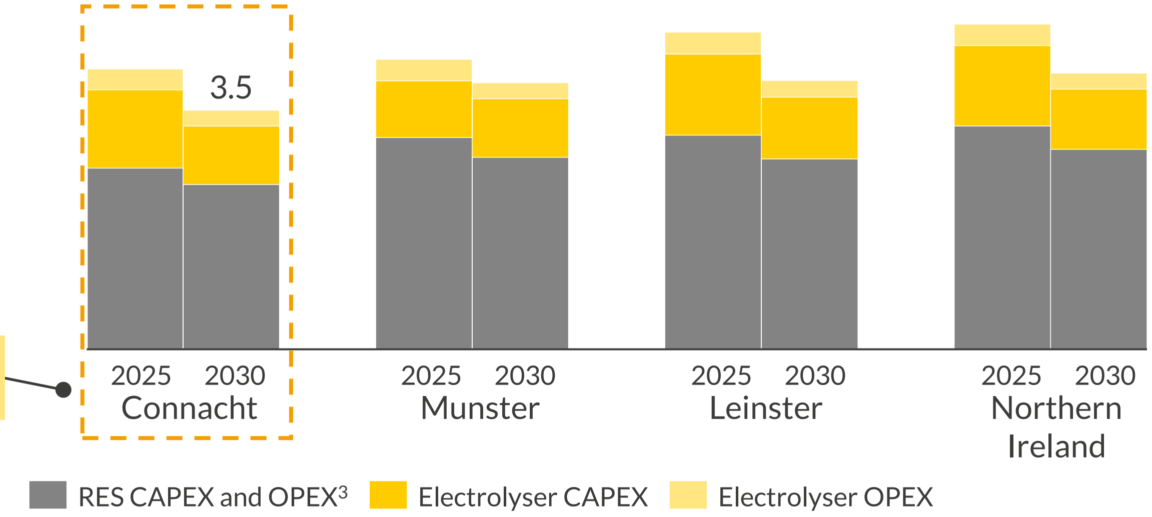
The optimal co-location ratio in Connacht is [redacted] wind to [redacted] solar PV when minimising LCOH

Onshore wind   Solar PV

LCOH of a co-located island electrolyser by location[2]

EUR/kgH_2 (real 2021)

Focus location of further analysis



Solar and onshore wind load factors at modelled locations

%

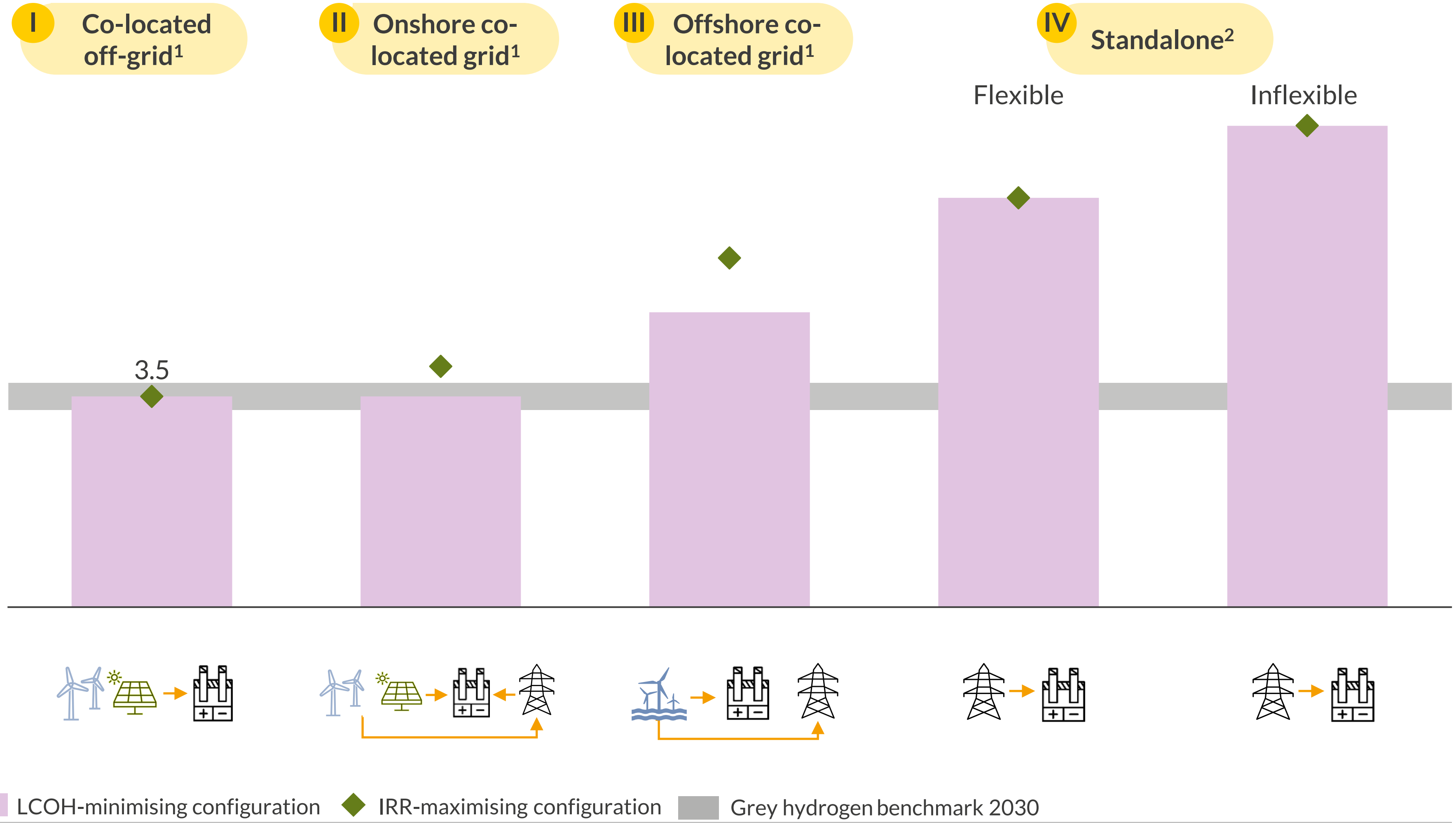
Some data has been redacted. 1) Optimising for minimum LCOH; average for 2025 and 2030. 2) 100MW electrolyser co-located with LCOH optimal onshore wind and solar PV capacities (region-specific). Assumes average turbine hub height of 91 m. 3) Renewables CAPEX and OPEX per kg of hydrogen produced.

Sources: Aurora Energy Research

The co-located off-grid electrolyser business model could produce green H_2 cost competitively with grey H_2 by 2030

Levelised cost of hydrogen production by business case, 2030 entry
EUR/kg H_2 (real 2021)

Assumed hydrogen off-taker price: €[redacted]/kgH_2



Some data has been redacted. 1) Located in the Connacht region. 2) Located in the Republic of Ireland.

Source: Aurora Energy Research

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- The co-located off-grid business model achieves the lowest LCOH, producing hydrogen cost-competitively with lower purity grey hydrogen production methods. By 2050, this business model could achieve an LCOH of €[redacted]/kgH_2
- Adding a grid connection to the co-located set-up increases the cost of hydrogen production but also increases the overall project profitability
- Using solely offshore wind to generate hydrogen further increases the LCOH, due to higher CAPEX and less optimal load factors compared with projects with both solar PV and onshore wind capacity
- Standalone electrolysers fail to compete on a LCOH basis with co-located configurations, due to the additional charges associated with importing power from the grid

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Ireland could produce some of the cheapest green hydrogen in Europe, but other countries rank higher in overall hydrogen potential

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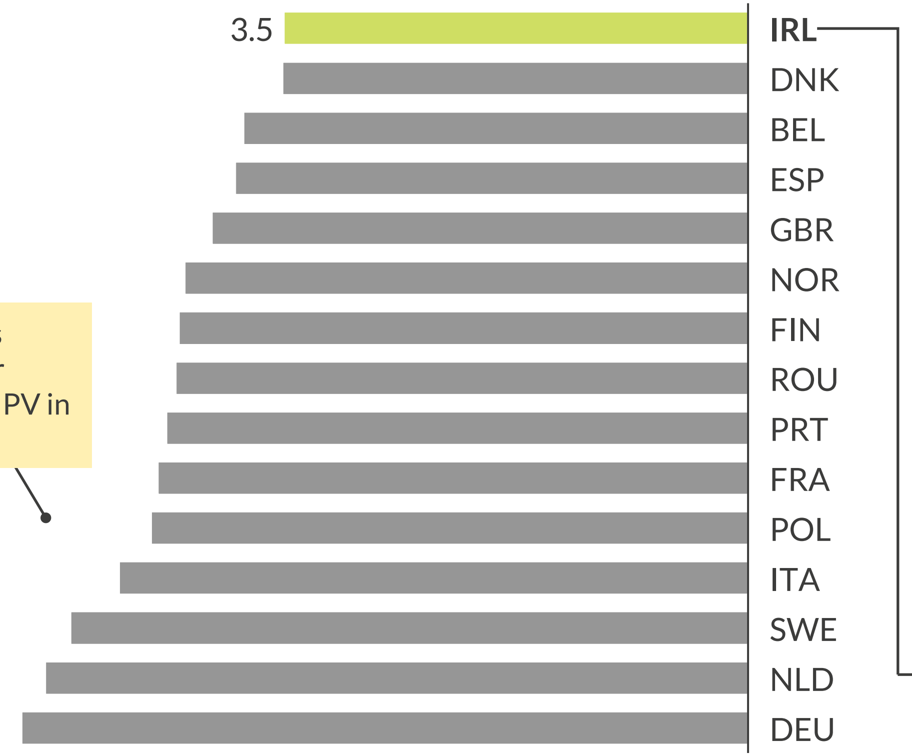
1 Ireland could have produce the cheapest hydrogen in Europe for market entry in 2030…

Off-grid island LCOH for an optimal location
EUR/kg H_2

I Co-located off-grid



Optimal renewables ratios include higher proportions of solar PV in southern Europe

2 … But Aurora's hydrogen market attractiveness (HyMAR) score for Ireland remains poor due to the lack of established policy

Country	Rank[1]
Germany	1
Netherlands	2
UK	3
Denmark	4
Norway	5
Spain	6
France	7
Portugal	8
Belgium	9
Sweden	9
Italy	11
Poland	12
Finland	13
Ireland	**14**
Romania	15

HyMAR Category	Weighting %
Supply	35
Policy and Regulation	30
Demand	25
Infrastructure	10

Some data has been redacted. 1) As of October 2022.

Source: Aurora Energy Research

A carbon price of €[redacted] per tonne of CO_2 would be necessary to make green hydrogen competitive with natural gas in 2030

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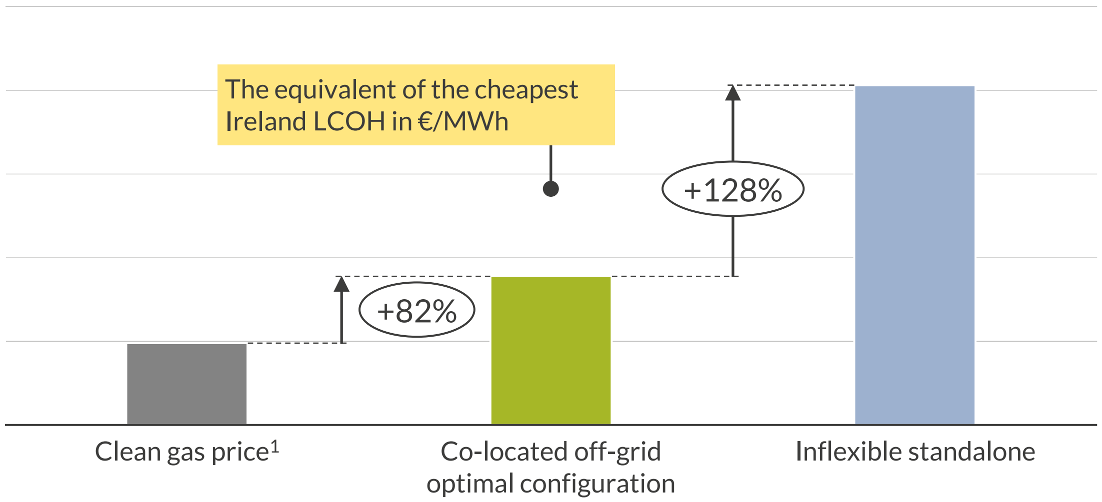
1 Without support, green hydrogen will remain uncompetitive relative to natural gas by 2030

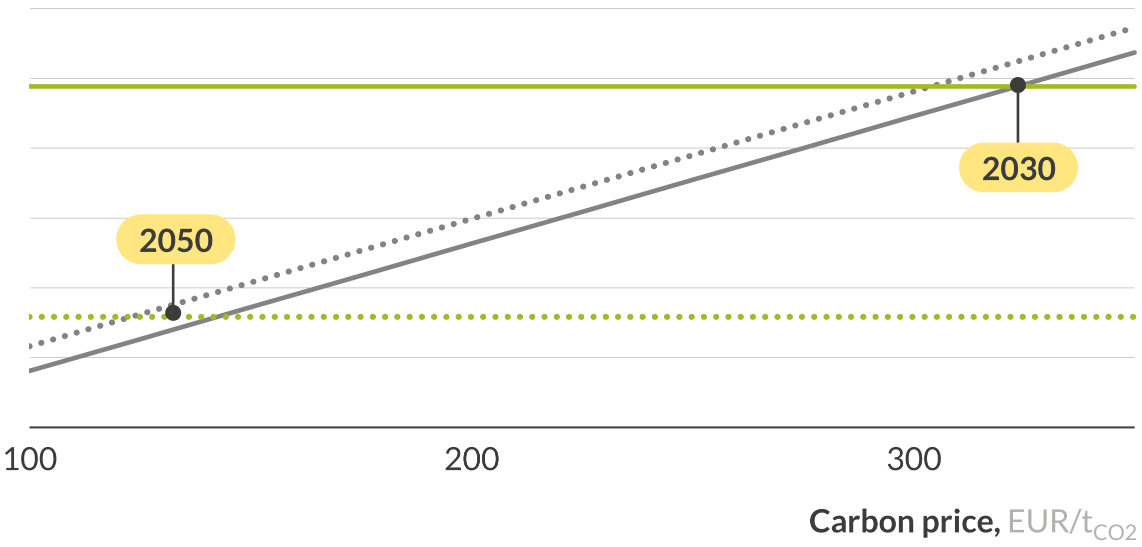
Fuel cost by production method, 2030
EUR/MWh(thermal) (real 2021)



- The above fuel costs are comparable as the efficiencies of gas CCGTs and hydrogen CCGTs are similar[2]
- To bring the levelised cost of green hydrogen into line economically with the clean gas price, support equivalent to [redacted]/MWh would be necessary
- Without such support, it remains unlikely that green hydrogen will be used commercially for power generation purposes by 2030

2 Under Aurora's carbon price forecast, green hydrogen production costs will be 2% lower than the clean gas price in 2050

Fuel cost as a function of carbon price
EUR/MWh(thermal) (real 2021)



Year	2030	2050
Carbon price required for price parity, EUR/t$_{CO2}$	[redacted]	[redacted]
Aurora carbon price forecast, EUR/t$_{CO2}$	[redacted]	[redacted]

Clean gas price[1] — Green hydrogen production cost — 2030 ··· 2050

Some data has been redacted. 1) The clean gas price is the sum of the gas price and carbon price per MWh of natural gas fuel. The latter was calculated by assuming a gas CCGT carbon intensity of 182 g_{CO2}/MWh of natural gas. 2) 50%-57% HHV.

Source: Aurora Energy Research

Policy makers could further reduce the LCOH of green hydrogen with CAPEX subsidies or HPA support in the upcoming H_2 strategy

I Co-located off-grid

	Hydrogen purchase agreement (HPA)	HPA and 20% CAPEX subsidy	HPA and 50% CAPEX subsidy
Offtaker price (equal to LCOH) (€/MWh)	3.5	3.3	2.6
Benefits ✓	▪ Guarantees revenue certainty for H_2 producers ▪ Protects early-moving offtakers from hydrogen price volatility ▪ Targeted support (increasing carbon prices will have knock-on impacts in other sectors)	▪ Guarantees revenue certainty for H_2 producers ▪ Protects early-moving offtakers from hydrogen price volatility ▪ Electrolyser investment case further bolstered ▪ Targeted support (increasing carbon prices will have knock-on impacts in other sectors)	▪ Guarantees revenue certainty for H_2 producers ▪ Highest level of CAPEX support strongly incentivises build of hydrogen production capability ▪ Fair hydrogen offtaker price is well below €3/kg, encouraging offtaker competition and a more liquid HPA market
Drawbacks ✗	▪ Does not support upfront costs ▪ Does not directly support the development of transportation and storage infrastructure or hydrogen technologies	▪ Does not directly support the development of transportation and storage infrastructure or hydrogen technologies	▪ Most costly upfront without guaranteeing a benefit to the economy ▪ Higher risk of oversaturating domestic hydrogen production capacity before transport/export infrastructure is prepared
Hydrogen price relative to the clean gas price in 2030 ([redacted]/MWh)	~+80%	~+70%	~+40%

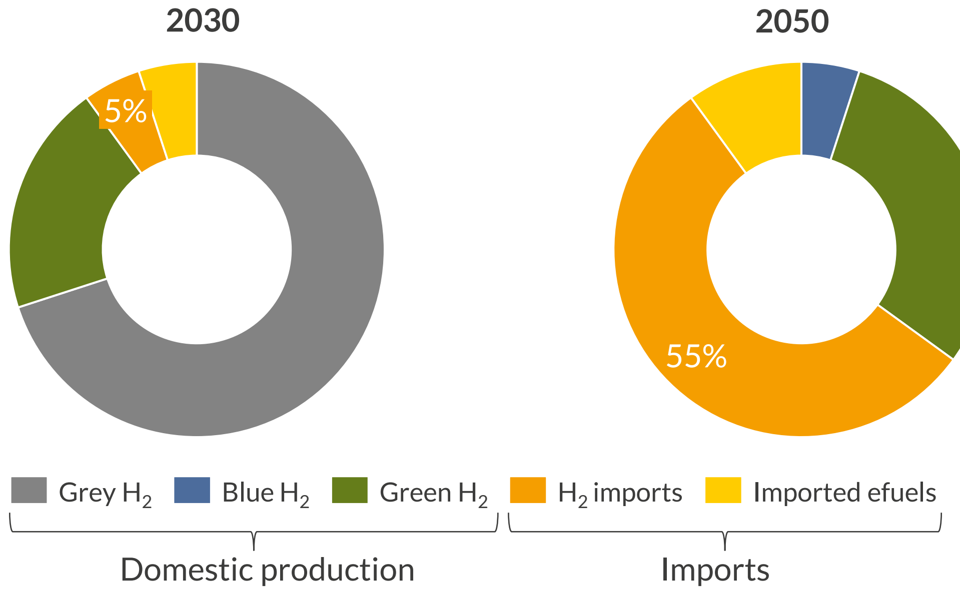
Some data has been redacted. 1) Electrolyser CAPEX in 2030, in real 2021 EUR. All standard modelling assumptions apply. 2) All analysis based on the co-located off-grid business case assuming 2030 entry, with 88MW onshore wind capacity, 12MW solar PV capacity, 60MW electrolyser capacity and no grid connection. This configuration minimises the LCOH in all cases.

Source: Aurora Energy Research

Despite incurring additional transport costs, Irish imports will be cheaper than domestically produced green hydrogen in Germany in 2030

II Onshore co-located grid

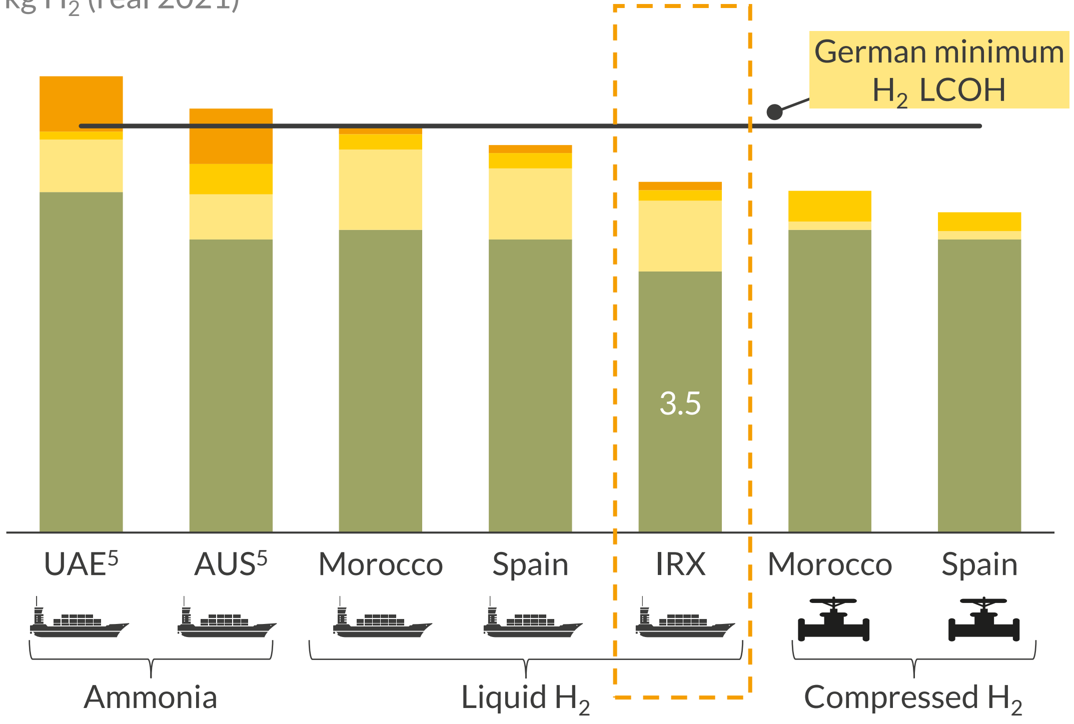
German hydrogen demand breakdown



- Hydrogen imports will make up an increasing share of hydrogen demand in Germany
- The growing German market is an attractive export destination for cheap Irish green hydrogen, shipped from the port of Cork to Wilhelmshaven, Germany

Levelised cost of hydrogen imports[4] to Wilhelmshaven, Germany in 2030

EUR/kg H_2 (real 2021)



- Pipelines provide the cheapest import route to Germany, however Aurora does not expect a fully developed network by 2030
- The Republic of Ireland could therefore compete with other hydrogen producers for hydrogen consumed in central Europe

Production   Conditioning[5]   Transport   Reconditioning   Pipeline   Shipping

Some data has been redacted. 1) Excluding any subsidies. 2) The preparation of hydrogen for transportation and storage, including the conversion to liquid H_2. 3) Wilhelmshaven port is targeted as a hub for green hydrogen. 4) The costs in the graph represent the cheapest route for each country. 5) UAE and AUS transport hydrogen as ammonia resulting in higher reconditioning costs.

Source: Aurora Energy Research

Key takeaways

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1. Ireland has a decarbonisation target of net zero by 2050, which will require targeted research, dedicated policy and increased investment in all sectors. Hydrogen will be vital fuel to achieving these goals as it does not release greenhouse gases when combusted, can be generated by renewable power through electrolysis and has a variety of use cases across energy generation, transport and industry.

2. Aurora expects hydrogen demand in Ireland to reach over 300,000 tonnes by 2050. Current projects in Ireland are predominantly in the early development stages, as investment has been limited due to a lack of domestic demand and government support. The Republic of Ireland is one of the last EU countries yet to publish a Hydrogen Strategy, but it is expected in 2023.

3. Based on our modelling of the hydrogen and power markets, Ireland has attractive conditions for green hydrogen production due to high renewable load factors. Aurora has found the lowest cost per unit of hydrogen produced can be achieved by co-locating an electrolyser with onshore wind and solar PV without a grid connection.

4. To promote further investment in Irish hydrogen production, government policy support, targeting both the supply and demand side, is necessary. Aurora has investigated the impact of hydrogen purchase agreements and electrolyser CAPEX subsidies and found a combination of these policies could further reduce the levelised cost of hydrogen.

5. Given Ireland's high potential for low-cost production, Aurora believes Irish green hydrogen would be competitive on the European hydrogen market, even after accounting for the additional cost of processing and transport. Assuming export to Germany, Ireland could compete with hydrogen exports from Spain and domestic German green hydrogen production.

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Details and disclaimer

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1st March 2023

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