Renewable Power and Hydrogen Integration

NexSys White Paper

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Project overview

NexSys (Next Generation Energy Systems) is an All-Ireland multidisciplinary energy research programme which aims to tackle the challenges of energy decarbonisation by developing evidence-based pathways for a net zero energy system. Within this programme, several targeted projects aim to provide evidence-based recommendations to research questions from industry partners. This white paper is related to the targeted project “Renewable Power and Hydrogen Integration” sponsored by RWE.

The goals of the targeted project were to:

- Develop and present a mapping tool that identifies LCOE Hydrogen from complex input parameters, such as geography, resources, hydrogen demand/export, timescale and access to infrastructure (Deliverable 1),
- Evaluate the development of green hydrogen within the Irish energy market, potential routes to market including national demand or export, and potential barriers to development (Deliverable 2),
- Develop a model to map costs of green hydrogen supply and use (Deliverable 3), and
- Provide recommendations on capabilities, training, policy, and regulation needed to support offshore wind developers in the potential growth of hydrogen (Deliverable 4).

This white paper summarises the findings of the project deliverables.

List of abbreviations

BOP	Balance-of-plant
CAPEX	Capital expenditure
CCS	Carbon capture and storage
DSO	Distribution system operator
HSP	Hydrogen selling price
GHG	Greenhouse gas
GNI	Gas Networks Ireland
LCOH	Levelized cost of hydrogen
MW	Megawatt
NPV	Net present value
OPEX	Operating expenditure
OSW	Offshore wind
PEM	Polymer electrolytic membrane
PV	Photovoltaic
RES	Renewable energy source
RESS	Renewable Electricity Support Scheme
SMR	Steam methane reforming
SNSP	System non-synchronous penetration
TEA	Techno-economic assessment
TSO	Transmission system operator
TWh	Terawatt-hour
VRES	Variable renewable energy source

1. Why do we need green hydrogen?

Anthropogenic climate change has also been referred to as the biggest threat that modern humans have ever faced, with implications for extreme weather events, food and water security, and availability of natural resources (IPCC, 2023). A large contributor to climate change is the extraction and use of fossil fuels such as natural gas, oil, and coal. To produce energy, fossil fuels are combusted, where the carbon and hydrogen contained within them react with oxygen (O_2), producing carbon dioxide (CO_2) and water (H_2O):

$$C_xH_y + \left(x + \frac{y}{4}\right)O_2 \longrightarrow xCO_2 + \frac{y}{2}H_2O + energy \quad (1)$$

Carbon dioxide is a greenhouse gas (GHG) which currently contributes to three-quarters of global anthropogenic emissions (IPCC, 2023). Additionally, fossil fuel extraction and use can produce methane (CH_4) through leakages, which is an even more potent GHG (Huijbregts et al., 2016). Consequently, there is a need to transition away from fossil fuels and towards sustainable, low-carbon fuels. As a fuel, hydrogen (H_2) is considered "clean" because it produces no carbon emissions when utilized:

$$2H_2 + O_2 \rightarrow 2H_2O + energy \quad (2)$$

While the hydrogen molecule is carbon-free, its sustainability is dependent on the production method. Hydrogen is not readily available as pure H_2; it therefore must be extracted from other molecules, such as methane or water. Currently, the majority of global hydrogen comes from steam methane reforming (SMR), which is a process where the methane contained in natural gas (~85-90%) is combined with steam and split into hydrogen and carbon dioxide:

$$CH_4 + 2H_2O + energy \rightarrow 4H_2 + CO_2 \quad (3)$$

At present, common practice is to release the CO_2, meaning that this form of hydrogen - called grey hydrogen - is fossil fuel dependent and has embedded carbon emissions (Ajanovic et al., 2022). Similarly, coal or lignite can also be used to produce hydrogen through gasification (black/brown hydrogen); this results in the highest carbon emissions and is considered to be the most environmentally damaging method of production (Longden et al., 2022).

Blue hydrogen uses the SMR process but is followed by carbon capture and storage (CCS). This is often considered as low-carbon hydrogen, as the CCS process results in 40-99% reduction in CO_2 emissions, depending on the technology (IEA, 2023). However, this method still contributes to fugitive methane emissions and requires additional energy for capturing and storing the carbon (Longden et al., 2022). Thus, blue hydrogen results in only a marginal improvement of 12% reduction in overall GHG emissions compared to grey hydrogen, and an even larger environmental impact than the direct use of fossil fuels (Howarth & Jacobson, 2021).

For truly zero-carbon hydrogen, the hydrogen should derive from a carbon-free molecule. Hydrogen can be produced from water through a process called electrolysis, where the water molecule is split into hydrogen and oxygen by applying an electric current:

$$2H_2O + energy \rightarrow 2H_2 + O_2 \quad (4)$$

If electricity from the grid is used, this method is not carbon-free, given that most countries are currently at least partially reliant on fossil fuels for electricity generation (IEA, 2024). In fact, if the grid is primarily reliant on fossil fuels, overall GHG emissions can be even larger than grey hydrogen (De Kleijne et al., 2022). However, if electricity is supplied entirely by zero-carbon sources, such as wind (green hydrogen), solar (yellow hydrogen), or nuclear (pink hydrogen), its embedded carbon emissions are substantially lower than other methods (Table 1). If used to replace fossil fuel use (Turconi et al., 2013), this would result in emissions savings between 79-99%.

Table 1: Carbon footprint (CF) of hydrogen production.

Hydrogen from:	CF (kg CO2-eq/kg)
Natural gas	9.6-12.0[1,2,3,4]
Natural gas with CCS	2.5-7.6[1,4]
Coal	18.0-23.4[1,2]
Coal with CCS	4.7-8.6[1]
Nuclear energy	0.2-0.6[6]
Wind power	0.03-1.0[2,3,4]
Solar energy	0.4-2.5[3,4]

[1](Longden et al., 2022)

[2](Wulf & Kaltschmitt, 2018)

[3](Suleman et al., 2015)

[4](Patel et al., 2024)

[5](IEA, 2023)

[6](Ji et al., 2023)

*Adjusted to 2020 values (average inflation 1.51%/year). Euro to USD exchange rate: 1.3.

The use of hydrogen in place of fossil fuels, particularly in hard-to-decarbonize sectors such as manufacturing and heavy-duty transport, could contribute significantly to global climate action (IEA, 2019). Consequently, there is significant interest from several countries in developing the market for hydrogen, particularly in the European Union (EU) (European Commission, 2020). In Ireland, the National Hydrogen Strategy outlines the goals for developing the Irish hydrogen sector: decarbonize the economy, enhance energy security, and create industrial and export market opportunities (Government of Ireland, 2023b).

2. Where do we need green hydrogen?

The National Hydrogen Strategy has projected hydrogen demand in Ireland to grow to 4.6-74.6 TWh per year by 2050 (Government of Ireland, 2023b); however, this wide range is not helpful in understanding the development of hydrogen demand within different sectors, nor the key factors which influence its growth. To investigate hydrogen demand within the energy sector in Ireland from now until 2050, several sources of literature are reviewed, including government policy papers, industry reports, and scientific papers on hydrogen technologies, economics, sustainability and energy systems modelling (Vance & Syron, 2024).

Hydrogen has a potential role to play within several sectors of the Irish economy but especially within the energy sector, which is expected to undergo substantial changes in the coming decades. As seen in Figure 1, Ireland is projected to have an annual energy demand of 116-180 TWh by 2050 (Balyk et al., 2022; Chiodi et al., 2013, 2015; Daly, 2022; Gaur et al., 2022; Yue et al., 2020), compared to 140 TWh today (SEAI, 2023a). Despite increasing energy efficiency, a decrease in energy demand will only be possible with widespread system and behavioural changes, which is a key challenge at the societal level (Government of Ireland, 2022); in most models, energy demand is expected to increase, driven by population growth, economic growth, and growth in data centres (Balyk et al., 2022; Daly, 2022).

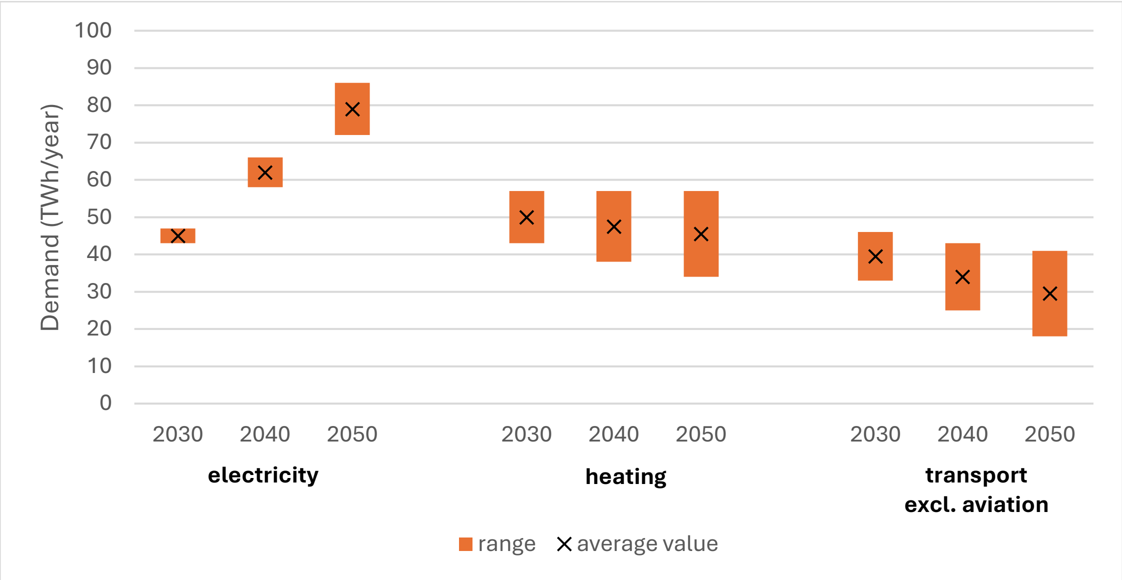

Figure 1: Expected development in Irish energy demand within the electricity, heating, and transport sectors, 2030-2050.

Due to the electrification of heat and transport, the highest growth in energy demand will come from electricity, which is expected to increase from 31 TWh today (SEAI, 2023a) to 72-86 TWh by 2050 (EirGrid & SONI, 2024b). While the majority of this demand is expected to be provided by variable renewable energy sources (VRES) (EirGrid & SONI, 2024b; SEAI, 2023b), due to their intermittency, there will still be some need for alternative energy sources. Currently, gas-fired power plants are used to balance VRES, as they are the most flexible type of plant which can start up or shut down rapidly (IRENA, 2021). To reduce the climate impact of such balancing plants, hydrogen could replace natural gas use within these turbines. In Ireland, currently operating gas power plants have indicated that up to 5 vol.% hydrogen blending can be achieved without major modifications and that up to 40 vol.% hydrogen blends can be achieved with more substantial retrofitting (Ekhtiari et al., 2023). Future gas turbines should be rated for 100% hydrogen to be part of a zero carbon energy system. An alternative to hydrogen combustion in gas turbines is its use in fuel cells, which can be more efficient than combustion-based power plants and produce no gaseous emissions (Mekhilef et al., 2012; Pashchenko, 2024; U.S. Department of Energy, 2017). However, fuel cells are significantly more expensive than gas turbines, with overall systems currently costing on average 10,000 $/kW (Cigolotti et al., 2021). It is therefore unlikely that fuel cell technology for power generation will be adopted before the 2040's.

Heating in Ireland is currently primarily covered by fossil fuels, with oil supplying 42%, natural gas supplying 41%, solid fuels such as coal and peat supplying 8%, and renewables and non-renewable waste supplying the remaining 9% (SEAI, 2023a). Future population growth will increase the number of residential and commercial buildings in Ireland, increasing total heat demand (Balyk et al., 2022). On the other hand, climate change is expected to decrease the heating demand, as warmer temperatures will result in milder winters. One study found that a 5-10% decrease in Ireland's residential and commercial heat demand could be expected by 2050, depending on global emission scenarios (Semmler et al., 2010). Furthermore, by switching to more efficient heating systems like heat pumps and district heating networks, a 20-30% reduction in heating requirements per residential dwelling could be achieved by 2050 (Gaur et al., 2022). Overall, a slight decrease is expected.

The vast majority of current heat demand is supplied by individual boilers; similar to the case of electricity generation, hydrogen could directly replace natural gas used in gas boilers. Preliminary tests have shown that blends of up to 20 vol.% hydrogen can be transported within the current gas network, with certain pipelines having the ability to transport up to 100% hydrogen (Ekhtiari et al., 2023). End-use devices have also been tested and found to operate effectively for hydrogen blends up to 20 vol.%. Medium- and long-term hydrogen demand depend on if more substantial changes to heating systems can be expected. Ireland has proposed banning natural gas boilers in new homes from 2025 (Gas Networks Ireland, 2021). Simultaneously, in the past few years, heat pump installations and home improvements for increased energy efficiency have risen dramatically, in part due to attractive government support schemes (SEAI, 2023b). For these reasons, some studies have suggested that by 2050 no gas could be needed in residential and service sectors, with all heat demand fully electrified (Yue et al., 2020). In other studies, gas demand is projected to increase, as currently rural regions are reliant on solid fuels, and some groups within these regions have been advocating for an expansion of the gas network to ensure a just transition towards a zero-carbon Ireland (Liquid Gas Ireland, 2023).

The main competitor to hydrogen use in electricity and heating is bioenergy (Government of Ireland, 2023b). According to the Sustainable Energy Authority of Ireland (SEAI, 2022), 4.4 TWh of Irish bioresources are currently used for bioenergy, mainly being used in combined heat and power (CHP) plants. If all bioresources (including all agricultural and forestry by-products as well as all municipal and industrial wastes of biological origin) are considered, a total of 6.5 TWh of bioresources are available for heat or power production. Additionally, if additional land is made available to grow energy crops by reducing the intensity of livestock farming, this could further increase the Irish bioresource availability up to 12.1 TWh by 2050. Based on these figures, up to 5.1 TWh of biomethane could be produced by 2050 (SEAI, 2023a). If this biomethane is used entirely for power production, it could cover up to 2.8 TWh of electricity demand or 4.3 TWh of heat demand.

Transport is currently the most significant energy mode in terms of total energy demand in Ireland, utilizing 58 TWh/year; 95% of this energy consumption is currently derived from refined oil products such as diesel, gasoline, and jet kerosene (SEAI, 2023a). Fortunately, due to a high political motivation to increase the uptake of electric vehicles (EVs), which are significantly more energy efficient than internal combustion engine (ICE) vehicles, transport demand (excluding aviation) is expected to decrease to 33-46 TWh by 2030, 25-43 TWh by 2040, and 18-41 TWh by 2050.

Hydrogen can be used as a transport fuel within ICE vehicles or fuel cell electric vehicles (FCEV), with the latter being much more likely. Currently, uptake of hydrogen-fuelled EVs is negligible, primarily due to the cost and lack of hydrogen fuelling stations in Ireland. However, it is envisioned that specific applications for hydrogen-fuelled transport will emerge in the categories of buses, vans, and light- and heavy-duty trucks. FCEVs could be particularly applicable for commercial vehicles as they require a greater autonomy and a fast charging time, all of which are advantages of FCEVs over BEVs (De Wolf & Smeers, 2023). For this reason, the first hydrogen refuelling stations in Ireland are aimed specifically at supplying light- and heavy-duty trucks, and are expected to be deployed from 2027, supplying up to 365 tonnes of hydrogen per year (eolas, 2024). Furthermore, between 2024 and 2030, Ireland plans to publish a National Policy Framework on Alternative Fuels Infrastructure, where support for rolling out hydrogen vehicles and fuelling infrastructure will be detailed (Government of Ireland, 2023b). Through this policy framework, grants could be provided to lower the capital cost of FCEV purchase, which would have a significant impact on the economic viability of hydrogen-fuel transport (Rout et al., 2022). Furthermore, the cost of FCEVs is expected to significantly decrease in the future, as some recently patented fuel cell designs have claimed production costs as low as 26-50 $/kW (Alaswad et al., 2016; Wang et al., 2018).

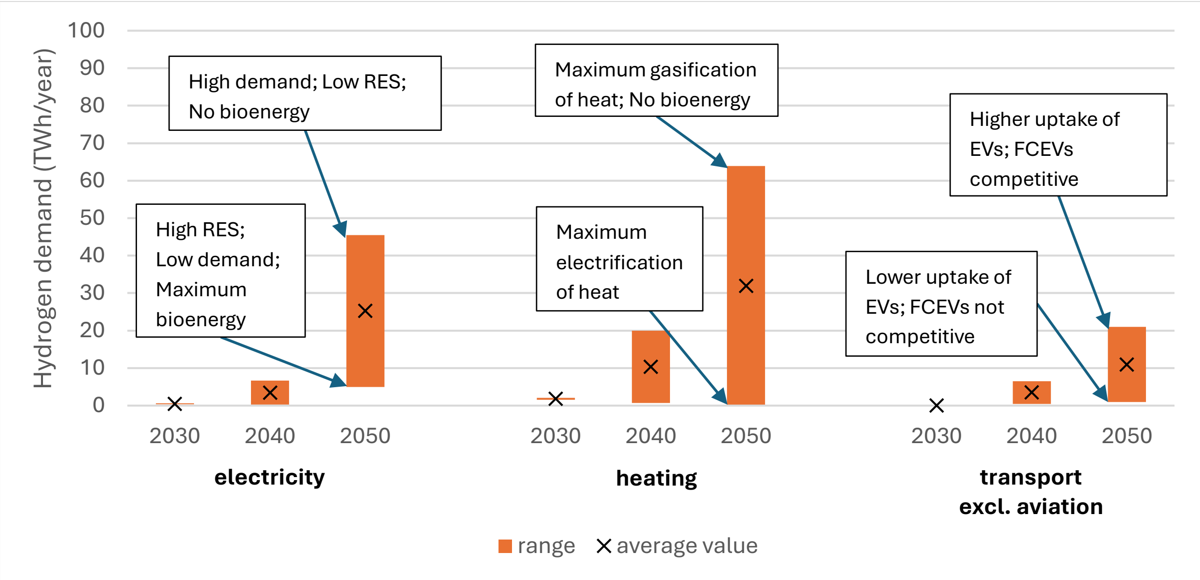

Figure 2: Expected development in Irish hydrogen demand within the electricity, heating, and transport sectors, 2030-2050.

Based on these considerations, total domestic hydrogen demand within the energy sector is projected to be 1.9-2.7 TWh by 2030, 1.4-33.1 TWh by 2040, and 6.0-130.3 TWh by 2050 (Figure 2). However, the use of hydrogen outside the energy system could further increase demand projections. Hydrogen is used in the production of ammonia (NH_3), which is used to produce chemical nitrogen fertilisers. Due to its large agricultural sector, current chemical nitrogen fertiliser use in Ireland is estimated at 280,000 tonnes per year, with a limit of 300,000 tonnes from 2030 (Teagasc, 2023). If domestic renewable ammonia production were to be initiated to offset demand for fossil fuel-derived nitrogen fertilizers, an estimated 0.6-1.7 TWh of hydrogen would be needed for this industry, declining over time as more nutrient recovery initiatives are implemented.

While energy demand for domestic road transport is expected to decrease, it is expected that energy demand for international aviation will increase from about 12 TWh currently to about 14 TWh (23-30% total transport energy demand) by 2030 and 17 TWh (29-49% total transport energy demand) by 2050 (Balyk et al., 2022; SEAI, 2023b). The aviation sector has substantial targets for increasing the share of sustainable aviation fuel (SAF) use to 6% by 2030, 34% in 2040 and 70% by 2050 (IATA, 2024), with the EU ReFuel initiative further mandating that the minimum proportion of aviation fuel which must be from synthetic (green hydrogen-derived) SAF is 1.2% in 2030, 10% in 2040, and 35% in 2050 (European Parliament, Council of the European Union, 2023). To produce this SAF in Ireland, hydrogen demand in the aviation sector would reach 0.5-6.3 TWh by 2030, 4.8-39.6 TWh by 2040, and 18.6-89.3 TWh by 2050 (Figure 3).

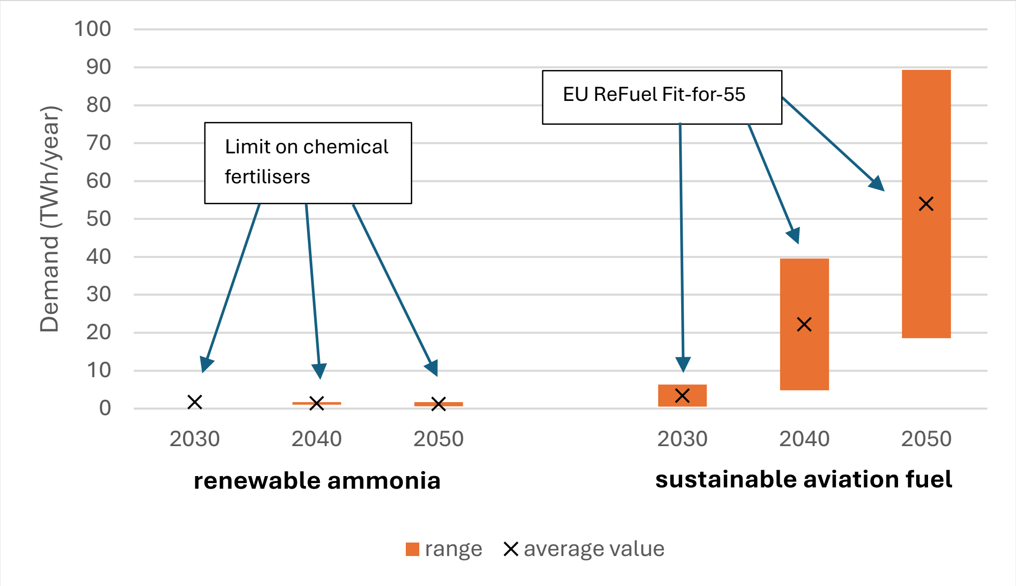

Figure 3: Hydrogen demand in Ireland for conversion to renewable ammonia or sustainable aviation fuel (SAF), 2030-2050.

Ultimately, demand for hydrogen in the short-term (~2030), medium-term (~2040), and long-term (~2050) is highly dependent on future energy demand, renewable energy uptake, levels of electrification, cost of present and future technology, retrofitting of existing fossil fuel infrastructure, and development of new hydrogen infrastructure. Understanding the developments in these areas, particularly with regards to energy policy, market developments, and social acceptance, will enable better projections to be made over the coming years.

3. How do we get green hydrogen (and how much will it cost us)?

Ireland has a particularly unique opportunity for producing green hydrogen, as renewable power potential is large and deployment expected to grow in the coming years. By 2030, Ireland aims to quadruple its current installed capacity of renewable energy, for a total installed capacity of 9 GW of onshore wind, 5 GW of offshore wind (OSW), and 8 GW of solar PV installations (Government of Ireland, 2023b). Furthermore, Ireland's offshore potential is substantial, with plans to install 30-37 GW of OSW capacity by 2050 (Government of Ireland, 2024; SEAI, 2011). Combined with the intended increase in onshore wind and solar PV, 54 GW of renewable energy capacity could be installed on the island by 2050 (Figure 4). Renewable energy capacity factors in Ireland are generally found to be 11% for solar PV (Ryan et al., 2023), 27% for onshore wind (EirGrid & SONI, 2024a), and 50% for offshore wind (Wind Energy Ireland, 2023). Thus, even if electricity demand increases to ~80 TWh/year by 2050, at this installed capacity, the renewable electricity generated would more than double annual electricity demand.

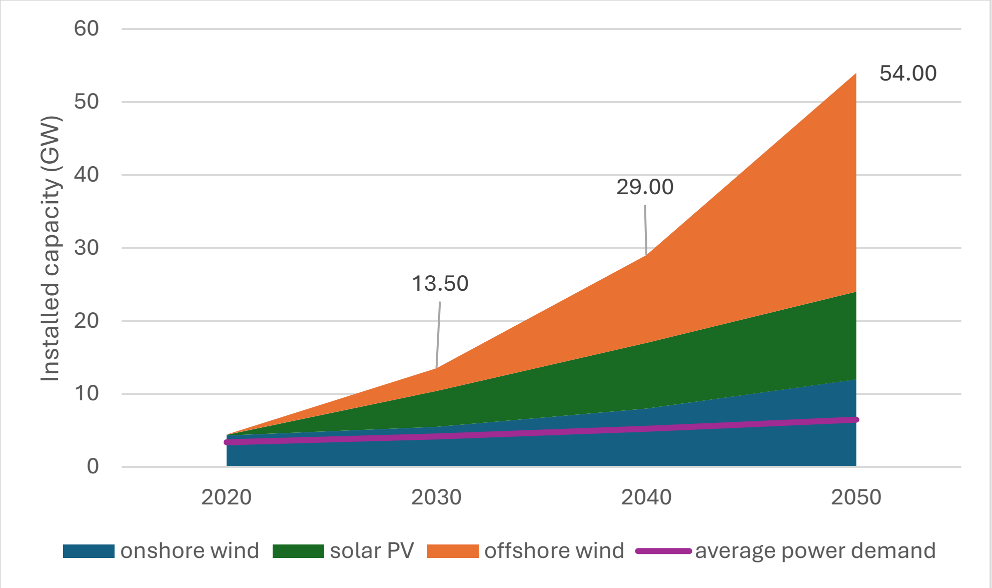

Figure 4: Installed capacity of variable renewable energy sources in Ireland, 2020-2050.

The cost of renewable electricity in Ireland is also favourable due to the market interventions in place. Ireland incentivizes renewable energy installations through their Renewable Electricity Support Scheme (RESS), which invites both communities and businesses to bid for strike prices (fixed electricity price) offered by the electricity transmission system operator (TSO), EirGrid, for 15-20 years. Most importantly, the RESS promises to compensate for curtailments: electricity which is available from variable renewable energy sources but cannot be accommodated by the grid. This scheme has already seen a significant increase in electricity generation from utility-scale solar photovoltaic (PV) installations from <0.1 TWh in 2021 to 0.4 TWh in 2023 (SEAI, 2023a). Furthermore, the scheme has enabled the first successful auctioning of OSW installations in Ireland (Figure 5), which will provide the country with 3 GW of offshore wind power (EirGrid, 2023; WindEurope, 2023).

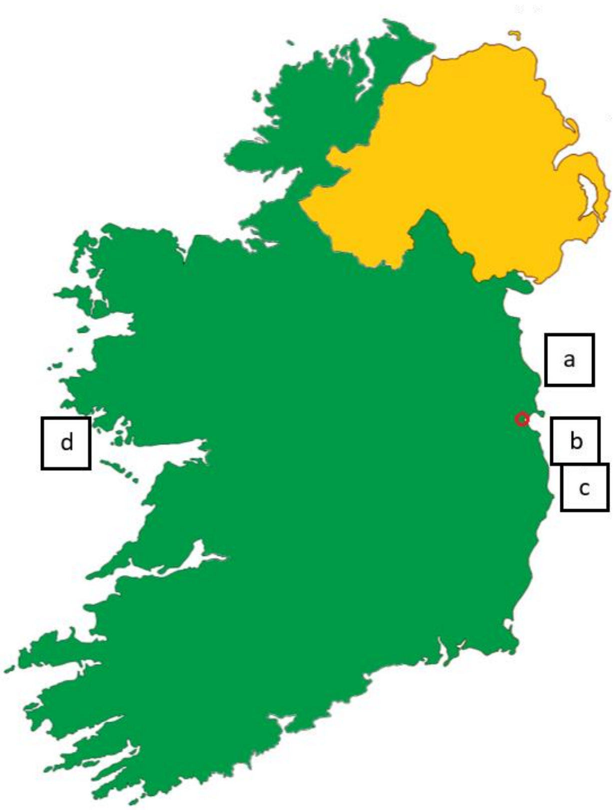

Figure 5: OSW sites successfully auctioned in ORESS 1 and included in cost model: a) North Irish Sea Arry (NISA), 500 MW. b) Dublin Array, 830 MW. c) Codling Wind Park, 1300 MW. d) Sceirde Rocks, 450 MW. Red circle: Dublin city centre.

Despite the successes, there are several barriers to the development of Ireland's renewable energy market. One area of particular concern is the speed at which renewable energy systems can be realistically deployed. In the short-term, Ireland's renewable energy targets are likely to fall short due to significant delays in the planning approval process for wind farms (Lee, 2024). Furthermore, researchers have pointed out that there are significant barriers to developing offshore wind in Ireland, including a critical lack of port infrastructure (Duggan & Carton, 2024). In the long-term, even more uncertainties are introduced, due to potential policy and market changes (IEA, 2021).

With regards to Ireland's renewable hydrogen market, even more barriers exist. Green hydrogen production is expensive, due to the high cost of electrolysers and electricity (IRENA, 2020). Furthermore, hydrogen has a low energy density and must be stored at high pressure, cryogenic temperatures, or converted into carriers (e.g., ammonia, LOHCs), all of which add complexity and cost (Abdin et al., 2022). Even if issues with hydrogen production and storage are addressed, existing gas pipelines and distribution networks are not fully compatible with hydrogen, requiring retrofitting or building of new infrastructure which is expensive and time-consuming (Topolski et al., 2022).

Because of these technical challenges, investors and businesses have been reluctant to invest in hydrogen technologies (Emodi et al., 2021). Government support, stable policies, and clear market signals could help accelerate the uptake of green hydrogen; however, in order to facilitate this, it is important to understand exactly how much the development of the hydrogen sector will cost in Ireland. To explore the potential business cases for renewable power and hydrogen integration, a cost model is created. The model considers different electricity supply profiles, electrolyser types, hydrogen demand profiles, and storage types, varying installed electrolyser and storage capacity to find the minimum LCOH. To apply the developed cost model, several hydrogen production and supply chain cases are considered which are relevant for Ireland (Table 2). These cases encompass two time frames: current and near-future, with the current time frame using curtailed power and gas demand from 2022/2023, and the near-future time frame projecting VRES generation, curtailments and gas demand in 2030 by integrating several data sources. Supply chain cases encompass different potential hydrogen demands and storage methods, where hydrogen can be used within the existing gas network at maximum 20 vol.% blends, used directly within a new hydrogen gas network, used directly for gas-fired power generation, or exported (Figure 6). These cases apply data from several academic, governmental, and industrial sources and are specific to the Irish context.

Table 2: Modelled time frames, production cases, supply chain cases, and storage types.

Time frame	Production case(s)	Electrolyser type(s)	Supply chain case(s)	Storage type(s)
Current (2022)	P1a: all curtailed power	PEM, alkaline	SC1a: injected into existing gas network	Pipelines, pressure vessels
Current (2023)	P1b: all curtailed power	PEM, alkaline	SC1b: injected into existing gas network	Pipelines, pressure vessels
Near-future (~2030)	P2a: all curtailed power including OSW	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels
		PEM, alkaline	SC3: injected into new hydrogen network	Pipelines (incl. new network)
		PEM, alkaline	SC4: produced on-site for power generation	Pressure vessels
		PEM, alkaline	SC5: exported to Europe daily (a) or weekly (b)	Liquefaction
	P2b: all curtailed power excluding OSW	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels
	P3a/b/c/d: dedicated power from individual OSW sites	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels
	P3e: dedicated power from all OSW sites	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels
		PEM, alkaline	SC3: injected into new hydrogen network	Pipelines (incl. new network)
		PEM, alkaline	SC4: produced on-site for power generation	Pressure vessels
		PEM, alkaline	SC5: exported to Europe daily (a) or weekly (b)	Liquefaction
	P4a/b/c/d: curtailed power from individual OSW sites	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels
	P4e: curtailed power from all OSW sites	PEM, alkaline	SC2: injected into existing gas network	Pipelines, pressure vessels

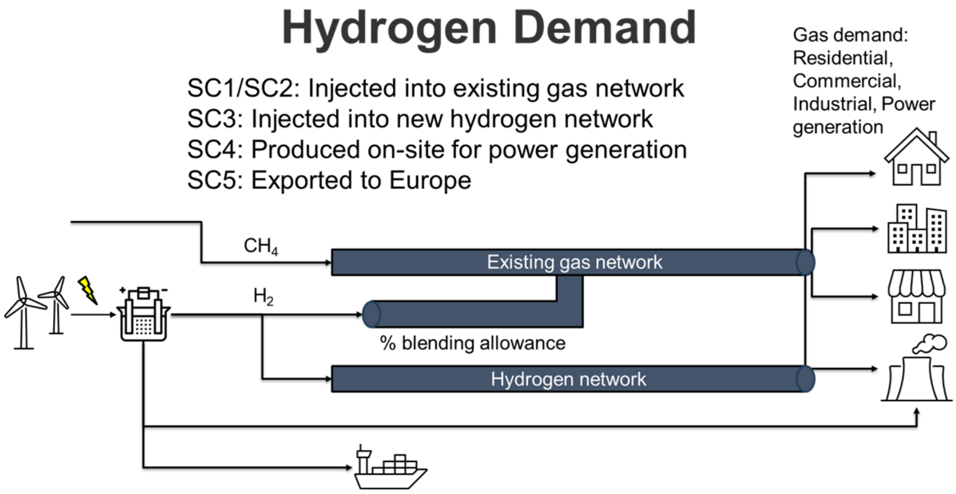

Figure 6: Methods for distributing hydrogen to meet final energy demand.

The results demonstrate the complexity of optimising hydrogen production within a rapidly changing energy system. Currently, the power curtailed in Ireland (excluding constraints) amounts to approximately 0.74 TWh per year, which is 2.54% of total VRES generation. If this power was instead used for hydrogen production (P1a/b), this would lead to a hydrogen production cost of 6.00-8.00 €/kg using PEM electrolysers and 3.50-4.50 €/kg using alkaline electrolysers if electrolyzer installed capacity is optimized (100 MW for PEM and 250 MW for alkaline). By 2030, the increase in renewable energy installations due to the Renewable Electricity Support Scheme is expected to outpace electricity demand, increasing onshore wind and solar curtailments to 1.25 TWh/year. As OSW is integrated onto the grid, if not managed correctly, curtailments could potentially increase substantially to 10.24 TWh/year (17.61% of all VRES generation). In this case (P2a), hydrogen produced from all curtailed power results in a minimum production cost of 1.75-2.80 €/kg by installing 600 MW of PEM electrolysers and 0.90-1.65 €/kg by installing 1200 MW of alkaline electrolysers. If the OSW sites were not connected to the grid but instead used for dedicated hydrogen production (P3a/b/c/d/e), the minimum achievable production cost would be 6.25-8.00 €/kg using PEM electrolysers and 5.50-7.25 €/kg using alkaline electrolysers, regardless of installed electrolyser capacity. In all production cases, alkaline electrolysers are identified as the most economical, as despite a lower efficiency when operating intermittently they are the more mature and benefit more from economies of scale (Reksten et al., 2022).

When considering hydrogen supply chains, key trade-offs must be considered (Table 3). Hydrogen produced from curtailed power is very affordable; however, this electricity source is limited and highly variable, leading to high storage costs if the goal is to meet maximum hydrogen demand. For example, hydrogen produced using all curtailed power including OSW in 2030 (P2a) can cover 45% of hydrogen demand in a blended gas network (SC2) at a LCOH as low as 1.01 €/kg. On the other hand, covering 100% of total blended hydrogen demand (SC2) would cost up to 14.16 €/kg, due to a larger-than-optimal installed electrolyser capacity and substantial required storage capacity. By contrast, using dedicated renewables generally results in higher LCOH due to the cost of electricity, but allows higher demand coverage, which may be preferable depending on the selling price of the hydrogen. For example, hydrogen produced using dedicated power from all auctioned OSW sites (P3e) can cover 84-100% of total blended hydrogen demand (SC2) at a LCOH of 5.64-11.05 €/kg. Generally, hydrogen is cheapest when the demand is very large and full coverage is not necessary, allowing the optimal electrolyser capacity to be installed with minimal installed storage capacity. If covering a larger proportion of the total demand is desired, the model finds that it is preferable to oversize the electrolyzer (resulting in more wasted hydrogen production) than install additional storage capacity.

Finally, short-term feasibility should be acknowledged. Both hydrogen export to Europe (SC5) or use within a 100% hydrogen gas network (SC3) require significant infrastructure projects which are not anticipated until the late 2030's at the earliest. Hydrogen use within a blended gas network (SC2) is technically possible, but requires changing the current regulatory limit of 0.1% hydrogen blending in the gas network. Hydrogen use within power generation (SC4) is the most feasible option in the short-term, as recent gas-fired power generation projects have advertised their hydrogen-readiness. In this case, the hydrogen could be produced from curtailed power at a cost of 1-2 €/kg, or from dedicated OSW at a cost of 5-6 €/kg.

Table 3: Overview of results from future supply chain cases, as well as their short-term feasibility.

Supply chain case	**Minimum achievable LCOH (€/kg) using hydrogen produced from curtailed VRES**	**Minimum achievable LCOH (€/kg) using hydrogen produced from dedicated OSW**	**Considerations for short-term feasibility**
Hydrogen blended into existing gas network (SC2)	1.01-14.16 (45-100% demand coverage)	5.64-11.05 (84-100% demand coverage)	Distribution network is currently being tested for blends up to 20 vol.%
Hydrogen used in new hydrogen gas network (SC3)	0.88-1.98 (7-14% demand coverage) 2.71-3.33 if cost of new gas network is included	5.32-5.86 (21-27% demand coverage) 6.19-6.73 if cost of new gas network is included	No construction of hydrogen gas network until 2037-2040
Hydrogen used for power generation (SC4)	0.89-2.20 (9-20% demand coverage)	5.36-6.23 (29-38% demand coverage)	Newer gas power plants are hydrogen-ready
Hydrogen exported to Europe (SC5)	Exported daily: 2.78-9.21 (23-52% demand coverage) Exported weekly: 6.64-13.16 (16-51% demand coverage)	Exported daily: 7.61-14.71 (42-94% demand coverage) Exported weekly: 11.05-15.06 (41-92% demand coverage)	Irish ports do not yet have infrastructure for gas shipping

4. Who will produce hydrogen?

With regards to production cases, potential business strategies can be discussed from the perspective of the offshore wind developer (Table 4). While it was modelled in this work, using dedicated power from the RESS auctioned sites (P3a/b/c/d/e) is not feasible, because the contracts are already in place to provide electricity to the grid (EirGrid, 2023). Utilising curtailed power from the RESS auctioned sites (P4a/b/c/d) is feasible, but contracts must be clarified. Currently, the Irish government compensates for curtailed power; it is therefore unlikely that the scheme would allow the curtailed electricity itself to be sold for additional profit to an off-grid service (such as a hydrogen producer), given that it has already been paid for. The curtailed power could be offered to hydrogen producers for free; however, there is currently no incentive for OSW developers to do this themselves. The more obvious option would be for the TSO or DSO to be the hydrogen operator, and that rather than request the power to be curtailed they could divert the flow of excess electricity to electrolysers located at various electrical connection points.

For future non-RESS offshore wind sites, dedicated hydrogen production can be done. Assuming those sites would be developed in similar locations and sell their power at a similar price to the RESS auctioned sites (86 €/MWh), the LCOH production could be assumed to be 5.50-8.50 €/kg. If connected to the electricity grid, selling curtailed power could be an important secondary revenue source (McDonagh et al., 2020); however, even a marginal increase in curtailed power cost of 10-20 €/MWh would increase the cost of hydrogen production by 125-200% (Vance et al., 2025). Furthermore, the lack of security from the feed-in tariff will make project financing more difficult and will increase the overall LCOE of OSW (Matthäus & Mehling, 2020).

An alternative option would be for OSW developers to invest in and operate the electrolysis systems themselves, selling the hydrogen to a third party. Hydrogen generated at the OSW site could either be generated onshore or offshore. Electrolysers located offshore would require additional infrastructure for transporting hydrogen to shore; however, the purchasing of land would be avoided. The trade-off between these options would need to be understood on a case-by-case basis.

The most feasible supply chain case involves using the hydrogen for power generation. This is because direct contracts with power stations could be made which would bypass the existing gas and electrical networks, either by sending the curtailed power to the power station and generating hydrogen on site, or generating hydrogen at the OSW site and transporting the hydrogen to the power station. Other potential hydrogen users include manufacturing facilities or data centres, which similar to power stations could use all hydrogen produced directly on-site. It is important to note that all of these cases would require either electrical lines or hydrogen pipelines to be built between the OSW site and the hydrogen user. According to Saadi et al. (2018), the cost of building electrical lines is cheaper, at about 0.5 million $ per km for a 3000 MW HVDC cable and 1-2 million $ per km (depending on the pipe diameter) for a new hydrogen pipeline. However, as previously mentioned, for RESS auctioned sites the direct selling of electricity would likely not be allowed; thus, transport of hydrogen would be necessary. Luckily, on the east coast, the distance between the locations of the auctioned offshore wind sites (Figure 7) and the locations of the hydrogen-ready power stations (Figure 8) is relatively small; for NISA, Dublin Array, and Codling Wind Park, each OSW site's onshore substation connection is 1-12 km from the closest hydrogen-enabled power station. Depending on the installed electrolyser capacity, the annual hydrogen production range for these sites are 9,000-41,000 tonnes; thus, the additional cost is 0.02-1.21 €/kg[1]. For non-RESS sites dedicated 100% to hydrogen production, an annual production range of 26,000-87,000 tonnes could be assumed, based on the production capacity of existing OSW sites. Assuming a transport distance anywhere between 1 and 50 km and either electricity or hydrogen transport, the additional cost would be 0.00-1.75[2]. To minimise the relative cost of infrastructure, distance should be minimised while annual hydrogen production should be maximised. This is yet another trade-off which should be analysed based on the specific case.

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[1] Lower value: assuming hydrogen pipeline, 1 km transport distance, and an annual hydrogen production of 41,000 tonnes. Higher value: assuming hydrogen pipeline, 12 km transport distance, and an annual hydrogen production of 9,000 tonnes. Lower capital cost for hydrogen pipeline is assumed as this diameter can transport up to 76,000 tonnes hydrogen per year. Costs converted to € using an exchange rate of 0.91 euros to 1 USD.

[2] Lower value: assuming HVDC cable, 1 km transport distance, and an annual hydrogen production of 87,000 tonnes. Higher value: assuming hydrogen pipeline, 50 km transport distance, and an annual hydrogen production of 26,000 tonnes. Lower capital cost for hydrogen pipeline is assumed as this diameter can transport up to 76,000 tonnes hydrogen per year. Costs converted to € using an exchange rate of 0.91 euros to 1 USD.

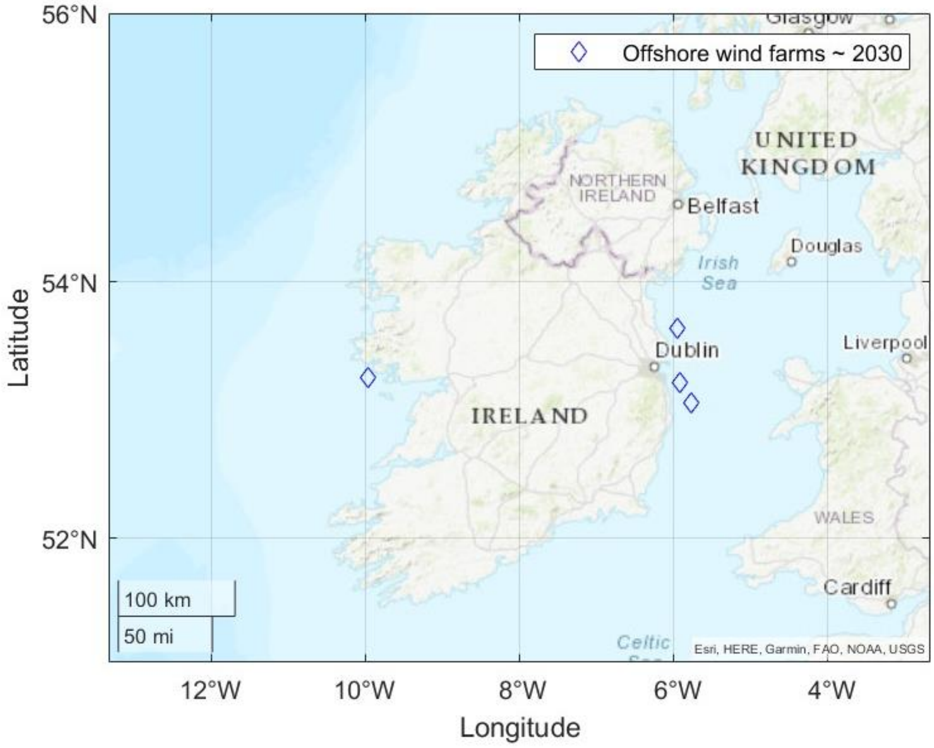

Figure 7: Locations of offshore wind parks successfully auctioned in ORESS 1.

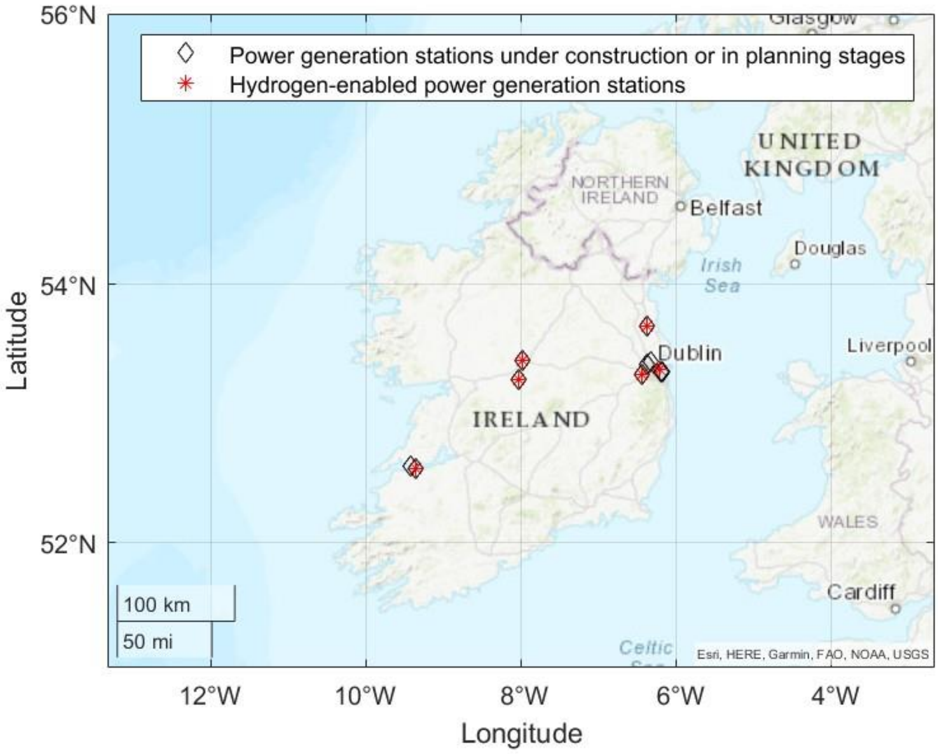

Figure 8: Locations of new power generation stations and those that are hydrogen-enabled.

A final business case involves building a new power station located exactly at the OSW site's onshore electrical connection point. This could either by operated by the OSW developer or by an external party. This is particularly interesting as Ireland has committed to building at least 2 GW of additional flexible gas-fired power generation capacity by 2030 (Government of Ireland, 2023a). Furthermore, this new power station could take advantage of Ireland's capacity auction, which has previously provided payments of 83,000-180,000 €/MW for gas turbine capacity to be made available by 2026/2027 (EirGrid & SONI, 2023). On the other hand, building a power station will require substantial additional investment, which may not be desired by OSW developers.

Table 4: Business opportunities for OSW developers.

Opportunities for OSW developers	Feasibility
Option 1: Sell renewable power to hydrogen producer	RESS sites: Unlikely to be accepted. Non-RESS sites: Feasible for both dedicated power and curtailed power.
Option 2: Operate electrolysis system, sell hydrogen to hydrogen user	RESS sites: Likely acceptable using curtailed power. Non-RESS sites: Feasible for both dedicated power and curtailed power. Hydrogen will need to be transported to demand location, incurring additional infrastructure costs.
Option 3: Operate electrolysis and hydrogen power plant, sell power and/or heat to energy user	RESS sites: Likely acceptable using curtailed power. Non-RESS sites: Feasible for both dedicated power and curtailed power. Significant capital cost will be needed to build the power station, but can take advantage of capacity auction payments.

5. What else is needed?

With regards to policy and regulation, several changes are needed to kickstart the hydrogen economy. As mentioned, hydrogen blending in Irish gas networks is currently limited to 0.1%, due to alignment with UK's GSMR rules. Until these regulations are changed, there will be no possibility to use existing infrastructure to distribute hydrogen. This is a significant missed opportunity, given that repurposing pipelines has been found to be 20-60% cheaper than building new hydrogen pipelines (Topolski et al., 2022). On the other hand, the limit to hydrogen blending is dependent on several network components including not only the pipelines but also valves, fittings, storage tanks, and compression, pressure reduction, and metering stations. While GNI is currently conducting tests on various components and appliances (Ekhtiari et al., 2022, 2023), this research should be expedited and integrated with detailed information on the gas network to set location-specific guidelines and standards.

As previously discussed, when electrolyser and storage capacity are optimised, an LCOH of 1-4 €/kg is achievable when using curtailed power and 5-8 €/kg when using dedicated OSW power. Including a profit margin of 1 €/kg, this translates to a price of 51-127 €/MWh and 152-228 €/MWh (by HHV), respectively. The current price of natural gas in Ireland is 70 €/MWh (by HHV); more typical prices historically have been 30-45 €/MWh (Eurostat, 2024). This means that green hydrogen produced from curtailed power requires only minimal additional financial support (0-97 €/MWh) to be economically competitive with natural gas, whereas green hydrogen produced from dedicated OSW power requires an additional financial support of 82-173 €/MWh to compete with natural gas.

Table 5: Minimum support cost (MSC) needed for hydrogen produced from curtailed or dedicated renewable power considering different LCOH.

Electricity source	LCOH (€/kg)	Hydrogen selling price (€/MWh) including 1 €/kg profit margin	MSC to compete with natural gas (€/MWh)
Curtailed power	1	51	0-21
	2	76	6-40
	3	102	32-72
	4	127	57-97
Dedicated renewable power	5	152	82-122
	6	178	108-148
	7	203	133-173
	8	228	158-198

Considering direct emissions only, replacing natural gas with hydrogen saves approximately 350–410 kg CO2-eq/MWh (Turconi et al., 2013). These emissions savings result in direct financial benefits, as there is a cap on emissions in the EU which is regulated through the EU's Emissions Trading System (ETS). Based on the minimum support costs identified, the carbon price would need to be 0-60 €/tonne to enable competitiveness of green hydrogen at a LCOH of 1 €/kg, 139-278 €/tonne to enable competitiveness at a LCOH of 4 €/kg, and 385-566 €/kg to enable competitiveness a LCOH of 8 €/kg. The average forecast for EU carbon permits in 2025 is 75.15 €/tonne CO2-eq (Twidale, 2025), meaning the current carbon price is sufficient only at a LCOH of 1-2 €/kg.

For any carbon credit from hydrogen use to be received, the hydrogen must be certified as renewable. The EU has set out specific requirements for hydrogen to be certified as a Renewable Fuel of Non-Biological Origin (RFNBO). Specifically, this legislation allows any hydrogen produced from at least 90% renewable electricity or with an emission intensity lower than 18 g CO2-eq/MJ to be certified as a RFNBO and counted as zero emission for the ETS (Commission Delegated Regulation (EU) 2023/1184 Supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by Establishing a Union Methodology Setting out Detailed Rules for the Production of Renewable Liquid and Gaseous Transport Fuels of Non-Biological Origin, 2023). No hydrogen certification scheme yet exists in Ireland; thus, hydrogen producers currently need to rely on international voluntary schemes to demonstrate compliance. Furthermore, if hydrogen is blended into the existing gas network, a Proof of Origin (PoO) certificate is necessary to allow the end user to claim ETS credits for their use of hydrogen. Ireland already has a Renewable Gas Registry (Gas Networks Ireland, 2023) which is set up to issue PoOs; however this system is currently focused on biomethane.

Given the high carbon prices needed to enable green hydrogen to compete with natural gas on the open market, additional funding is needed. Since 2023, the European Hydrogen Bank has been operating a 'pay-as-bid' auction in which European producers can bid for a subsidy per kg of hydrogen produced, with the winning bids under 0.48 €/kg (European Commission, 2024a). Thus far, no Irish projects have been awarded subsidies through the European Hydrogen Bank. Furthermore, there has been no clear indication from the government that Ireland will utilise the European Hydrogen Bank's Auctions-as-a-Service scheme, which is available to member states (European Commission, 2024a). It is highly recommended that the Irish government applies for this scheme to help fund green hydrogen projects in the country.

6. Why should we act now?

While it is clear that there are still significant challenges and action needed to enable hydrogen production and consumption within Ireland, the only way to improve the situation is by continuing forward. The pace of deployment has a direct effect on technological advancement and associated cost reductions; for example, the cost of electrolysers is dependent on the amount of electrolysers that are manufactured per year (Badgett et al., 2024). If hydrogen projects continue to be delayed in the hopes that technology costs will further decrease, there will be no opportunities to optimise the process and learn by doing. Furthermore, a lack of deployed projects results in lower confidence in the technology, limiting external investment which is heavily needed for hydrogen research and development (R&D) (European Commission, 2020).

Lack of action also puts Ireland at risk of continuing its energy dependence on other countries. The UK is currently Ireland's only gas trading partner and is investing heavily into hydrogen (UK Department for Energy Security & Net Zero, 2023), providing a Contract-for-Difference (CfD)-type subsidy for low-carbon hydrogen, which covers the difference between the strike price, which is based on the LCOH, and reference price, which is based on the cost of conventional fossil fuels (Nishimura & Asahi, 2024). It is anticipated that the gas pipelines already connecting Ireland to Britain will be repurposed or expanded for hydrogen import and export; if domestic production is delayed, Ireland will need to import significant amounts of hydrogen from the UK to achieve their decarbonisation goals, costing in excess of €12.5 billion (at 4 €/kg). Furthermore, while Ireland has ambitions to be a net hydrogen exporter, the rest of the EU has been rapidly developing hydrogen projects; Spain, Lithuania, and Austria have all announced national funding schemes totalling almost €800 million (European Commission, 2024b).

Ireland needs to rapidly support their hydrogen sector to remain competitive in Europe and globally. To enable market growth, Ireland urgently needs regulatory reform, a national certification system, and participation in EU funding mechanisms. Ultimately, the potential for decarbonising the Irish energy system using green hydrogen is massive, but only if we act now.

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