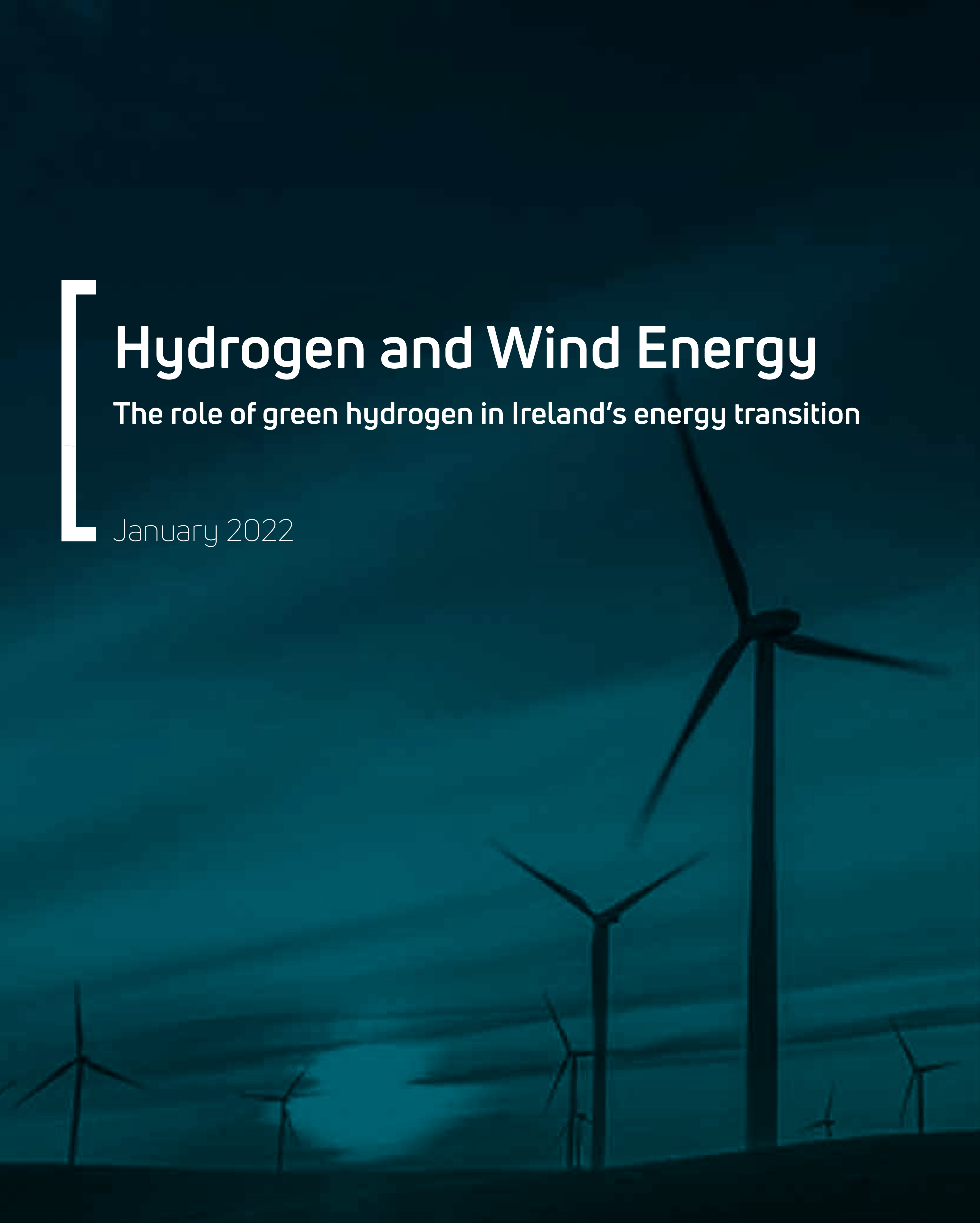

Hydrogen and Wind Energy

The role of green hydrogen in Ireland's energy transition

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Green Tech Skillnet
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Wind Energy Ireland

Preface

Gavin & Doherty Geosolutions Ltd (GDG) has been commissioned to critically examine the potential for hydrogen produced by wind turbines to assist in Ireland's transition to a low-carbon energy system. The present report explores this coupling in detail and outlines both the challenges – technical, economic, and policy – and opportunities associated with the development of an wind-based green hydrogen industry in Ireland.

Wind Energy Ireland

Wind Energy Ireland is the representative body for the Irish wind industry, working to promote wind energy as an essential, economical and environmentally friendly part of the country's low-carbon energy future. Wind Energy Ireland is an all-Ireland body, working in Northern Ireland through a partnership with our colleagues in RenewableUK. It is Ireland's largest renewable energy organisation with more than 160 members who have come together to plan, build, operate and support the development of the country's chief renewable energy resource. Wind Energy Ireland is the promoting organisation of the Green Tech Skillnet.

Green Tech Skillnet

Green Tech Skillnet is a business network facilitating the workforce and talent development needs of the Irish renewable energy industry. Reflecting the diversification of Irelands energy system, the network will support the optimisation of renewables on the Irish grid in the short, medium and long term through learning and development initiatives. In this regard the network aims to deliver impactful training and networking events to a growing workforce, facilitate thought leaders within the renewables sector whilst contributing to Ireland's decarbonisation and energy transition.

Gavin & Doherty Geosolutions Ltd.

GDG is a specialist engineering consultancy with a multidisciplinary team dedicated to the delivery of sustainable design solutions which maximise the social, economic, and environmental benefits of engineering projects. In the 10 years since its inception, GDG has supported more than 35 offshore wind energy projects through all stages of development, from consenting through to end-of-life decision making. Through these projects, GDG has contributed to the development of more than 40GW of offshore wind energy capacity in 10 countries.

Executive Summary

This report was commissioned by the Green Tech Skillnet in partnership with Wind Energy Ireland and Skillnet Ireland. The aim of the research was to examine the likely role of green hydrogen in Ireland's energy transition and the associated future talent and skills requirements. This analysis focused primarily on the period pre 2030 and included the development of an interrogable Levelised Cost of Hydrogen (LCoH) model, the assessment of potential green hydrogen end users, a stakeholder survey, and an economic comparison with current fossil fuel alternatives.

The concept of a hydrogen-based economy was first suggested by General Motors in 1970. The idea has seen renewed attention in recent years driven by the increasing pressures of climate change and a lack of suitable low carbon alternatives in difficult to decarbonise sectors. Long term hydrogen strategies have now been published by Canada, Chile, Colombia, Czech Republic, France, Germany, Hungary, the Netherlands, Norway, Portugal, Russia, Spain, the United Kingdom, and the European Union. Following COP26, the green hydrogen targets in several of these strategies are now being revised upwards. With Ireland's own strategy currently in development, a review of the national situation is timely.

This report concludes that a definite role for green hydrogen in Ireland's energy transition has been secured by technology trends, economics, and regional political will. However, early developments will be constrained by a lack of an existing domestic market for large quantities of hydrogen. We are at a disadvantage to countries such as Germany and Norway where there is the availability of both low-cost renewable electricity to produce, and significant existing industrial demand to consume, large quantities of hydrogen. There are two distinct opportunities for the stimulation of near-term domestic hydrogen demand in Ireland. Such early markets are vital if we are to be positioned to supply future high demand sectors such as power generation, aviation fuel, shipping fuel and a potentially vast export market.

The first domestic opportunity is hydrogen injection into existing natural gas pipelines where a blend of up to 20% is considered technically achievable. Meeting this demand in Ireland would require c. 4.2 GW of wind energy generation dedicated to the production of green hydrogen. Whilst long term it is projected that natural gas demand will fall due to increased electrification, pipeline injection is our leading option to rapidly stimulate a domestic hydrogen market.

Secondly, increased demand can be achieved at the only significant existing domestic user of hydrogen, the Whitegate refinery in Cork. This facility processes c. 40% of national liquid fuel demand and has been both producing and utilising hydrogen in the refining process since 1959. Part of the facility's existing hydrogen demand is for the production of hydrogenated vegetable oil (HVO) and Fatty Acid Methyl Este (FAME), biofuels which can replace or be blended with fossil diesel.

To increase green hydrogen demand at the facility, close consultation with the operators is critical to overcome technical and regulatory barriers to allow the rapid increase of biofuel production up to and beyond the Climate Action Plan target of 20% by 2030. Low carbon transport fuels are the first markets where hydrogen can compete directly with fossil fuels. As such, the Whitegate facility is expected to be central to the early development of Ireland's green hydrogen economy and it is important that existing expertise and infrastructure are leveraged.

Whilst focusing on the domestic market pre-2030 may be seen as lacking ambition, it should be noted that the potential scale of this market is significant. If just heavy goods vehicles and buses were to switch from diesel to green hydrogen it would require at least 1.4 GW of dedicated wind energy generation. Synthesising just 50% of shipping and aviation fuels would require a further 6.6 GW. The construction of the required wind farms and the electrolysis alone would require an investment of c. €18.4 bn, resulting in the generation of approximately 16,000 direct and a further 32,000 indirect jobs.

Currently, talent gaps and employment opportunities related to green hydrogen are primarily related to energy systems modelling, planning and the analysis of energy / carbon regulations. Our stakeholder survey indicates that as the industry develops, we will see significant employment opportunities in construction and skilled technical roles. Long term employment opportunities will be found in the operation of facilities along with the provision of services and expertise to the global green hydrogen industry.

By focusing on near term opportunities and working with the existing hydrogen expertise at our disposal, Ireland has the potential to be a leader in green hydrogen utilisation. Reducing our carbon footprint, building energy security, and providing long term sustainable employment opportunities.

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Glossary

BEV	Battery Electric Vehicle
CAP	Climate Action Plan
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
DSM	Demand Side Management
FT	Fischer-Tropsch (Synthesis)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCoE	Levelised Cost of Electricity
LCoH	Levelised Cost of Hydrogen
OPEX	Operational Expenditure
SMR	Steam Methane Reforming
VRG	Variable Renewable Generation

1. Introduction

Motivation

To avoid the worst effects of climate change[1] , which is unequivocally linked to human activity [1], immediate and sustained action is required to reduce emissions and, in particular, the use of fossil fuels [2]. Globally, however, the gap between the promises of the Paris Agreement [3] and the reality of greenhouse gas (GHG) emissions continues to widen [4]: energy-related CO2 emissions peaked in 2019, with annual emissions having increased by 4% since 2015, and emissions for 2021 are expected to be just 1.2% lower, despite the impact of the COVID-19 pandemic [5]. As well as exacerbating the climate crisis, Ireland's reliance on fossil fuels is a major source of pollution [6] and creates both energy security and economic issues [7,8], with fuel imports costing €5 billion in 2018 alone [8].

The European Union's Renewable Energy Directive (RED) has set a binding target of 32% renewable energy by 2030 [9]. This target is currently being reviewed [10] and is likely to be revised upward as the EU seeks to effectively double its contributions from renewable energy over the next decade [11]. The EU has also recently introduced its European Green Deal, which seeks to accelerate the union's recovery from the COVID-19 pandemic through investments in renewable energy technologies. This package also targets GHG emissions, increasing the 2030 reduction target from 40% to 55%[2] [12].

Ireland's 2021 Climate Bill set a national target to reduce GHG emissions by 51% by 2030 [13]. This target equates to a 7% reduction in annual emissions each year, and represents a significant increase on the 30% target set in the 2019 Climate Action Plan (CAP) [14]. For context, the onerous travel restrictions introduced in 2020 to reduce the spread of COVID-19 produced only a 6% reduction in annual emissions [15]. To better align the CAP with the increased ambition of this Climate Bill, it was updated in 2021, building upon interim publications [16].

Progress towards climate goals has typically been measured against the emissions of previous years, but the 2021 Climate Bill introduces the concept of the carbon budget. Much like a financial budget, the carbon budget sets out the maximum carbon emissions allowed over a given period, focusing on the total emissions in place of those in a single year. As such, there is now a sharp focus on cumulative emissions and near-term action [13]. This will create a greater sense of urgency and perhaps encourage a shift from the traditional economic arguments surrounding low-carbon technologies. Both the Climate Bill and CAP include a stated target of net zero emissions by 2050 but fossil-fuel generation still dominates in Ireland: in 2019, only 12% of Ireland's energy demand was provided by renewable resources [17].

Ireland's energy future

Much of Ireland's focus to date has been on the production of renewable electricity[3] [17]. The composition of the future electricity mix will be determined by competitive auctions[4], but the country has also set specific targets for certain technologies [16]. With an installed capacity of 4.3GW, onshore wind was Ireland's largest source of renewable electricity in 2020, providing 36% of the total demand [17,18]. An additional 1.8GW will be installed in the next few years, with various contracts in place and connections already underway [19], and the country aims to increase its total onshore wind capacity to 8.2GW by 2030 [14]. Due to reductions in costs [20], Ireland is also set to exceed its target for solar photovoltaic (PV) technology: the CAP set a target of 1.5GW of solar PV capacity by 2030 [14] and there is currently 2.5GW either contracted or in process [19].

As an island on the western periphery of Europe, Ireland is well positioned to take advantage of its large sea territories and significant offshore wind resources. Ireland's wind energy resources are among the best in Europe [21] and offshore wind power, in particular, will play a significant role in its zero-carbon electricity system [22]. This is reflected in Ireland's ambition to install at

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[1] Typically defined as limiting global warming to 1.5°C above pre-industrial levels [2].

[2] This target is union-wide and relative to 1990 levels. In Ireland, for example, the primary energy requirement has increased by c. 65% since 1990 [161], which means that a 55% reduction relative to 1990 levels would require c. 75% reduction from present levels.

[3] The 2020 renewable targets for each sector were 40% for electricity, 10% for transport, and 12% for heat [17].

[4] The Renewable Electricity Support Scheme (RESS) includes specific mechanisms to support a broad range of technologies [162].

least 5GW[5] of offshore wind capacity by 2030 [23], which would represent a significant expansion but only a fraction of the country's technical capacity [21].

If all announced capacity is brought online, Ireland can expect to produce up to 42.7TWh[6] of renewable electricity per year by 2030. The current annual electricity demand is 39TWh, and expected to increase to between 46TWh and 56TWh by 2029[7]. This amount of renewable generation would present significant technical challenges for the Irish electricity grid, not least in ensuring that the variable supply matches with demand [24]. There will be periods when supply of renewable electricity exceeds the demand (and the supply must then be reduced or curtailed), or grid congestion means that the power cannot be allocated where it is required (where the supply is constrained) [25].

Ensuring energy security, even when wind and solar power are unavailable, requires innovative solutions such as interconnectors [26,27], batteries and other storage [28], as well as demand side management (DSM)[8] [29–31]. Fossil-fuel generators[9] are also being shut-down, which makes the task of maintaining grid stability even more challenging [32]. Studies have shown that as Ireland changes from importing fossil fuels to independently producing clean energy, electrification increases to best utilise Variable Renewable Generation (VRG) [33,34]. Ireland's targets for Battery Electric Vehicles (BEVs) and heat pumps complement its renewable energy ambitions [14]: the electrification of transport and heat is key to decarbonisation of the energy system [35]. Similar trends are predicted worldwide and, by 2050, electricity is set to be the main energy carrier, accounting for more than 50% (direct) of final energy use – a significant increase on the current figure of 21% [39].

However, Ireland consumes 4 times as much energy in the form of liquid and gaseous fuels for transport and heating as it consumes in the form of electricity[10] [17]. Even when accounting for the greater efficiency, and hence lower energy demand, of BEVs [36] and heat pumps [37] compared to their fossil fuel alternatives, the electrification of the transport and heating sectors represents a considerable challenge and it is clear that additional renewable electricity, such as from offshore wind, will be required. Complementary technologies are therefore required to act as a buffer between times of high and low VRG, and to provide low-carbon alternatives for the almost 50% of energy demand that will not be electrified [38].

Green Hydrogen

At present, hydrogen is a leading candidate for addressing these various challenges [4,39]. Hydrogen can be used in a fuel cell[11] for a range of purposes [40], injected into the natural gas grid [41], or used to make synthetic liquid and gaseous fuels [42].

Traditionally, hydrogen has been produced via Steam Methane Reforming (SMR) of natural gas, a process which releases substantial volumes of CO2, but it can also be paired with Carbon Capture and Storage (CCS) systems, which sequester the resulting emissions [43]. Such storage involves considerable logistic and economic challenges, however [44]. An emerging alternative is Methane Pyrolysis (MP), a process in which natural gas is decomposed into hydrogen and easily storable solid carbon [45]. Hydrogen produced using fossil fuels and CCS is often referred to as "blue hydrogen" [39].

Because natural gas is an inexpensive feedstock [46], both SMR with CCS and MP can be used to produce blue hydrogen at relatively low cost [39,45,47]. However, both technologies have carbon capture rates of less than 100% [39] and suffer from fugitive emissions of methane, which is one of the most potent GHGs [48]. Without additional measures, these processes are neither carbon-neutral nor net zero compatible. Accordingly, their viability as hydrogen production mechanisms requires further investigation [49].

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[5] The 2021 updates to the CAP increased the offshore wind target from 3.5GW to 5GW [23].

[6] Assuming capacity factors of 0.11 [163], 0.29 [17], and 0.45 for solar PV, onshore wind, and offshore wind, respectively.

[7] The all-island system demand.

[8] Demand side management (DSM) refers to the cooperation between transmissions system operators and consumers, where electricity demand is adjusted to accommodate the variable supply [26,29].

[9] These generators can be quickly activated (dispatched) at times of increased electricity demand [32].

[10] In 2019, the final energy consumption was 19.7% electricity, 42.1% transport, and 38.3% heating [17].

[11] An electrochemical cell that can combine hydrogen and oxygen to produce electricity, the only emission being water [71]. Fuel cells can be used in vehicle propulsion or stationary applications.applications.

Electrolysis, by contrast, is a more sustainable process which uses electric current to split water into hydrogen and oxygen. When renewable electricity is used, the resulting product is termed "green hydrogen" to signify that it is climate-friendly [39]. Electrolysis can be used to convert VRG into hydrogen, is highly scalable, and could be used to meet the increasing demand for dispatchable low carbon fuel in a future energy system [35]. As the technology develops and its decarbonisation potential is increasingly recognised, there is also scope for further technology-driven improvements in the performance and cost of electrolysis systems [49]. These systems also have the advantage of greatly simplifying life-cycle assessment studies: as long as the electricity is obtained from a renewable source, the resulting hydrogen fuel is carbon-neutral [9].

For countries like Ireland with ambitious wind energy targets [14], green hydrogen could act as an energy storage medium when the energy supply and demand are mismatched [50]. The use of Ireland's abundant onshore and offshore wind resources could be optimised by creating a hydrogen supply network which complements the country's electricity system [4,51]. Green hydrogen technology can be used to support the rapid deployment of VRG [39], enable renewable electricity to generate emission reductions beyond the electricity sector [52], and mitigate the issues of variability and storage associated with high penetration levels of wind and solar PV technology [53].

Wind turbines could also be directly connected to electrolysis systems, transforming wind farms into dedicated hydrogen production systems [54] and thereby avoiding additional strain on the electricity grid [19,30]. By 2050, it is estimated that electrolysis could consume 20% of the global electricity supply, with green hydrogen and its derivates accounting for 8-10% of final energy use [35,38]. The level of adoption would likely be higher in Ireland as the country lacks the fossil fuel resources of other nations but boasts abundant wind energy resources [21,35].

Endorsements and Policy

In their 2019 report, the International Energy Agency (IEA) declared that "hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly" [39]. With the climate crisis now requiring countries to seek deeper emissions reductions than ever before, the hydrogen opportunity is receiving increased attention [13]. There is also increasing focus on other issues which favour green hydrogen's use, including air pollution (low or zero tailpipe emissions, zero fugitive emissions), energy security (utilisation and storage of indigenous renewable energy resources), and economic development (investment in local infrastructure).

Japan has already embraced the hydrogen opportunity, and expressed its aim to become the world's first "hydrogen society" [55]. The country sees the opportunity to increase energy security and export fuel cell technology as key to its energy future [56]. To support this goal, the Japanese government has outlined its Strategic Roadmap for Hydrogen and Fuel Cells, which includes 800,000 fuel cell vehicles, 900 filling stations, 5.3 million residential fuel cells, and 1GW of hydrogen power generation by 2030 [55].

In Europe, Germany is at the forefront of green hydrogen research, with the difficulties that the country has experienced in accommodating wind energy (losing 5.5TWh of power in 2017, which cost an estimated €1 billion[12]) provide additional motivation [39]. Germany recently approved a further 10 years' worth of research funding (totalling €1.4 billion), which includes subsidies for public hydrogen refilling stations, fuel cell vehicles, fuel cell home appliances, and support for the first commercial operation of a hydrogen-powered train [39]. These developments are set to be supported by an additional €2 billion in private investment.

Green hydrogen technology has also been endorsed in the recent European Strategy for Hydrogen. As well as encouraging member states to provide financial stimuli and dedicated funding schemes to develop hydrogen markets, the strategy emphasises the importance of phasing out fossil-based hydrogen as soon as possible. The strategy also builds upon the aspirations of the European Green Deal, which calls for 6GW of electrolysers to be installed across the union by 2024 and 40GW by 2030 [57].

In the 2021 update of the CAP, Ireland has placed a focus on integrating the electricity and gas networks using hydrogen grid injection, but has not yet set specific deployment targets [23]. In advance of explicit government support, individual stakeholders have announced the development of new hydrogen projects. As the owner and operator of Ireland's natural gas grid, Gas

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[12] $1.2 billion USD [39].

Networks Ireland (GNI) recognised the need to decarbonise their system and produced a plan to do so: Vision 2050 [58].

GNI has planned to inject green hydrogen into the gas network but this will not be done until 2034. In the updates to the CAP, which were published after Vision 2050, a target is set to test the feasibility of injecting green hydrogen blends into the gas grid in Q4 of 2022, which may indicate that green hydrogen could make an impact ahead of GNI's initial target. Whilst there is significant interest in hydrogen, there is no firm policy support to encourage the adoption of this technology in Ireland. If this remains the case, green hydrogen is unlikely to play a significant role in achieving its 2030 emissions reduction targets.

Falling Technology Costs

While opportunities emerge, policies form, and support solidifies behind different options, technology costs are falling rapidly. Electrolysis, the key technology in green hydrogen production, has seen significant year-on-year cost reductions [59] but the cost of green hydrogen is also highly dependent on the cost of the renewable electricity used. Offshore wind power has shown steep cost declines over the past decade, greatly increasing the viability of its pairing with electrolysis [60]. This is exemplified by the Electricity Supply Board's (ESB) "Green Atlantic at Moneypoint" project, which includes a 1,400MW floating offshore wind farm and a green hydrogen production, storage, and generation facility [61]. This offshore wind farm development is conceived to replace the existing 915MW coalfired power station [62] within the next decade, with the hydrogen element presumably following thereafter [61].

Worldwide, the cumulative offshore wind energy capacity has increased from 3.1GW in 2010 to 34.4GW in 2020 [20]. In that time, the cost of electricity from offshore wind has fallen by 28-49% [60]while the cost of electricity from onshore wind declined by 45% [4]. These lower costs for renewable electricity, combined with reduced electrolyser costs owing to technology development and competition between manufacturers [63], have made green hydrogen one of the most attractive options for low-carbon technology [49].

Hydrogen from Wind Energy

Hydrogen will certainly play a role in the long-term decarbonisation of Ireland's energy system, and green hydrogen offers promising synergies with Ireland's renewable electricity ambitions. This report focuses on the production of green hydrogen by means of electrolysis powered by offshore and onshore wind turbines and will outline both the challenges and opportunities associated with this coupling.

Given Ireland's emission reduction goals, the current momentum behind green hydrogen technology, and its vast offshore wind energy resources [21,64], it is appropriate that the potential for combining these technologies is explored now. Opportunities are also presented in onshore wind with Government setting out a 2030 ambition of up to 8GW of capacity [14]. At the same time, the sector faces several challenges, such as low success rate in the strategic infrastructure development (SID) process, high levels of pre-planning attrition and relatively long consenting durations, along with transmission capacity lacking in areas of the country where large numbers of renewable projects are planning to connect [65]. The present report will use a detailed review of the literature and cost modelling to critically assess the viability of green hydrogen produced by wind energy in the near (pre-2030) and long term (by 2050).

The report is also informed by a survey of key stakeholders in industry, academia, and the public sector. This survey was designed to identify the sectors likely to derive the greatest benefit from green hydrogen in the near-term (pre-2030), and the policies required to support the development of this new industry, as well as the potential for job creation. The results of the survey are presented in Appendix A and referred to throughout the report.

The report is laid out as follows: Chapter 3 outlines the potential uses for green hydrogen in Ireland's low-carbon energy system; Chapter 4 examines the cost drivers for green hydrogen production; Chapter 5 uses a hydrogen cost model to explore the viability of coupling green hydrogen with wind energy; and Chapter 6 concludes the study with some recommendations for policymakers. The report is followed by Appendix A, which presents the results of the stakeholder survey, and Appendix B, which describes the development of the hydrogen cost model.

2. Potential Uses for Green Hydrogen

For Ireland to meet both its national and international climate change obligations, it must decarbonise all sectors of its economy. Electrification is an important element of any such decarbonisation strategy, but there are also sectors for which electrification is impractical [66]. Even the most aggressive switch to the direct use of electricity in industry, transport, and heating leaves many applications still reliant on fossil fuels [34]. Meanwhile, falling production costs and difficulties in managing large volumes of variable renewable generation (VRG) have led to renewed interest in green hydrogen technology [67]. The stakeholder survey accompanying this report (see Appendix A) shows that the respondents are actively engaged in research, capacity building, and feasibility studies. Almost 70% of those surveyed hope to be engaged in the development or planning of a hydrogen project within the next 5 years.

Hydrogen can be used for many applications, but the specific roles will ultimately be dictated by engineering and economics [68]. With this in mind, the following sections outline the various sectors in which green hydrogen may prove useful in Ireland's transition to a low-carbon energy system.

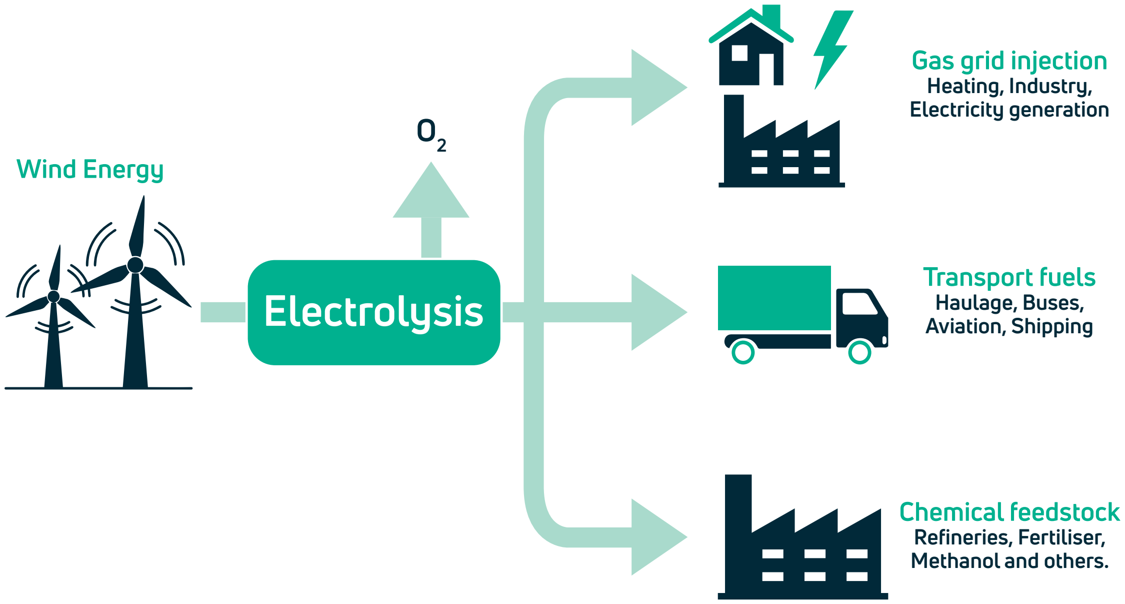

Figure 1: Potential uses for green hydrogen produced using wind energy.

2.1 Potential Uses for Green Hydrogen

The EU has set a target for renewable energy to provide 14% of transport energy demand and 1.3% of heating and cooling energy demand by 2030: both of these targets are likely to be revised upward and/or made binding [10,11]. As noted previously, hydrogen can be used in a fuel cell, combusted in modified engines, or used to produce fossil-fuel-like hydrocarbons to help achieve these emissions reduction targets [66].

However, the efficiency and cost advantages of battery electric vehicles (BEVs) and heat pumps, preference for direct electrification [9,14,35], and substantial head-start in the roll-out of electric vehicle charging infrastructure mean that it is unlikely that there will be a role for hydrogen in the passenger car or residential heat markets in the near term [36]. The quicker refuelling times and greater vehicle ranges offered by hydrogen fuels do not appear sufficient to justify the higher fuel and vehicle costs [69].

For heating, the extraordinary efficiency of the heat pump (250-400%) makes it a much more economical choice than the hydrogen boiler (up to 63%[13]) [37]. These findings are supported by those from the stakeholder survey: 82% of respondents rated the near-term market potential for domestic heating and passenger cars as small.

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[13] Assuming maximum efficiencies of 70% for electrolysis and 90% for a condensing boiler.

Although it is unlikely that hydrogen will play a role in the Irish home heating or passenger car market, there are many other sectors where green hydrogen technology can be utilised. These will be discussed in the next section.

Hydrogen-based Fuels

The nascency of the technologies behind fuel cell propulsion and direct hydrogen combustion limit the potential rollout of hydrogen-based fuels in the short to medium term [66]. Fuels which are compatible with internal combustion engines (ICEs) have significant advantages, not least of which is the ability to utilise the vast existing fossil fuel infrastructure [70]. The energy density of hydrogen-based fuels also presents an issue: although hydrogen fuels are more energy dense than current battery technology, when accounting for both fuel and storage, diesel fuel is 8 times more energy dense than hydrogen at 700 bar, and almost 5 times more energy dense than liquified hydrogen [66], which must be stored at -248°C [71].

Fisher-Tropsch (FT) synthesis, also known as "power-to-liquid", is a process whereby green hydrogen can be combined with a source of carbon[14] to produce a range of fuels which could be used as replacements for petrol, diesel, and kerosene (jet fuel and home heating oil), and other hydrocarbons [72,73]. However, the production process for these drop-in fuels [66] has a relatively low efficiency, with the liquid fuel products containing approximately half of the input energy [74]. The overall production cost, then, is on the order of 2-5 times the fossil fuel equivalent [66] depending largely on electricity costs and plant scale [75].

Green hydrogen can also be used to convert bio-lipids, including slaughterhouse wastes and used cooking oil[15] into renewable diesel, commonly known as Hydrotreated Vegetable Oil (HVO). Unlike traditional biodiesel, HVO more closely matches the properties of fossil diesel and is subject to less stringent blend limits [76]. The hydrogen demand for this process is approximately 1MWh per thousand litres of HVO, or 10% of the energy content [77,78]. Hydrogen can also be used to produce synthetic methane[16] but this process, too, has a low overall efficiency; although there have been milestone projects in operation since 2013 [79], the process has not yet seen widespread use [80–82]. By 2050, it is estimated that 30% of electricity could be solely dedicated to the production of green hydrogen, which could be used either directly or in the form of fuels such as synthetic ammonia and methanol, which make more efficient use of the hydrogen than the FT process [38].

Haulage and Buses

Heavy Goods Vehicles (HGVs), which currently account for 15% of transport energy demand (approximately 9.2TWh in 2019), are almost entirely reliant on diesel [17]. HGVs are also an increasing source of emissions and their energy demand is set to double by 2050 [83]. Despite a lack of specific emissions reduction targets[17], it is clear that a low-carbon solution to the HGV problem is urgently required. However, the Irish haulage sector is a competitive environment, and its low margins make it highly sensitive to costs [84]. To date, the CAP has committed only to exploring hydrogen as a fuel source for medium and heavy-duty trucks [14]. Despite this, the findings from the stakeholder survey suggest that green hydrogen could play a significant role in the decarbonisation of HGVs: 70% of respondents rated the near-term market opportunity as medium to large.

As with passenger cars, where suitable BEV options are available, they will likely be preferred over hydrogen-based technologies [85]. However, for the largest vehicles[18], which typically have much greater daily mileage which makes them much more difficult to electrify, hydrogen has several key advantages [66]: It can offer refuelling practices similar to diesel and natural gas, with similar range and performance [40]. This is also true for buses, for which centralised hydrogen refuelling can match existing practices and hence replace the current system with less resistance to change, even potentially achieving cost parity in Dublin

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[14] Suitable sources include carbon dioxide separated from the air, flue gases, or as a by-product from another process.

[15] Bio-lipids are fatty biological substances. Some, like rapeseed and palm oil, are commonly used to produce fuel. Strict criteria regarding the production of renewable fuels are laid out in the EU Renewable Energy Directive [9] the use of waste products is viewed as inherently sustainable and a key part of a circular economy.

[16] This process is also known as power-to-gas: hydrogen from electrolysis is combined with a source of carbon dioxide to produce methane, the main component of natural gas, in a Sabatier reaction ($4H2 + CO2 = 2H2O + CH4$) [128].

[17] Only public buses and light goods vehicles (LGVs) have targets for vehicle numbers in the CAP [14], though the promotion of compressed natural gas (CNG) is assumed to target HGVs primarily.

[18] Defined here as having an unladen weight (UW) of greater than 10 tonnes.

by 2030 [86]. There are currently three hydrogen fuel cell buses operating in Belfast [87], and a successful trial has also been performed in Dublin [88] in what could be the first steps toward a wider rollout of the technology.

For just one large HGV, the hydrogen required to complete a return trip from Dublin to Cork would require 0.7MWh of electrolysis [54]. At present, there are approximately 25,000 such vehicles on Irish roads, a number which is growing rapidly [89] and, as such, the scale of the hydrogen opportunity in this sector is substantial. Enabling all of these vehicles to travel an average of just 1000km per week each using hydrogen fuel would require 1,400MW of dedicated wind energy capacity[19].

Aviation

Aviation now represents 22% of Ireland's transport energy demand, totalling 13TWh and accounting for almost 10 times the energy used by buses and taxis [17]. As with haulage, aviation is dependent on a single fuel, but unlike haulage, no alternatives to jet fuel (kerosene) have yet been approved. Stringent requirements on jet fuel leave little room for innovation but blends of up to 50% are permitted for certain renewable fuels, such as hydrogen-based FT and HVO [66]. The European aviation industry is also subject to a cap-and-trade emissions scheme, which provides further incentive to produce low-carbon fuels compatible with existing aircraft; particularly as the energy demand associated with aviation is growing rapidly [66]. Some airlines have already announced ambitions to produce sustainable aviation fuels [90]. On aviation fuels, however, the stakeholder survey produced mixed responses: the greatest share of respondents (30%) rated the near-term market opportunity for hydrogen-based synthetic fuels as small.

Airbus is working on a liquified hydrogen aircraft which it expects to enter into service in 2035 [91], but even then, this is likely to only be used in regional applications [92]. Alongside the technical barriers in producing the aircraft itself, the airport operations required to store and refuel with liquid hydrogen would have to be developed and extensively tested [71]. Reliance on conventional engines and fuels is thus likely to continue to 2050 [92]. As an island, there is little room to avoid refuelling in Ireland, meaning that a substantial indigenous demand for such fuels is feasible. Supplying just 50% of current Irish aviation energy demand through hydrogen fuels and FT synthesis would require 4,200MW of dedicated wind energy capacity.

Maritime Shipping

Despite carrying 80-90% of global trade by volume [93], maritime shipping has until recently represented an emissions blind spot, with the first reduction targets only announced in 2018 [94]. Although demand is growing, the sector is aiming for a 40% reduction in global emissions intensity[20] by 2030, and an overall 50% emissions reduction by 2050 when compared to 2008 figures [94]. The international nature of the sector makes estimating energy consumption difficult, however. Figures can be based solely on the fuel purchased, or all the fuel consumed in a country's territory. By one estimate, Ireland is thought to have consumed 11.5TWh of energy in shipping in 2018 [66], while another study suggests a demand of 3TWh in 2050 [95], which reflects the uncertainty inherent in these calculations[21]. However, given that the average lifespan of a shipping vessel is 30-40 years, both estimates suggest significant and sustained demand for low- and zero-carbon fuels compatible with new and existing ships [66,74].

Liquefied hydrogen can be burned or used in a fuel cell with similar efficiencies for marine applications [74]. The cost and difficulties associated with the retrofitting of ships and the construction of additional infrastructure represent significant challenges [66] but hydrogen fuels in shipping are expected to be competitive with fossil fuels by 2030, and have lower overall costs by 2040 [74]. Shipping, then, is a sector which could provide a large market for renewable hydrogen. This finding is reflected in those from the stakeholder survey, which suggested greater support for hydrogen-based marine fuels than aviation fuels: 60% of respondents rated the near-term market potential as medium to large. One large ferry travelling from Belfast to Cork each day would require 0.43GWh of hydrogen fuel, and a single large container ship on the same route could carry more than 10 times this amount [66]. Using the lower estimate (3TWh), supplying 50% of shipping energy demand through liquefied hydrogen would require 1,200MW of dedicated wind energy capacity, doing so through FT synthesis would require twice as much power: 2,400MW.

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[19] All calculations in this section apply to a combination of onshore/offshore wind and assume the following capacity factors/efficiencies: wind 0.45, electrolysis and compression 0.65, fuel cell 0.55, FT-synthesis 0.6.

[20] Carbon emissions per unit of transport work, e.g., tonnes of CO2 per tonne of cargo.

[21] Neither reference provides detailed calculations or traceable sources for their final figures.

2.2 Industry and Chemicals

Ireland does not manufacture substantial amounts of steel, glass, electronics, or chemicals and, as such, its demand for green hydrogen is somewhat limited. At present, its pure hydrogen demand is largely limited to a single refinery at Whitegate in Cork, where hydrogen is produced and used on-site as part of the refining process [96]. Ireland does, however, consume vast amounts of hydrogen in the form of ammonia, which is used to make fertilisers: approximately 560,000 tonnes of nitrogen-containing fertilisers were used in 2020 alone[22]. At present, this fertiliser in manufactured across the EU using hydrogen derived from natural gas [97], and as such there is an opportunity for green hydrogen to reduce the associated emissions [98]. Producing sufficient green hydrogen to satisfy Ireland's fertiliser demand would require 780MW of dedicated wind energy capacity[23].

A by-product of green hydrogen production is pure oxygen, which is another product commonly used in industrial applications [82]. For every 1kg of hydrogen produced, 8kg of oxygen are also produced. There is an established demand for pure oxygen in medical applications but supplies are generally plentiful: the USA, for instance, recently experienced significant oxygen shortages during the COVID-19 pandemic, but even when shortages were greatest [99], as little as 460MW[24] of electrolysis would have been able to supply the demand.

Although the exact size of the Irish oxygen market is unknown, it can be assumed to be small as none of the largest industrial users, steelmaking and chemical production, have a significant presence in Ireland. However, in the future, wastewater treatment and fish farming may provide additional markets to supplement the demand for medical applications [100]. Changes in cement production could generate additional demand for oxygen [101] in any case, the Irish oxygen market would be expected to quickly reach saturation, given the scale of electrolysis required to impact the energy market. Just 20MW of electrolysis could supply the wastewater treatment oxygen demand of up to 1 million people[25], for instance.

2.3 Natural gas

At present, 35% of Irish households (approximately 550,000) use natural gas for heating and cooking [102]. There are, however, several technical and economic challenges associated with replacing this natural gas with hydrogen. The lower energy density of hydrogen means that a 20% blend by volume will reduce emissions by just 8% for a given energy demand[26]. There are also issues with metering, steel embrittlement, and gas quality consistency [103,104]. GNI is currently exploring these issues and is due to publish its assessment in Q4 of 2022 [23]. Still, projects have shown that hydrogen injection into the distribution network[27] is feasible, with downstream consumers less sensitive to gas composition [103]. Moreover, in Ireland, the distribution network pipelines are made from polyethylene and therefore already "hydrogen-ready" [105].

However, this solution appears to offer the potential for only local constraint relief, and not dedicated MWh-scale storage suitable to offshore wind energy projects [51,104]. Electric heating and cooking are also more energy efficient, and electricity is also less expensive than green hydrogen (as will be discussed in a following chapter) [66]. Therefore, residential hydrogen use is likely only an interim measure and, as with other sectors, electrification will likely be preferred where possible. This finding is also supported by those from the stakeholder survey: 62% of respondents rated the near-term market in displacing natural gas for home heating opportunity as small.

Injection into the larger transmission network is also being explored as a cost-effective option for long-distance transport of green hydrogen. A consortium of gas network owners and operators have proposed to create a hydrogen network of 39,700km

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[22] Based on estimates received through correspondence with the Department of Agriculture, Food, and the Marine.

[23] The hydrogen requirements vary by fertiliser type but an average of 30% of the mass of nitrogen was assumed as the hydrogen mass required, based on the following equation: $N_2 + 3H_2 = 2NH_3$.

[24] Assuming annual capacity factor of 0.8, MW required to produced predicted shortage across the year.

[25] Oxygen demand taken from [164] and effluent created per person from [165].

[26] Assuming zero carbon hydrogen production and equal usage efficiency.

[27] The gas grid is roughly divided into the transmission (high flow rates/pressure linking large towns and end users) and distribution (branches that service smaller more diverse users) networks.more diverse users) networks [167].

by 2040, 69% of which would comprise repurposed natural gas grid [106,107]. Retrofitting existing natural gas generation to run on blended or 100% hydrogen may yet prove to be an important part of the electricity system, providing both generation and inertia in a system increasingly reliant on VRG and inverter-based resources [32].

However, such a project would likely require a wind farm and power plant entering into partnership backed by the appropriate infrastructure (dedicated hydrogen pipeline), market structures (mass balance movement of hydrogen through the gas grid, profitable electricity grid services provision) and/or incentives [103]. Replacing just 20% of Ireland's natural gas demand (in energy terms) with green hydrogen would require 4,200MW of dedicated wind energy capacity.

2.4 Energy Storage and Curtailment Mitigation

What causes curtailment?

The total installed capacity of variable renewable generation (VRG) in Ireland is set to be as high as 16GW by 2030 [14,23]. With demand expected to peak at less than 9GW and average between 5.3 and 6.3GW [19], there will clearly be times when supply exceeds demand. The system non-synchronous penetration (SNSP) limit is a system-wide measure of how much non-synchronous VRG and inverter-based generation can be accommodated instantaneously, including import and export capacity [108]. The limit currently stands at 75% and plans are in place to increase this to 90% by 2030 [23,109]. Even with this increased SNSP limit, however, Ireland will see a rise in energy that cannot be accommodated on the grid, known as curtailment [110], and times when there is insufficient grid capacity to move the energy around, known as constraint [25]. For ease, this report will collectively refer to these concepts as curtailment[28].

Increased interconnection and storage will allow for a greater share of VRG by effectively increasing demand. Demand side management (DSM) operates in a similar manner by increasing and decreasing consumption to match renewable generation [31,111]. Still, market structures and system limitations mean VRG is prone to curtailment, and this will affect project risk and profitability [54]. Excessive curtailment can cause large fluctuations in, and further downward pressure on, spot market prices [112], meaning that VRG can receive less revenue when they produce most energy [39,50]. As such, mitigating curtailment is vital to ensuring the viability of both existing and future renewable energy projects [39].

When investigating the feasibility of achieving 70% renewable electricity by 2030, Baringa consultants developed and modelled a likely scenario for Ireland [27]. In this scenario, coal plants are shut down, peat generation is reduced by more than 50%, natural gas use is reduced by approximately 20%, which equates to a total reduction in dispatchable capacity[29] of over 3.5GW. At the same time, the total wind energy capacity is doubled to approximately 10GW and solar PV capacity is increased six-fold to 2.9GW.

This scenario predicts that, in order to compensate for this increase VRG and decrease in dispatchable fossil fuel generation, approximately 1.5GW of additional interconnection (export) capacity[30] will be required, resulting in a total of 2GW by 2030. A linear increase from 0GW in 2020 to 1.7GW by 2030 of battery storage is also assumed to be made operational. DSM is also included via heat pumps and BEVs to aid renewable integration [27].

Even with the proposed infrastructure improvements, a 90% SNSP limit, and a rise in demand of 6TWh (15%), there is still an estimated 7% curtailment in 2030 [27]. This figure is lower than the 11.4% observed in 2020 [18], but highly dependent on the development of the substantial infrastructure described above. It is also difficult for single models (computer-generated scenarios) to capture the variability and constraints of real-world operation [113] meaning that curtailment could well be higher than the 7% estimated. The CAP, which was released after the Baringa report, also includes more VRG than modelled in the

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[28] Eirgrid, for example, prefer to differentiate system stability (curtailment) from network capacity (constraint) issues and hence, use the term "Dispatch-Down" when describing the total energy that could not be used.

[29] Generation that can be turned on and off, gas is by far the most flexible of the dispatchable fossil fuels, able to quickly ramp up and down to accommodate wind. Others are less flexible but provide substantial inertia.

[30] This includes the planned Greenlink (500MW) and Celtic (700MW) interconnectors, as well as an additional 250MW provided by either increasing the Moyle's export capacity or by increasing Greenlink to 750MW [27].

aforementioned scenario (16GW as compared to 13GW), which would be expected to increase curtailment should storage and demand not also increase [108].

The role of Electrolysis

Although some level of curtailment will remain even in an optimised system [110], transmission system operators (TSOs) aim to reduce curtailment [114]. By converting this excess electricity to pressurised hydrogen, electrolysis can act as high-capacity storage [51], and either supplement or offset the requirement for interconnection and more traditional storage methods [115]. By changing the energy vector, electrolysis also enables the decoupling of supply and demand, unlike electricity which requires that supply and demand be instantaneously matched. Using hydrogen in transport, for example, means that vehicle refuelling and VRG can occur at different times.

Several studies have shown that the presence of electrolysis both increases the feasibility [35,116] and reduces the overall cost of decarbonising the energy systems it connects [51,117,118], particularly when biofuel supply is limited [34]. The EU's hydrogen strategy also underlines the need for an integrated energy system in order to achieve climate neutrality by 2050 [57]. Whilst profitable business cases may be possible, they will require complex scenarios such as electricity balancing markets or government support through taxes or subsidies [103]. In the stakeholder survey, many respondents noted that green hydrogen can play a role in providing crucial energy storage, but opinions on the size of that role in the near term varied considerably.

Section 2: Summary Table

Role	Equivalent Offshore Wind Capacity
HGVs	1,400MW to displace diesel in the 25,000 largest vehicles
Aviation	4,200MW to produce 50% of aviation demand through FT synthesis
Shipping	1,200MW to produce 50% of shipping demand directly, 2,400MW if through FT synthesis
Fertiliser	780MW to produce hydrogen to satisfy national demand for nitrogen containing fertiliser
Natural Gas	4,200MW to displace 20% of current natural gas demand
Energy Storage/DSM	Green hydrogen can act as an effective storage medium, linking the electricity market to other sectors and competing with solutions like batteries, but with much more complex interactions. Ultimately the extent of this role will depend on there being sufficient demand for the hydrogen produced, such as in the sectors above.

3. Cost Drivers of Green Hydrogen

The cost of green hydrogen depends largely on the source of the electricity used to produce it. This chapter compares the Levelised Cost of Electricity (LCoE)[31] for onshore and offshore wind power, using figures obtained from the relevant scientific literature, and then considers the costs of both electrolysis and hydrogen storage. The chapter also examines the variation in LCoE over time, the potential for cost reduction of key system components and their likely effects on the Levelised Cost of Hydrogen (LCoH), and finally some economic principles which will determine how and where this green hydrogen will be produced.

3.1 Cost Drivers of Green Hydrogen

Figure 2 shows estimates of the LCoE of floating offshore wind energy (red), bottom-fixed offshore wind energy (green), and onshore wind energy (purple) over the period 2021-2050. These estimates are adapted from an expert elicitation study by Wiser et al. [60]. In 2020 they used an online self-administered survey to establish estimates of LCoE for 2025, 2035, and 2050. 140 experts were surveyed in total, 97 responded with respect to onshore wind, 71 with respect to bottom-fixed offshore wind, and 37 responded with respect to floating offshore wind. When considering cost reduction potential, only factors that would impact the industry as a whole were to be included [60]. Whilst an expert elicitation process is opinion based, it can be assumed that for each technology the upper limits incorporate lower capacity factors, greater capital costs, etc., while the lower limits are characterised by economies of scale, shorter commissioning periods, etc. [60,119]. Also shown in Figure 2 for reference are estimates from a DNV GL study [120].

The water depth and distance to shore are significant cost drivers for offshore wind power, because these can necessitate more complex designs and operations [121]. Logic would dictate that the most expensive sites will be developed later when costs have fallen or, at very least, that the most economical sites would be developed first.

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[31] LCoE and Levelised Cost of Hydrogen (LCoH) are metrics that discounts the lifetime costs and generation to give a cost per unit of hydrogen/electricity produced. It is the minimum sale price required for a project to breakeven [166].

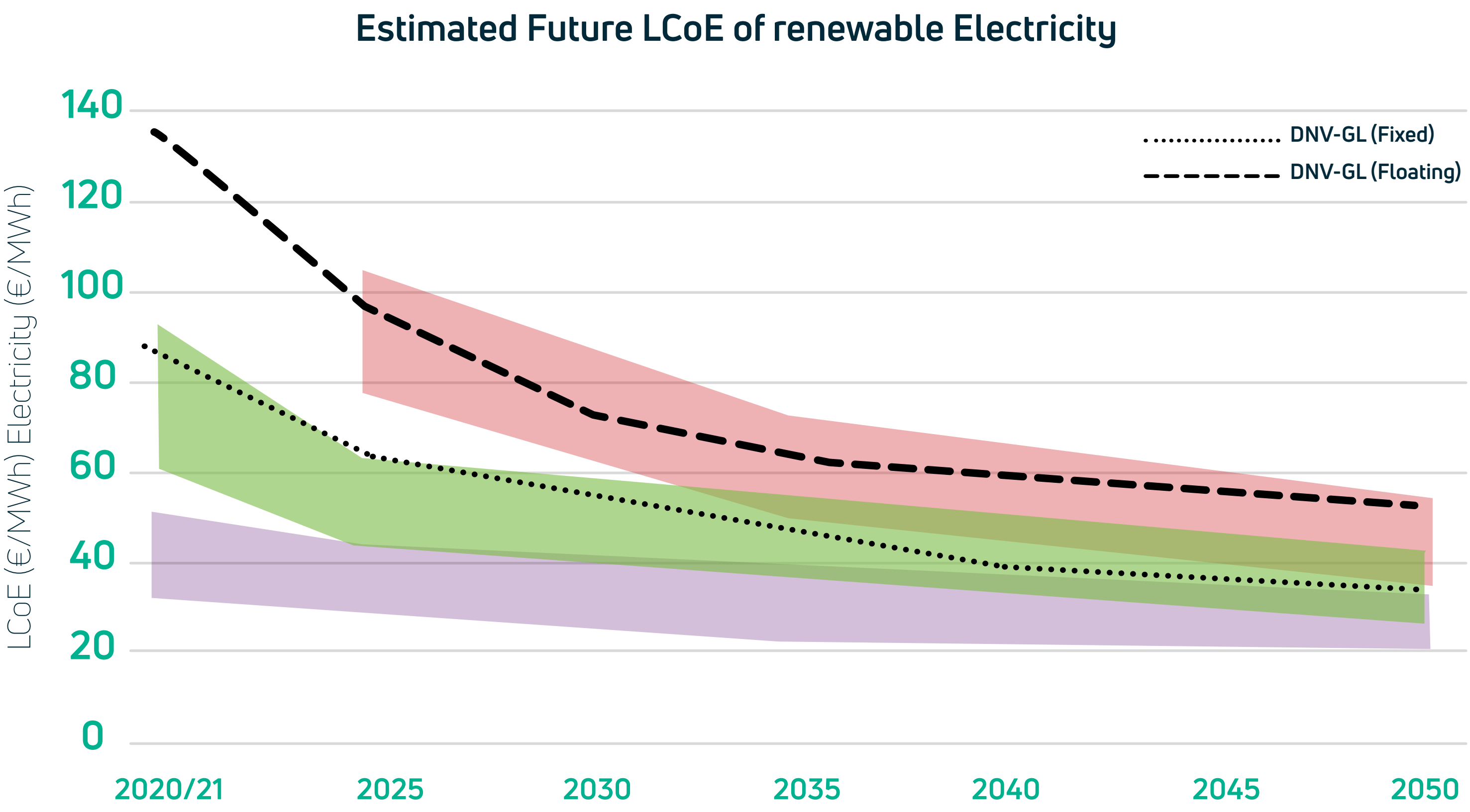

Figure 2: Levelised Cost of Electricity (LCoE) for floating (red) and bottom-fixed (green) offshore wind and onshore wind (purple) over the period 2021 – 2050. (Adapted from Wiser et al. [60].) DNV GL [120] estimates for bottom-fixed (long dash) and floating (short dash) offshore wind are also shown.

The cost estimates shown in Figure 2 incorporate a large degree of uncertainty, which is to be expected because the cost of a wind farm is highly site-specific and these technologies are still developing [20]. Figure 2 also shows that onshore wind (which has lower maintenance costs, greater accessibility, and more developed sites) is now, and will remain until 2050, less expensive in terms of LCoE than offshore wind. One source, the IEA, estimates that offshore wind will be less expensive than onshore wind by 2028 and achieve cost parity with solar PV by 2050[32], though this is considered ambitious and less applicable to Ireland [35]. Our research suggests that onshore will remain cheaper than offshore up to 2050.. Due to its limited grid capacity, current planning environment, and historical status as a technology importer, the costs of onshore wind farms in Ireland have typically been higher than average and this is expected to be the case also for offshore wind farms [122].

3.2 Component Costs

Figure 3 demonstrates the clear decline in the cost of major components of a green hydrogen production system. However, there remains significant potential to further reduce these costs through a number of technical innovations as explored in the sections below.

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[32] Estimates of Solar PV LCoE are not plotted because there is insufficient data available to produce these at the same level of accuracy in Figure 2.

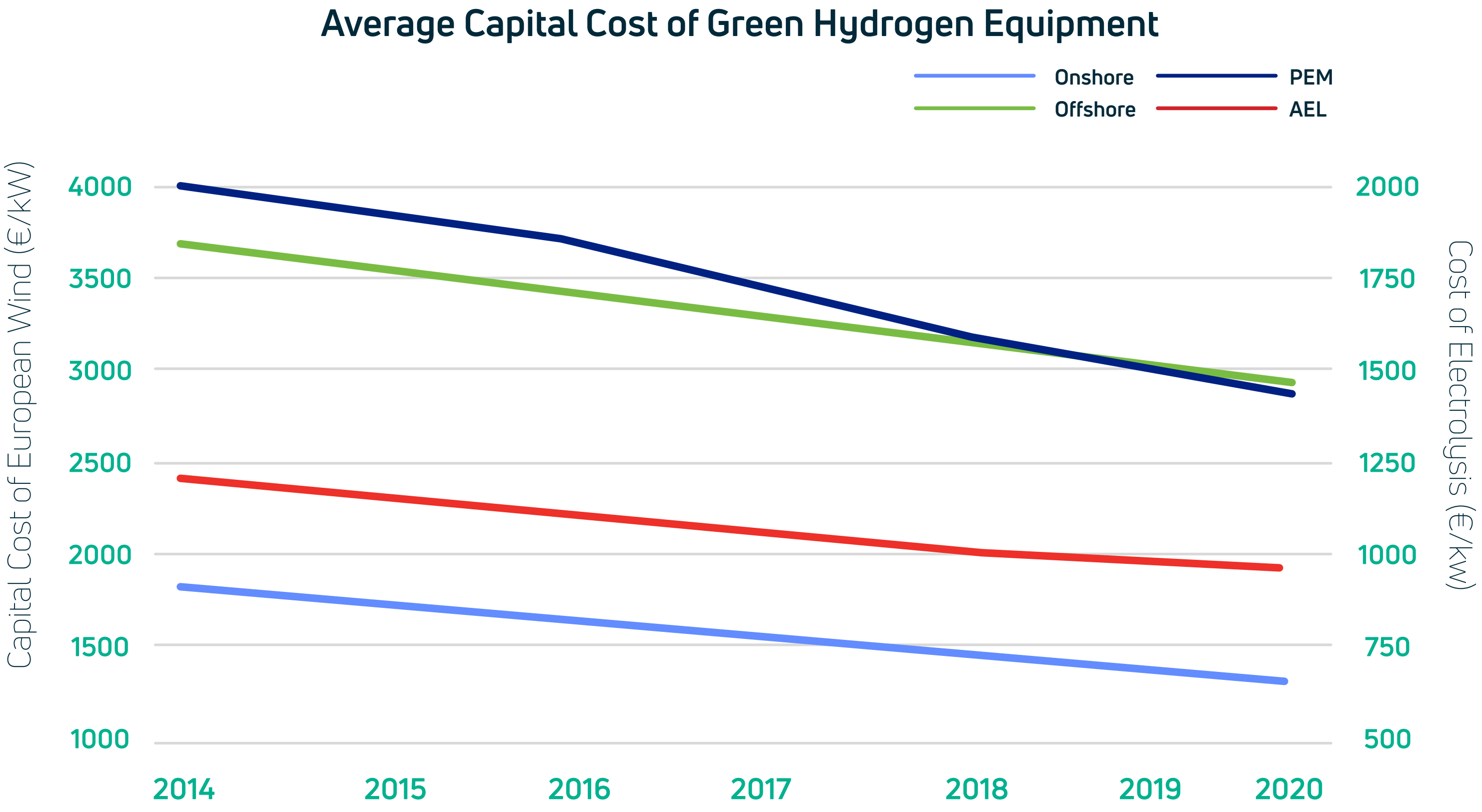

Figure 3: Average capital costs of European wind (left axis) and electrolysis (right axis), showing both have fallen substantially since 2014. Wind cost estimates are adapted from IRENA [20] and do not include floating wind, given the nascent state of the technology during the period examined. Electrolysis figures are adapted from Glenk et al. [59] and are divided into proton exchange membrane (PEM) and alkaline electrolyser (AEL), the two most mature options.

Offshore Wind Farm

Onshore wind remains the lowest cost wind technology, with costs having declined by 45% between 2010 and 2019, and a further decline of 25% expected between 2018 and 2030 [4]. Due to increased technological maturity and high levels of knowledge transfer from onshore wind, the costs of offshore wind have fallen more sharply than predicted in recent years: decreasing by 28-49% since 2014 [60]. Although the cost will continue to fall, further reductions are likely to be less dramatic [119]. Novel and optimised commissioning procedures, designs that require less maintenance, and general "learning by doing" benefits are expected to yield further reductions [20,60], but operational expenditure (OPEX) represents only ca. 20% of the lifetime cost of an offshore wind farm, so these innovations will have a limited effect on LCoE [123]. The capital expenditure (CAPEX), which involves the purchase of components and transmission assets, accounts for ca. 75% of the lifetime cost, with the remaining 5% spent on decommissioning [124].

Floating offshore wind is becoming increasingly viable as the costs continue to fall [64,125]. However, even with the significant contribution of floating platforms to the CAPEX, halving their cost of these components would produce a mere 5.3 - 12.4% reduction in the LCoE of floating wind farms [124]. This suggests that advances beyond cost reduction of the most expensive components are needed to impact the LCoE. Rather, the greatest cost reductions though will come from increasing the turbine size, the scale of the farm, and the ability to exploit the higher capacity factors often available at greater distances from shore [60,125]. Offshore wind farms offer such advantages and floating offshore wind, which allows access to deep water sites, further increases the potential for cost savings. An increase in energy production, via either more favourable conditions or decreased energy losses (turbine, wake, transmission) leads to a roughly equivalent decrease in LCoE: that is to say, a 2% gain in energy production, for instance, will reduce the LCoE by 2% [124].

The cost of financing is another important consideration: a 20% reduction in the discount rate[33] could result in a 14% LCoE reduction [124]. Familiarity with the technology, policy certainty, and increased investor participation should lead to more favourable financing terms [35,60]. Studies have shown that industry experts are anticipating that the LCoE of bottom-fixed offshore and floating wind farms will fall by 20% and 30% respectively by 2030, relative to current costs, and by 40% and 50% respectively by 2050. These studies did, however, also note that there was considerable uncertainty attached to these estimates [60].

Electrolysis

Electrolysis, including balance of plant, accounts for 15-50% of the cost of hydrogen production, and these costs vary primarily with the cost of electricity [35]. Depending on the configuration and whether the electrolysis is directly connected to the offshore wind farm, the installed capacity can be less than that of the wind farm, which provides an opportunity to optimise the scale of this expensive component (as will be discussed in greater detail in the next section) [54,59]. Like offshore wind, electrolysis has a seen sharp decline in cost over recent years and after much development, the technology is now mature enough to be deployed at scale [63].

Due to the size of the Irish market and its historical status as a technology importer, further cost reductions will depend largely on developments in other regions [49,126]. Whilst there are substantial plans for hydrogen and ambitious strategies developed in many regions, there remains a risk that such developments do not materialise to the extent anticipated.

Several factors have contributed to cost reductions for green hydrogen; IRENA has noted that a further 40% reduction in cost may be achievable by 2030 but this will require the aggressive pursuit of near-term decarbonisation goals [49]. Owing to varying maturities and working principles, cost reduction pathways vary considerably between different technology options. Generally, however, the key areas for innovation are improvements in catalyst utilisation, power densities, efficiencies, optimisation of balance of plant, and finding alternatives to expensive materials [49]. Greater automation and mass production would also drive down investment costs [63].

Achieving an 80% reduction in electrolyser costs by such means could lead to a ca. 40% drop in the levelised cost of hydrogen (LCoH) [49]. However, because the LCoH is highly dependent on the cost and availability of the electricity supply, generalised prices come with uncertainty. One study found that in an offshore wind-hydrogen system, reducing the cost of the hydrogen production system by 40% would lead to a ca. 15% drop in LCoH with all other variables fixed [54].

Competing technologies

Having been designed with flexibility in mind, proton exchange membrane (PEM) electrolysis offers excellent response times from a cold start, and is thus suitable to offering grid services [127,128]. At present, however, PEM involves high costs associated with the use of precious metals (iridium, platinum) as well as lower durability [49]. Alkaline electrolysers (AEL) are the most mature and least expensive option for electrolysis. These devices must be kept at operating temperature in order to be able to be offer grid services and are thus less flexible in general [127,128], though advancements are being made [127]. Solid oxide electrolysis (SOE) and anion exchange membrane (AEM) electrolysis techniques are still largely in development, though they promise reduced reliance on expensive materials (in the case of AEM) and the potential for reversible operation (in the case of SOE) [129].

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[33] In this report, the discount rate is used interchangeably with the weighted average cost of capital (WACC).

Though PEM can currently cost up to 60% more than AEL [49], there is no clear advantage to either option because small efficiency improvements have been shown to justify much greater capital costs over the project lifetime [82]. The choice comes down to: future development, availability, and, most significantly, whether the flexibility can be monetised [39]. Both technologies are somewhat modular and their efficiencies and costs show little scaling above 2MW, but PEM shows greater potential for further cost reduction due to its relative immaturity [49,130]. If electrolysis is to be performed at sea, PEM has a clear advantage because AEL requires a consumable KOH-solution [127,128] which would result in much higher maintenance costs.

Hydrogen Storage

Hydrogen storage remains expensive and minimising the requirement for storage can have a significant effect on the overall costs [131,132]. At scale, compressed hydrogen storage can cost €144,000 per MW of electrolysers for a day of hydrogen production, which means that a week's worth of storage for a 500MW wind farm would add €504M to the CAPEX for the project [54]. The volume of storage required depends primarily on the end use and if hydrogen can be supplied intermittently, storage is less of a concern [39]. When aiming to supply a relatively constant demand of hydrogen, extended periods of low wind would necessitate large buffers and increase projects costs [132]. The task of optimising the sizing of the electrolysers and hydrogen storage to maximise profitability is complex and project specific. However, adequate hydrogen storage would be an integral part of a functioning hydrogen economy.

Power Transmission

Where electricity is exported to shore via power cable, it can be imported into the electricity grid, used to produce hydrogen, or both [54]. Power cables are mature technology but still represent a significant expense because they usually require both offshore and onshore substations when 10km or more from shore [64,133]. The cables are also expensive, typically costing €970,000/GW.km [134]. Accordingly, transmission and inter-array cabling typically account for 20-30% of the CAPEX for an offshore wind farm [64].

The transmission of wind energy to shore using decentralised electrolysis and hydrogen pipelines is an area of active research [130]. In this case, a substantial share of the pipeline cost is offset by the fact that cabling is no longer required. Hydrogen pipelines could thus offer a more economical solution, but the choice of export method is sensitive to both component cost and distance to shore, as well as wider energy system considerations[34] [135,136]. Where pipelines are used, there will be no opportunity to choose between selling electricity or hydrogen, and a greater overall electrolyser battery system will be required to capture the energy [130] since the surplus cannot be exported to the electricity grid.

One study found that in the absence of confounding factors such as planning, logistical, technical, or environmental constraints, electrolysis should be performed onshore to maximise socio-economic benefits[35] [135]. Another study found that hydrogen pipelines offered the lowest cost solution only at distances greater than 740km [137]whilst a third concluded that hydrogen pipelines offered the best solution in general [136]. This difference of opinion demonstrates the sensitivity of the modelling study to the variables involved. In general, grid constraints and increased farm scale both favour pipelines, which means that this option should be considered as costs continue to fall and VRG penetration increases.

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[34] These can include electricity grid access, storage, VRG penetration, and hydrogen demand.

[35] The provision of grid services is the primary socio-economic benefit noted in the study.

3.3 Current Perspectives

Direct connection is preferable in terms of policy but not cost

To produce hydrogen which is truly green as per EU RED rules, the wind farm must be directly connected to the electrolysis plant, or the plant operators must provide evidence that the hydrogen has been produced without taking electricity from the grid [9]. This appears to give scope to build a hybrid system, one that can both sell to the grid and/or produce hydrogen. Studies also place particular emphasis on additionality[36], meaning there is a preference for green hydrogen to be produced using new generation capacity, rather than diverting existing capacity [9]. However, such a framework has not yet been established and there are calls for its delay [138]: given the nascent status of the industry, a strict clause for additionality may inadvertently stifle development.

Hydrogen offers a route to market where grid capacity is limited

Where grid congestion presents issues, an isolated hydrogen production system can allow an offshore wind farm to be developed where it may not otherwise have been permitted [135]. Producing hydrogen alone may also allow for a less volatile revenue stream (via purchase agreements and the elimination of constraint/curtailment). However, in the absence of very generous subsidies and/or high hydrogen prices, electricity production remains more profitable [54].

It is preferable to convert "low-value" electricity to hydrogen

An electrolysis plant which relies solely on otherwise curtailed electricity is unlikely to be economically viable due to its low capacity factor, even if the electricity is considered to be free[37] [139]. Effectively capturing curtailment is difficult as it is temporally diverse [110] with diminishing returns in terms of capacity factor as the installed capacity of electrolysers increases [140]. Systems which can utilise both curtailed and dedicated electricity production are thus more attractive because they can participate in both the electricity and hydrogen markets [50]. In essence, the market value of hydrogen provides a new minimum price which a wind farm may be willing to accept for their electricity [54]. Electricity which is expected to be valued at less than this minimum price can instead be converted to hydrogen, and revenue can be maximised by selling the energy as electricity when prices are high [54]. A system which can convert low-value[38] electricity to hydrogen becomes increasingly attractive as both anticipated curtailment and the market value of hydrogen increase [54].

The influence of curtailment

One study found that even at 8.5% curtailment, a level which is greater than that projected for Ireland in 2030 [27], ca. €4.5/kgH2 profit is required to match the net present value[39] (NPV) of an offshore wind farm selling electricity to the grid [54]. Even severe curtailment at 25% does not necessarily make hydrogen an attractive prospect. Even at this level of curtailment, €4/kg profit is still needed to match the NPV of the electricity-producing wind farm [54]. Addressing the curtailment issue, then, may be preferable to investment in electrolysis in terms of profitability [141]. In order to increase the NPV, the net cost of hydrogen production must be less than the potential loss in revenue due to curtailment, and such a situation would currently require high hydrogen prices. This must be addressed through policy.

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[36] The increased demand for electricity to produce green hydrogen should be supplied by new or additional capacity so as not to increase demand for conventional (fossil fuel) generation.

[37] As curtailment increases this begins to change, although it is true in most cases.

[38] This includes, but is not limited to, electricity that would otherwise be curtailed.

[39] The difference between the discounted income and expenditure over the project lifetime.

Optimal electrolyser investment depends on hydrogen demand

When fixed and variable costs are known with a degree of certainty, the installed capacity of electrolysis that produces the lowest LCoH can be calculated [59]. However, the attractiveness of producing hydrogen depends on the market value [54], and production will require prices greater than those secured from electricity sales. The highest profit will be gained by building sufficient electrolyser capacity to satisfy this demand. The optimal electrolyser capacity is therefore a function of market size and not based on minimising any potential losses due to suppressed electricity prices or curtailment. Hence, the establishment of demand for hydrogen which allows for longer run hours (electrolysis capacity factor) will be the key to the market success of electrolysis.

Section 3: Summary Table

LCoE	Onshore wind is expected to remain less expensive than both bottom-fixed and floating offshore wind, with competitiveness reached ca. 2035 and 2040, respectively.
Offshore wind cost reductions	The cost of offshore wind will continue to fall due to a combination of technology improvements, but mainly due to increasing turbine size and farm scale.
Electrolysis cost reductions	Continued cost developments are dependent on a rapid and substantial rollout of green hydrogen, but could result in a 40% cost reduction by 2030.
Configurations	Policy (direct connection, additionality) may have a greater influence on where electrolysis will be built and how it will be connected than economics.
Principles	Curtailment increases the attractiveness of green hydrogen to a much lesser extent than may be expected. Rather, generating demand is key.

4. Green hydrogen and wind power

The needs to decarbonise energy systems and address the climate crisis are the main drivers behind the current interest in green hydrogen technology [39]. While the aim is to have these low-carbon energy solutions replace fossil fuels, rather than outcompete them, the associated costs must also be considered. In this chapter, a simple model is used to calculate the levelised cost of hydrogen (LCoH) produced by both onshore and offshore wind, and track the competitiveness of the proposed solutions as compared to both blue hydrogen and fossil fuels. The conclusions of the study are then used to construct an argument for the incentivisation of green hydrogen technology in Ireland.

4.1 Hydrogen cost model

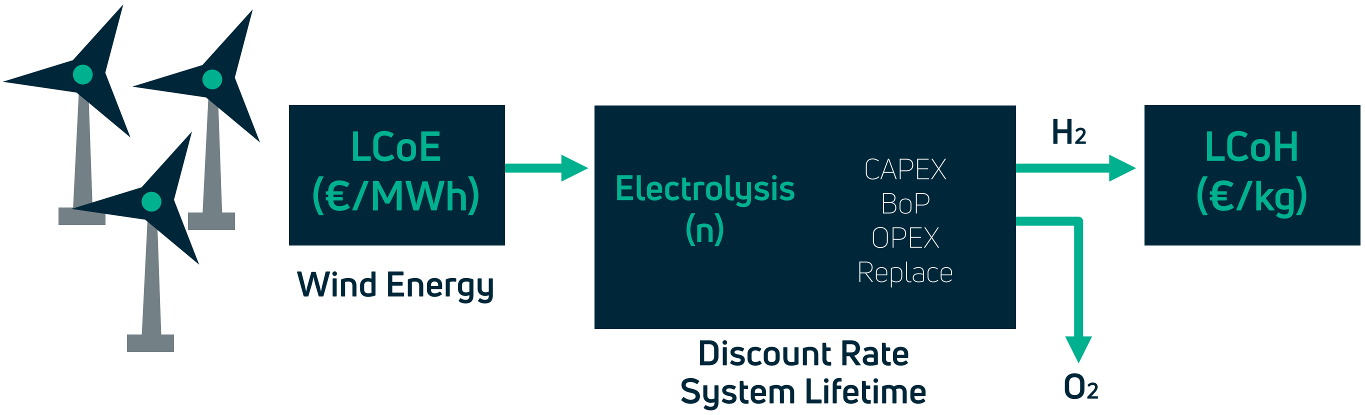

Figure 4: Idealised Levelised Cost of Hydrogen (LCoH) model.

An idealised cost model, described in Figure 4, is used to compare the cost of hydrogen produced using different energy sources with fossil fuel alternatives. This model assumes that the hydrogen is produced at 30-70bar [49], using an energy source with a rated power of at least 10MW[40] [82], and that all energy produced is converted to hydrogen. Depending on the application, additional costs will be incurred for compression, transport, and most significantly storage of the produced hydrogen, but these costs will depend primarily on the application. A complete list of the model parameters and associated assumptions is given in Appendix B, Table 2 and Table 3.

The oxygen produced could also be sold to reduce the LCoH, but at the scales envisaged the Irish market would quickly become saturated (see section 2.2) and so this additional revenue is not considered here [54]. In addition, the present model does not consider the revenue available from the provision of grid services, or the potential to use grid electricity to produce additional hydrogen, because these processes are dependent on the system configuration and thus not generally applicable. It is also worth noting that the model does not include the cost of converting hydrogen to a compatible fuel or the cost of retrofitting or upgrading equipment to run on hydrogen, although these will contribute significantly to the effective cost[41] [66].

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[40] Minimal additional economies of scale are typically noted for rated capacities greater than 10MW.

[41] Fischer-Tropsch (FT) synthesis, for instance, has an efficiency of ca. 60% and so hydrogen produced at €100/MWh (€3.94/kg) would produce a liquid fuel costing at least €166/MWh (€6.56/kg) [167].

Achieving the anticipated costs

Due to the nascent state of the technology, there are uncertainties associated with the costs of both electrolysis and offshore wind power. This uncertainty increases as assumptions extend further into the future [60]. It is clear, however, that the cost estimates obtained from the relevant scientific literature are dependent on the widespread adoption of these technologies, particularly in the period 2021-2030 [49,60]. As noted previously, the anticipated cost reductions will only be made possible due to projects which are commissioned in advance of cost competitiveness with fossil fuels.

4.2 Levelised cost of green hydrogen

Electricity consumption accounts for more than half (between 50% and 65%) of the cost of green hydrogen [35,82]. Excluding CAPEX, the minimum cost of hydrogen is given by the LCoE divided by the process efficiency[42]. Low-cost electricity is thus essential for a competitive LCoH [82]. Capacity factors are also critical because the LCoH depends on both LCoE and run time [50,139]. Electrolysers have high CAPEX which is expected to be recouped through the sale of hydrogen[43]: these high costs are undesirable and may lead to low demand for electrolysis. As such, each electrolyser must run at a high capacity factor in order to reduce the LCoH and thus the time required to recoup the initial investment [139].

It is also possible to pay more for electricity and produce a lower LCoH; this scenario is often desirable [50,139]. In high technological development and deployment scenarios, offshore wind, onshore wind, and solar PV are expected to have capacity factors of 51-59%, 29-31%, and 13-14%, respectively [35]. Depending on the configuration, then, offshore wind may have an advantage over competing VRGs.

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[42] For instance, at 70% electrolysis efficiency and €40/MWh for electricity, hydrogen would be expected to cost a minimum of €57/MWh, excluding the CAPEX of the hydrogen system.

[43] Additional incomes from subsidies, incentives, provision of grid services, and the sale of oxygen may also contribute.

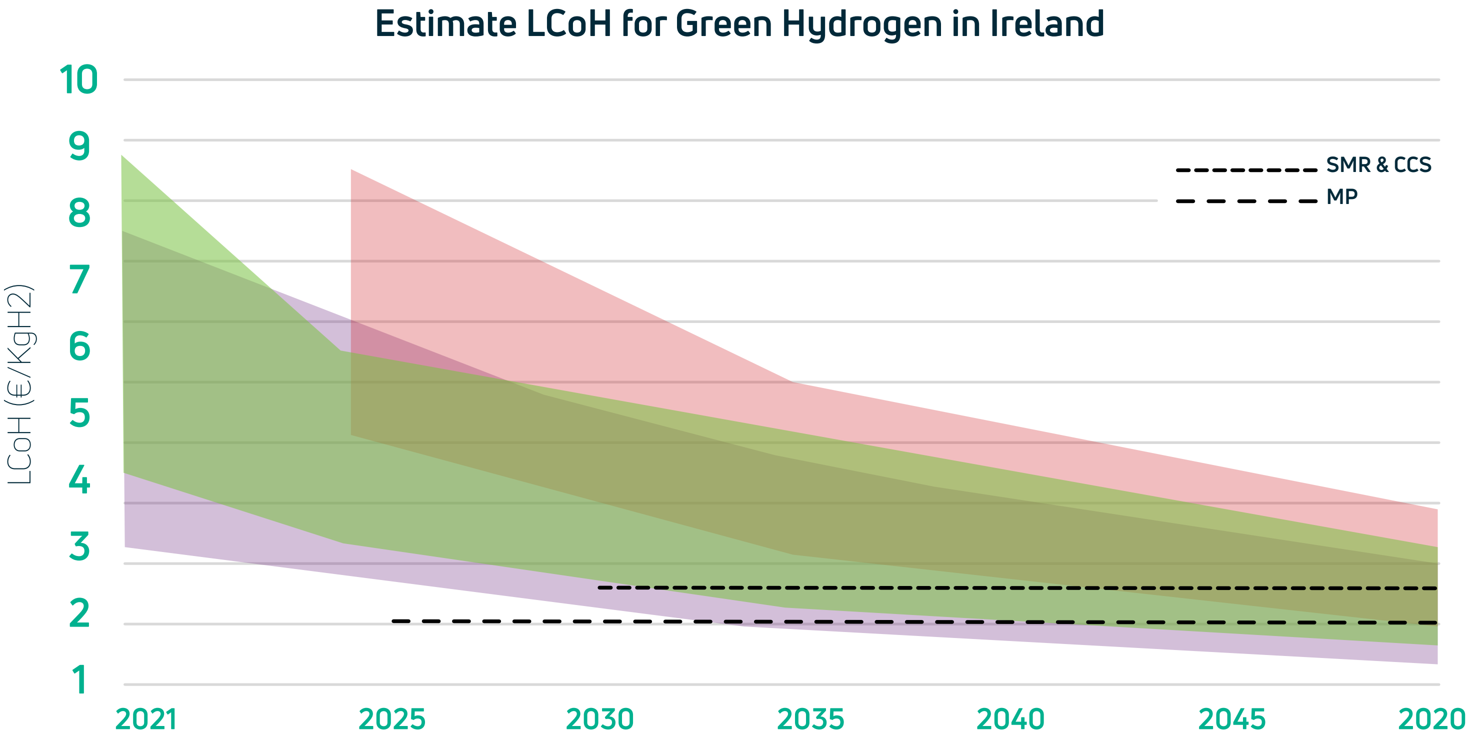

Figure 5: Levelised cost of hydrogen (LCoH) from dedicated floating offshore wind farms (red), bottom-fixed offshore wind farms (green), and onshore wind farms (purple) over the period 2021 – 2050. Upper and lower limits indicate a combination of the most and least favourable financing and technological parameters. The estimated LCoH from steam methane reforming (SMR) with carbon capture and storage (CCS)[44] (long dash) and from methane pyrolysis (MP)[45] (short dash) are also shown.

The cost estimates shown in Figure 5 are the same as those used to produce Figure 3 [60]. What we see in Figure 5 is that the greater capacity factor of both bottom-fixed and floating offshore wind cannot compensate for the higher LCoE, and produce hydrogen at a lower LCoH than onshore wind. Onshore wind is consistently the lowest cost due to its maturity and lower CAPEX. However, it also shows that LCoE alone cannot determine the suitability to hydrogen production or the anticipated LCoH. Floating offshore wind LCoE is more than double that of onshore wind in 2025, but due to increased capacity factors (see Appendix B) the difference in LCoH is just ca. 50%.

Competing with blue hydrogen is difficult

The cost of blue hydrogen from both steam methane reforming with carbon capture and storage (SMR & CCS) and methane pyrolysis (MP) is particularly sensitive to the cost of natural gas [45] but natural gas is still 3-4 times less expensive than electricity [46]. Pyrolysis also uses 3-5 times less electricity than electrolysis for the same amount of hydrogen produced [39]. This electricity can be obtained from renewable sources, but the potential viability and sustainability of blue hydrogen requires further investigation [49].

Natural gas is an openly traded commodity, for which the extraction costs are largely sunk, which means that the marginal cost of extraction is very low and, as such, price decreases can be used to maintain sales. In fact, North America has recently experienced negative prices for natural gas (in this case, a by-product of oil extraction [142]), and there has been prolonged flaring of natural gas worldwide [143]. If this natural gas could instead be used to produce hydrogen, the resulting product could contribute greatly to achieving the Paris agreement targets of many nations [143].

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[44] Costs for SMR & CCS are obtained from the IEA's "Future of Hydrogen" report [39] and converted into 2021 euros. Following Parkinson et. al (2017) [45], the natural gas price is estimated to be €10/MWh.

[45] A 30% premium is applied to the cost of hydrogen from MP with respect to SMR & CCS, in line with in the estimates provided by [45].

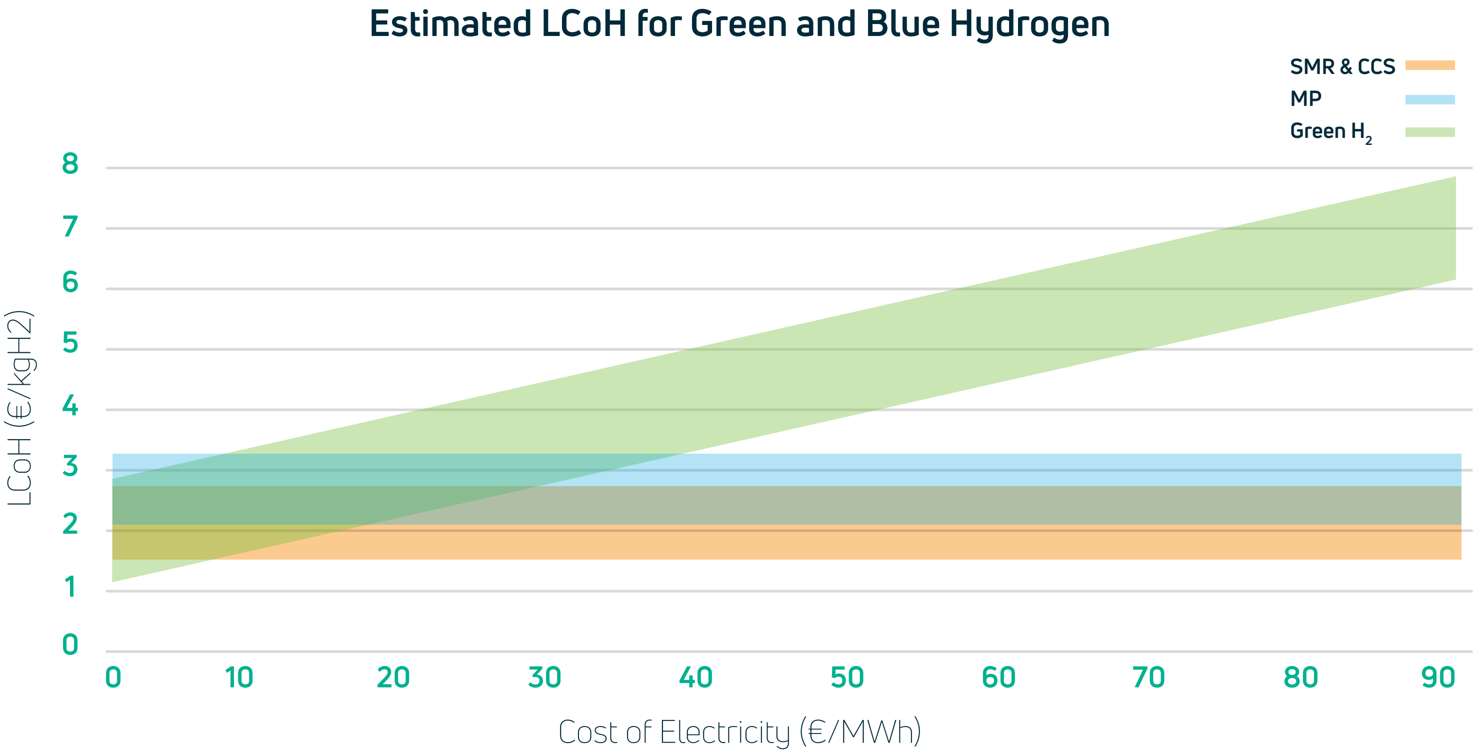

Figure 6: Variation in the cost of green hydrogen (varying capacity factor and electricity cost) with respect to the estimated cost of hydrogen from steam methane reforming with carbon capture and storage (SMR & CCS), and from methane pyrolysis (MP). See Appendix B for assumptions[46].

At present, the production cost of green hydrogen is estimated to be 2-3 times that of blue hydrogen [49]. Figure 6 shows that a combination of LCoEs (€10-40/MWh) and capacity factors (30-70%) would be required for green hydrogen to become cost-competitive with blue hydrogen. The required electricity prices are unlikely to be observed before 2050 (Figure 3). It is also worth noting, however, that the cost estimates used to produce Figure 6 do not include carbon or other taxes which may enhance the competitiveness of green hydrogen, depending on carbon dioxide capture and methane leakage rates.

Export potential

Hydrogen transport could become a key aspect of low-carbon energy systems, ensuring supply and competitiveness between different regions [39]. However, this transport will require multilateral cooperation and large investments in infrastructure, and despite Europe's favourable policies, the potential for producing hydrogen for export is likely to benefit regions with lower production costs [39].

Chile, for instance, has abundant solar resources in the north of the country, and abundant wind resources in the south of the country, with wind costs expected to reduce to €9-18/MWh in the future, targeting €1.3/kgH2 by 2030 [49]. Australia has also adopted standards and committed funding to its "H2 under 2" project, and has explicitly targeted the export market [49].

Closer to home, the Netherlands aims to take advantage of its existing port infrastructure for hydrogen transport, while Portugal will use its low-cost solar power (€12/MWh) to produce green hydrogen, and these countries have signed a memorandum of understanding to enable them to trade hydrogen with each other at a large scale [49].

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[46] To construct Figure 6 costs and other variables were fixed (see Appendix B, Table 4). Only the electricity source LCoE and capacity factor are varied to show at what levels they would allow green hydrogen to compete with blue hydrogen. This calculation is relatively independent of time, but the cost assumptions used are in line with estimates for ca. 2025-2035 depending on several factors.

The costs of production in Ireland are high, and unless they are lowered, it is unlikely emerge as a key player in the export market [122]. This is reflected in the findings of the stakeholder survey: only 42% of respondents rated the near-term market opportunity for hydrogen export as medium to large. More industrialised countries such as Germany have the conditions required to produce hydrogen at lower cost, as well as existing demand [49], policy support and financial incentives [39], and demonstration projects [144]. Germany has also signed a cooperation agreement with Morocco, which has extensive solar energy resources, to develop its green hydrogen production facilities [49]. In terms of hydrogen export, then, Ireland is at a competitive disadvantage compared to other countries, some of which are already actively targeting the international hydrogen market.

4.3 Competing with fossil fuels

In reality, the costs of green hydrogen cannot be compared directly with those of fossil fuels because the negative externalities associated with conventional generation (pollution, climate change) are not effectively captured in the price. For the development of green hydrogen, however, it is crucial that these cost benchmarking studies be undertaken. This section compares the LCoH figures above to the average cost of the most common fossil fuels in haulage (diesel), aviation (kerosene), maritime shipping (fuel oil), and industrial energy applications (natural gas) industries, excluding VAT [46] incentives required to displace fossil fuels depend largely on the application. This report considers only the direct use of hydrogen as fuel.

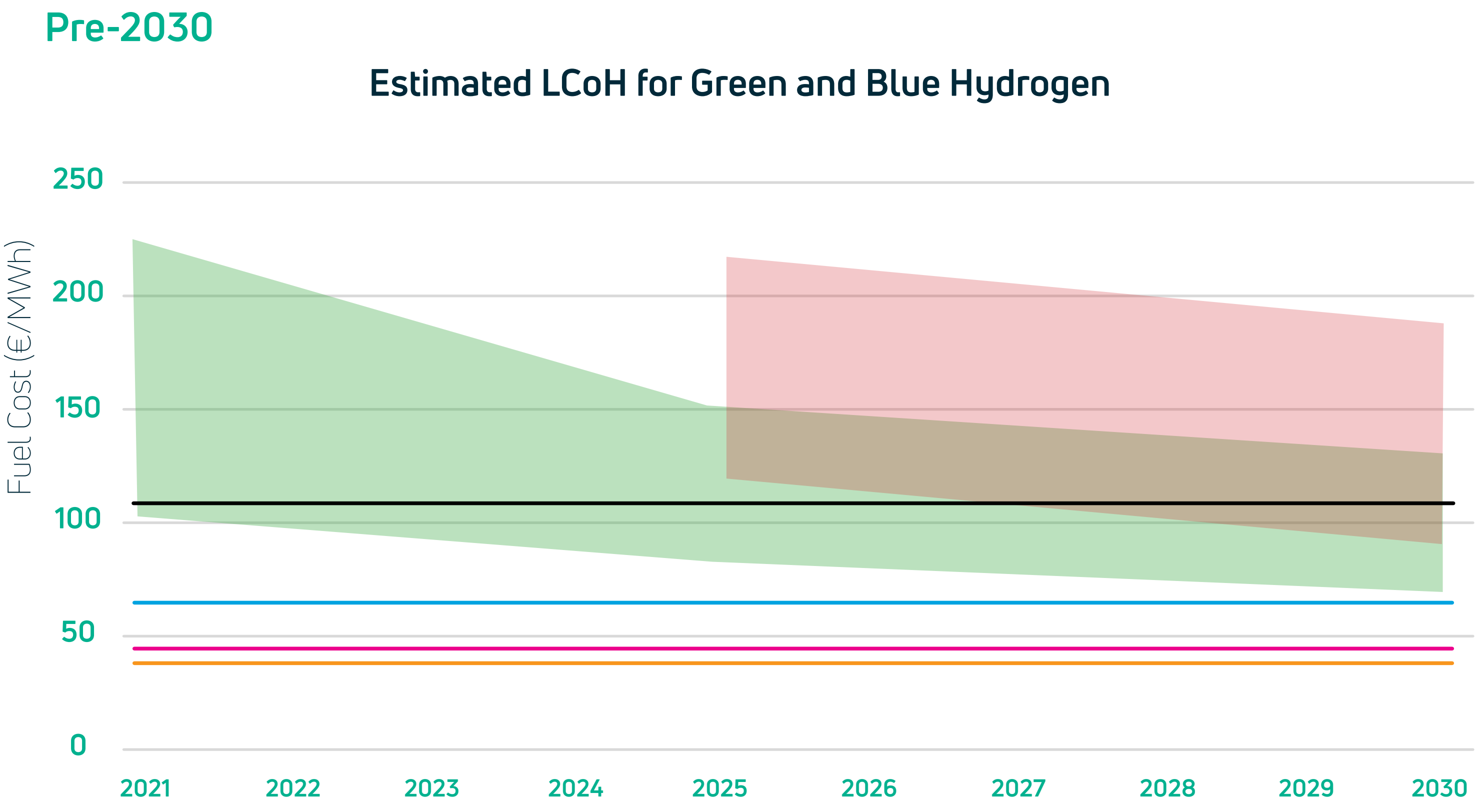

Figure 7: Cost of green hydrogen produced by floating (red) and bottom-fixed offshore wind farms (green) compared to the costs of diesel (black), kerosene (blue), fuel oil (brown), and natural gas (orange) for the period 2021-2030. All cost figures are exclusive of VAT but include duties; the production of green hydrogen is assumed to be exempt from duties and taxes.

Figure 7 clearly demonstrates that, before 2030, green hydrogen will only be cost-competitive in the haulage sector, and this is due to the significant duties applied to diesel [145]. The average price difference between green hydrogen and diesel is €116/MWh in 2021, but this will reduce to just €23/MWh in 2030. Although the greater efficiency of fuel cell vehicles can compensate for the ca. 30% higher fuel costs[47], this does not consider the cost of vehicles and associated infrastructure required to replace fossil fuels with hydrogen fuels [66]. The competitiveness of haulage would still depend on the vehicle purchase subsidies and roll-out of associated infrastructure [40].

In the marine sector, the average price difference between green hydrogen and fuel oil is €179/MWh in 2021, and this reduces to €86/MWh in 2030. For kerosene (jet fuel), the cost difference is €165/MWh in 2021 and €72/MWh in 2030. Although the reduction in hydrogen production costs represent great advances in a relatively short period of time, the remaining cost differences remain much greater than those typically targeted by incentive schemes [146].

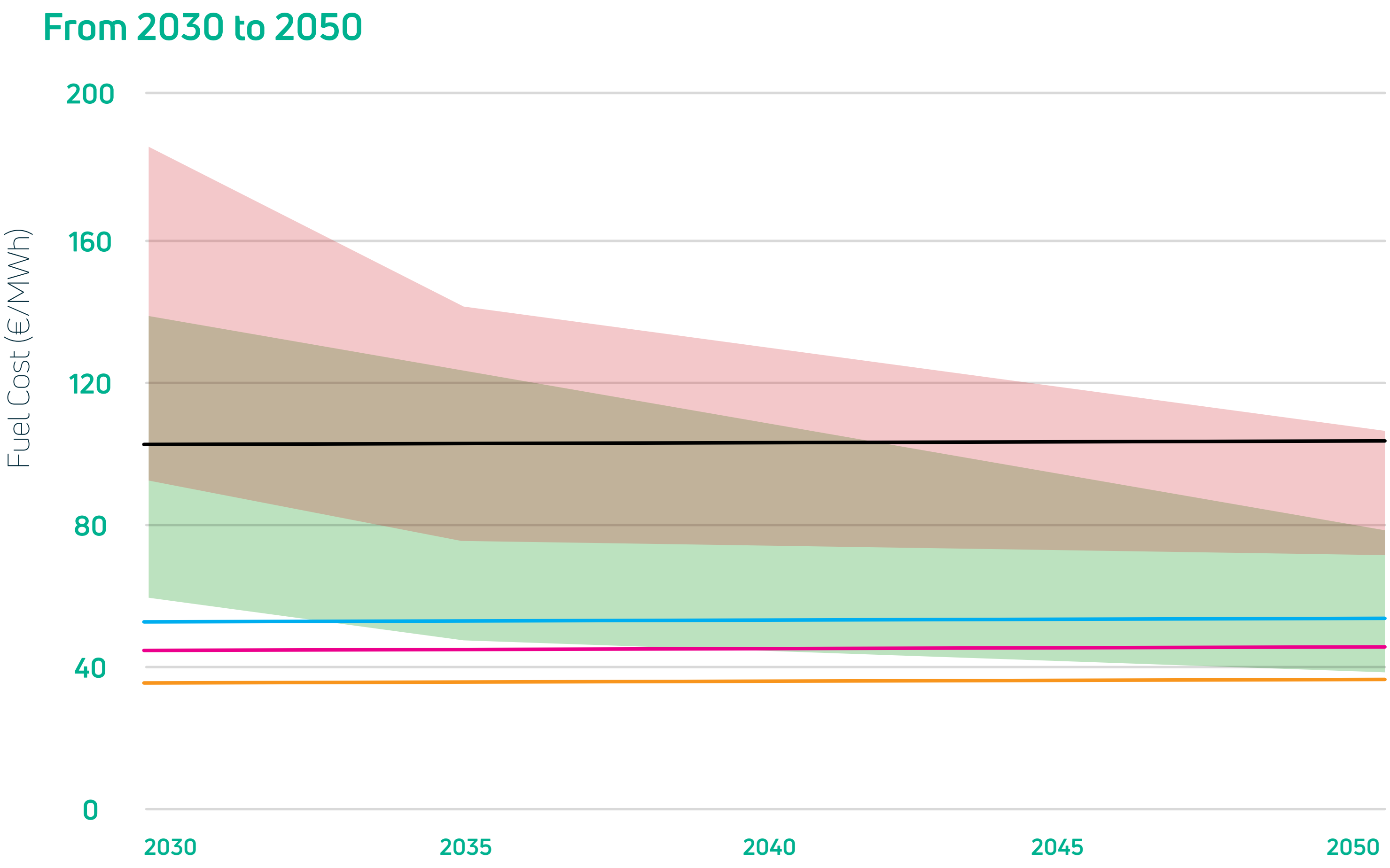

Figure 8: Cost of green hydrogen from floating (red) and bottom-fixed offshore wind farms (green) compared to the costs of diesel (black), kerosene (blue), fuel oil (brown), and natural gas (orange) for the period 2030-2050. All cost figures are exclusive of VAT but include duties; the production of green hydrogen is assumed to be exempt from duties and taxes.

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[47] The comparative efficiencies of the fuel cell (55%) and diesel engine (40%) [54] mean that diesel engines also require 30% more energy (fuel).

Figure 8 shows the corresponding cost comparison for the period 2030-2050, and demonstrates that green hydrogen from offshore wind becomes cost-competitive with fossil fuels, and less expensive in some sectors. This cost reduction is due to significant advances in electrolysis as well as considerable reductions in the LCoE of offshore wind. In this report, hydrogen is assumed to be exempt from taxes and duties, but one study found that even in the absence of incentives, liquified hydrogen is set to become competitive in marine shipping after 2030[48] [74]. Figure 8 also shows that green hydrogen will become cost-competitive in certain aviation applications after 2035, which aligns well with industry plans for the direct use of hydrogen [91,92].

4.4 The case for incentivisation

System-level benefits

Electrolysis systems provide not only alternative fuels which can be used in transport but, when connected to the electricity grid, can also provide flexible storage and thus reduce overall system costs [147]. When considered in isolation, green hydrogen is more expensive than battery storage, for instance, but the scalability of electrolysis, coupled with the need to decarbonise beyond the electricity sector provide justification for its inclusion [148]. This finding is also reflected in the stakeholder survey, with respondents highlighting a broad range of additional system benefits[49].

Energy security

Green hydrogen can allow for Ireland to meet a greater share of its energy requirements using indigenous renewables. This can reduce imports, increase energy security, and reduce reliance on complex and often sensitive supply chains [8]. By supporting the electricity system it also reduces the likelihood of oversupply from VRG (frequency and curtailment issues [32]), simultaneously providing a store of energy for times of undersupply [8]. Providing an alternative route to market for VRG also means that additional generation is likely to be built than would otherwise have been, further increasing supply.

Emissions reduction potential

Green hydrogen can also be used to decarbonise other sectors where alternatives are limited [66]. In addition, electrolysis has a technology readiness level which is more advanced than many competing low-carbon technologies [28]. As Ireland seeks deeper emissions reductions than ever before [13], green hydrogen offers the potential to use vast amounts of VRG to achieve emissions reductions in difficult to decarbonise sectors. There is also potential to create new industries, such as green fertiliser production.

Uncertainty among industry

Although green hydrogen has been identified as an essential part of the future low-carbon energy system, there remains much uncertainty as to when and where it will contribute. This, too, is reflected in the results of the stakeholder survey, which shows that respondents have not come to a clear consensus on the near-term use cases. Only DSM received broad support, with 65% of respondents rating the scale of the near-term market opportunity as medium to large.

However, if the industry is to develop the knowledge and gain the skills necessary to achieve its future targets, it is vital that green hydrogen development be incentivised now [35,49]. Targeted incentivisation could direct the industry in advance of hydrogen becoming cost-competitive, reducing the risk for the relevant stakeholders: this type of incentivisation was specifically requested in the survey responses. The international nature of shipping and aviation mean that although there is significant potential to decarbonise these sectors, the abilities of the Irish government to support these measures may be limited.

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[48] Assuming a carbon price of €61/tCO2. The CAP aims for a €100/tCO2 price by 2030 and €265/tCO2 by 2050 [14].

[49] Question 5 of Appendix A includes several survey responses that highlight the complex system benefits.

Resource availability

Ireland's winds are its most abundant renewable energy resource, and its large coastal area offers the opportunity to generate vast amounts of energy offshore [21]. Other low-carbon technologies, including biofuels (which have other sustainability issues, including competition with food [149]) and onshore wind (where there may be a lack of suitable sites and more stringent planning restrictions [122]), present difficulties in producing the quantities of energy required; by comparison, offshore wind has much greater potential to produce large amounts of green hydrogen [21]. This is particularly true in terms of land use [66]. Green hydrogen is also inherently sustainable compared to many competing solutions (limited sources of emissions) and provides a much-needed route to market for offshore wind beyond the electricity sector.

Job creation and talent needs

A sustainable and competitive hydrogen industry is an opportunity for Ireland to strengthen its economy and support future-proofed jobs. This finding, too, is reflected in the results of the stakeholder survey: 60% of respondents have already started hiring for hydrogen-specific roles. These stakeholders anticipate hiring across a range of skill levels and skill sets but have already noticed a gap in the available knowledge, training, or skills.

At EU level, green hydrogen could create up to 1 million direct, high-quality jobs by 2030 and up to 5.4 million such jobs by 2050 [150]. This works out to be ca. 10,300 jobs per €1 billion invested and includes jobs generated in the renewable electricity sector [151].

In Ireland, this would translate to between 80 and 600 new jobs in the green hydrogen industry by 2030, with a further 170 to 1200 indirectly related to the sector. These upper and lower limits correspond to electrolyser capacities of just 31MW to 290MW [152]. Therefore, installed capacities in line with those required to decarbonise current demand, as found in Section 2: Summary Table, would create substantially more jobs, ca. 10,000 if 5GW were installed[50]. These estimates are also supported by the results of the stakeholder survey, with respondents seeking to create, on average, 10 new jobs each.

However, Ireland is already experiencing a shortage of workers across the economy [153]. One of the hardest hits sectors is the Irish construction industry [154]. Our survey indicated that many of the potential hydrogen jobs will be in the technical/construction sector, meaning there will be increased competition with the housing construction sector for skilled labour. This is at a time when the new "Housing for all" plan states that up to 80,000 workers, or double today's numbers, are required to meet the new targets it has set, further straining the supply available to any potential hydrogen industry [155]. Therefore, the requirement for a large number of workers may provide a barrier to development. Reskilling of workers in the petroleum and peat industries [156] could play a critical rolei n addressing any potential shortages.

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[50] Assuming job creation scales linearly with installed capacity, and based on 600 workers per 290MW.

5 Discussion and conclusions

Achieving a net zero economy requires both whole system thinking and the linking up of previously disparate sectors. It will also require policymakers to recognise the ongoing climate emergency and move beyond traditional economic arguments [1,2]. Previously, solutions were compared on the basis of cost but going forward, these solutions should be compared in terms of sustainability. Ireland will not achieve its target of net zero carbon emissions by electrification alone [35] but, with the right policies in place, existing technologies such as electrolysis and wind power can contribute significantly to the achievement of this goal.

Why should Ireland be interested in green hydrogen?

The recent Intergovernmental Panel on Climate Change (IPCC) report includes stark warnings for the world to urgently reduce its GHG emissions [1]. As a developed country, Ireland must lead the way and implement economy-wide measures to hasten its transition to a carbon-neutral economy [3]. Much of the progress made to date has been in the renewable electricity sector [17] but the majority of the country's on-demand energy needs cannot be easily electrified [17,38]. Even with considerable advances in technology, sectors such as shipping, aviation, and heavy transport will continue to rely on energy-dense fuels [66]. Decarbonising industry also requires a switch away from fossil fuels to renewable options [35].

Hydrogen has emerged as the best available option for decarbonising these sectors. Blue hydrogen, which is produced using fossil fuel generation, is expected to soon become cost-competitive with existing fossil fuels [45,47], but the sustainability of the process remains questionable due to methane leakage [48] and residual carbon dioxide emissions [39]. Green hydrogen, which is produced by the electrolysis of water, has zero production emissions when renewable electricity is used. The key strengths of green hydrogen are its versatility and scalability; it can be used directly for energy or in place of fossil fuel feedstocks. By utilising indigenous renewable electricity, green hydrogen would also boost Ireland's economy and improve the country's energy security [13].

Though 2-3 times more expensive than blue hydrogen[51] [49], green hydrogen has many co-benefits such as acting as high-capacity energy storage, linking the transport and electricity sectors, and enabling wind and other variable renewables to generate large emissions reductions [35,39]. Delaying green hydrogen for the promise of sustainable blue hydrogen would be a high-risk strategy and inconsistent with EU policy [57]. It is also worth noting that green hydrogen would only represent part of a net zero energy system, and begin to play a greater role only as the decarbonisation targets and VRG penetration levels increase [52].

Is offshore wind a suitable electricity source?

Producing green hydrogen requires substantial amounts of renewable electricity, the cost of which dictates the cost of the resulting hydrogen. While surplus electricity might be available at times, the main share will have to be covered by dedicated sources [152]. In terms of levelised costs, onshore wind energy is cheaper than offshore wind energy [119], and thus could produce green hydrogen at lower cost [82]. Offshore wind energy will also face competition from grid-connected electrolysis and the increasingly competitive solar PV [50,119]. As such, traditional least-cost approaches to energy system planning will likely not result in the coupling of green hydrogen and offshore wind energy; rather, targeted policy will be required. However, there are significant advantages to this pairing [39].

Ireland has abundant offshore wind energy resources which could be used to produce vast quantities of green hydrogen. Further, green hydrogen could provide a route to market for offshore wind farms which may not otherwise be developed due to difficulties in accommodating the resulting electricity on the grid [19]. Green hydrogen would also enable emissions reductions

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[51] As outlined in this report, the cost difference depends on several factors, the most important of which is the timeline.

beyond the electricity sector without adding to the requirement for additional interconnection, storage, grid improvements, and curtailment [19,27]. This would be particularly advantageous, given the explicit support for such configurations in both the EU Hydrogen Strategy and Renewable Energy Directive [9,57]. Connecting renewable electricity such as that produced by offshore wind turbines to hydrogen production increases the rate at which the technologies can be rolled out and allows for greater levels of installed capacity [22]. Although their pairing is unlikely to emerge naturally, offshore wind appears well-suited to green hydrogen production, given the wider system benefits.

How much does green hydrogen from wind cost?

The idealised cost model, which included the most sensitive variables (electricity costs, capacity factor, electrolysis cost, discount rate, and others), showed that in 2030, green hydrogen can be produced by floating and bottom-fixed offshore, and onshore wind farms at costs of ca. €5.4/kg, €3.9/kg, and €3.6/kg, respectively. Achieving these costs requires the continued development of offshore wind turbines [130], substantial investments in electrolysis [49], as well as favourable financing conditions [35]. The effective cost of hydrogen is reduced when accounting for the avoided investments but remains relatively expensive. However, achieving the deep emissions reductions that green hydrogen can enable is invariably expensive when viewed in financial terms without considering the wider environmental and energy system benefits [35]. Waiting for the cost of green hydrogen to decrease in line with fossil fuels is incompatible with Ireland's current emissions reduction commitments, and this cost will only reduce if investments are made now.

Green hydrogen will only achieve lower production costs than blue hydrogen under the most favourable market conditions. The cost of fossil fuels, including taxes and duties, varies considerably between sectors but green hydrogen production is expected to be 2-3 times more expensive in 2030, and between 1 and 2 times more expensive in 2050. Additional costs will also be incurred for the shipping and storage of hydrogen. However, the current and projected prices of diesel, kerosene, natural gas, and others do not account for the costs of pollution and climate change [1,14]. Though a useful comparison, it is more appropriate to compare renewable energy solutions only to one another.

Green hydrogen provides a range of benefits, including emissions reduction, energy independence, and grid services: increased reliability and quality of the power supply [157]. A more holistic evaluation of the technologies suggests that there may be advantages to coupling green hydrogen and offshore wind energy [147]. Where electrification is not yet practical, green hydrogen is the best available solution in terms of sustainability, scalability, flexibility (to applications in difficult to decarbonise sectors), and ultimately cost. The present model estimates that by 2050, the cost of green hydrogen produced by floating and bottom-fixed offshore wind farms will reduce to €2.6/kg and €2.3/kg respectively.

Which policies are required to support the development of the industry?

Supportive hydrogen policies can be summarised as follows [39]:

- Establishing targets and/or long-term policy signals.
- Supporting demand creation.
- Mitigating investment risks.
- Promoting R&D, strategic demonstration projects and knowledge sharing.
- Harmonising standards, removing barriers.

If green hydrogen is to play a role in the decarbonisation of Ireland's energy system, it will have to do so from a standing start. At present, there is little demand for hydrogen in Ireland, and much inertia to overcome. Many plans that include hydrogen are aspirational without necessarily including a roadmap for delivery [58]. Policies and targets will thus be critical to the development of Ireland's green hydrogen industry [158].

Hydrogen should be supported as part of overall emissions reductions programmes in areas where direct electrification is impractical. This will start with recognising the available opportunity, establishing key policies, and building up the relevant skills. The stakeholder survey has shown that the respondents are already seeking collaborations and building capacity in advance of these policy signals. Respondents also noted a growing skills gap, and so hydrogen-specific training will also be required.

Technology-neutral policies such as those aiming to reduce the cost of renewable electricity through improved planning and licensing will be vital for green hydrogen to become cost-competitive, and should be prioritised [122]. Carbon taxes are another technology-neutral and important part of a comprehensive policy suite [159,160] but the taxes aligned with government targets [16] will not be sufficient to close the cost gap between hydrogen and fossil fuels [57]. The stakeholder survey showed strong support for these measures, but also showed that respondents expected their efficacy to be limited, emphasising the need for more targeted policy.

Hydrogen production subsidies received the strongest support (with 93% of respondents rating the potential effect as medium to large) but cost analysis shows that the levels required to achieve cost parity with fossil fuels would be impractical. When considering incentivisation, the external benefits should not be overlooked [157]: widespread use of hydrogen will be driven by policy and not economics. The range of incentives required would be expensive and complex and perhaps insufficient to encourage renewable energy developers to produce hydrogen rather than the more lucrative electricity [54]. The survey results show that obligations and mandates would be more effective at generating demand for hydrogen. Mandates also offer greater protection for producers against falling fossil fuel prices and provide assurance when investing [39,158].

If the market price of hydrogen becomes attractive, through a combination of incentives and demand, it is likely that the least expensive sources of renewable electricity will begin to produce hydrogen, because each actor will aim to maximise their individual profits. In the absence of strong policy or targeted incentives, the coupling of green hydrogen with offshore wind energy is unlikely to materialise, despite being preferable in terms of whole-system decarbonisation [130].

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Appendices

Appendix A: Results of stakeholder survey

As part of this report a survey of a wide selection of enterprises was conducted.

Survey respondents included a broad range of stakeholders and industry sectors

- Purpose of the survey?
- When do they expect staff to be hired? How many?

Q0: Who has responded?

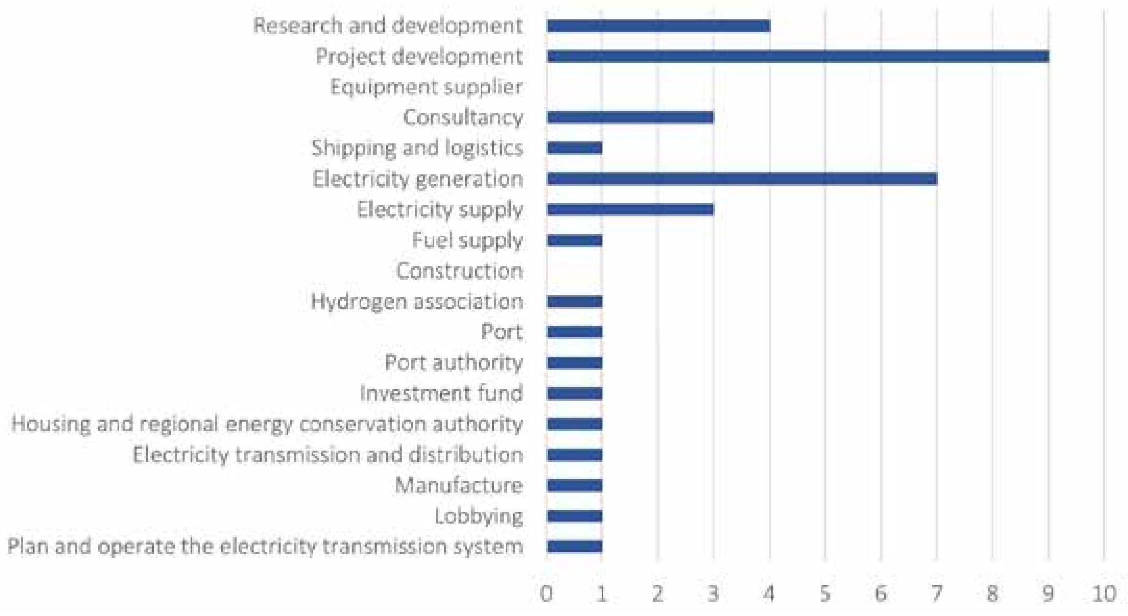
29 responses, from:

- Hydrogen Ireland
- Port of Galway (2)
- National University of Ireland, Galway
- Everoze Partners Ltd
- EDF Renewables
- Simply Blue Group (3)
- RWE AG
- Shannon Foynes Port Company
- NTR PLC
- Mullan Grid Consulting
- ESB (2)
- Parkwind
- Ulster University
- Northern Ireland Housing Initiative
- Mutual Energy
- Mercury Renewables
- Scottish Power
- NIE Networks
- Xodus Group
- Queen's University Belfast
- Ei-H2 Ltd
- DNV GL
- Electricity Association of Ireland
- Petroleum Infrastructure Program
- SONI Ltd

Q1. What is the principal activity of your enterprise? Please select all that apply.

29 responses:

- Research and development (4)
- Project developer (9)
- Equipment supplier (0)
- Consultancy (3)
- Shipping and logistics (1)
- Electricity generation (7)
- Electricity supply (3)
- Fuel supply (1)
- Construction (0)
- Electricity transmission and distribution (1)
- Housing and regional energy conservation authority (1)
- Plan and operate the electricity transmission system (1)
- Manufacture (1)
- Investment fund (1)
- Lobbying (1)
- Port (1)
- Port authority (1)
- Hydrogen association (1)



Q2. With respect to your enterprise's interest in hydrogen, in which of the following are you currently engaged? Please select all that apply.

29 responses:

- General internal research (15)
- Feasibility study for specific project (17)
- Detailed design for specific project (9)
- Project development/planning for specific project (13)
- Project construction (post-planning) (4)
- Collaboration with academia or training provider (17)
- Collaboration with industry partner (16)
- Engagement with a consultant (8)
- Building/hiring hydrogen expertise (12)
- Retraining staff (3)
- I'm not sure (0)
- Exploring opportunities to collaborate (1)
- Engagement with European H2 groups (1)
- Hydrogen association (1)

Q3. With respect to your enterprise's interest in hydrogen, in which of the following do you hope to be engaged in the next 5 years? Please select all that apply.

29 responses:

- General internal research (12)
- Feasibility study for specific project (17)
- Detailed design for specific project (18)
- Project development/planning for specific project (20)
- Project construction (post-planning) (16)
- Collaboration with academia or training provider (17)
- Collaboration with industry partner (21)
- Engagement with a consultant (13)
- Building/hiring hydrogen expertise (16)
- Retraining staff (4)
- I'm not sure (1)

Q4. For which of the following sectors do you see a definite role for hydrogen before 2030? Please select all that apply and indicate the size of the market. For example, if you select "Large" for "Electricity generation" this would indicate that you feel that this market will be a significant customer for producers of hydrogen.

Electricity generation:
  - small (7)
  - small to medium (9)
  - medium (6)
  - medium to large (2)
  - large (3)

- Natural gas grid injection:
  - small (7)
  - small to medium (7)
  - medium (6)
  - medium to large (5)
  - large (3)

- Industrial feedstock:
  - small (4)
  - small to medium (6)
  - medium (7)
  - medium to large (5)
  - large (5)

- Domestic heating:
  - small (16)
  - small to medium (3)
  - medium (4)
  - medium to large (3)
  - large (0)

- Industrial heat:
  - small (3)
  - small to medium (11)
  - medium (4)
  - medium to large (7)
  - large (2)

- Demand side management:
  - small (7)
  - small to medium (2)
  - medium (13)
  - medium to large (3)
  - large (0)

- Passenger cars:
  - small (22)
  - small to medium (2)
  - medium (2)
  - medium to large (1)
  - large (0)

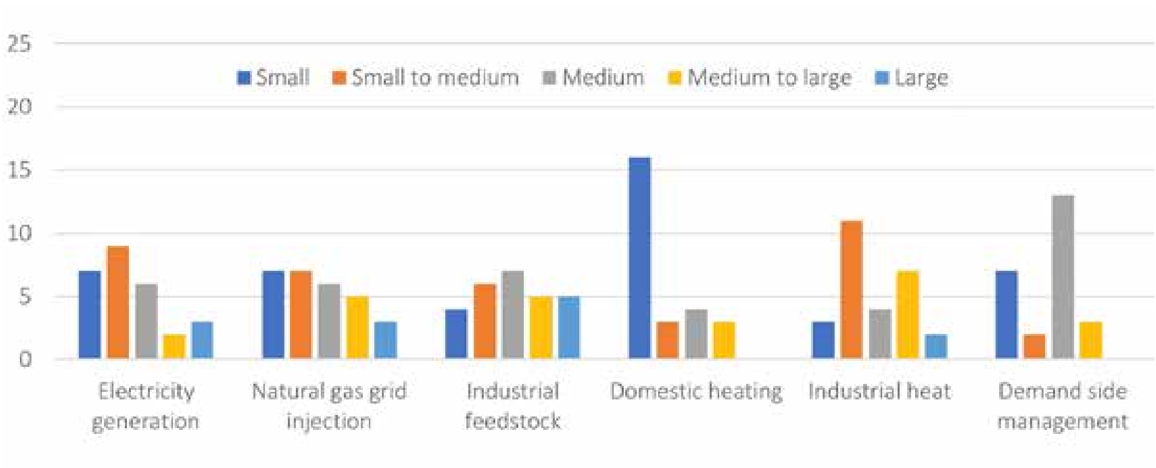
- Heavy duty vehicles:
  - small (1)
  - small to medium (6)
  - medium (10)
  - medium to large (7)
  - large (3)

- Synthetic shipping fuels:
  - small (3)
  - small to medium (6)
  - medium (7)
  - medium to large (6)
  - large (5)

- Synthetic aviation fuels:
  - small (8)
  - small to medium (6)
  - medium (4)
  - medium to large (6)
  - large (3)

- Data centres:
  - small (11)
  - small to medium (9)
  - medium (3)
  - medium to large (3)
  - large (1)

- Export:
  - small (8)
  - small to medium (6)
  - medium (3)
  - medium to large (4)
  - large (4)


25
20
15
10
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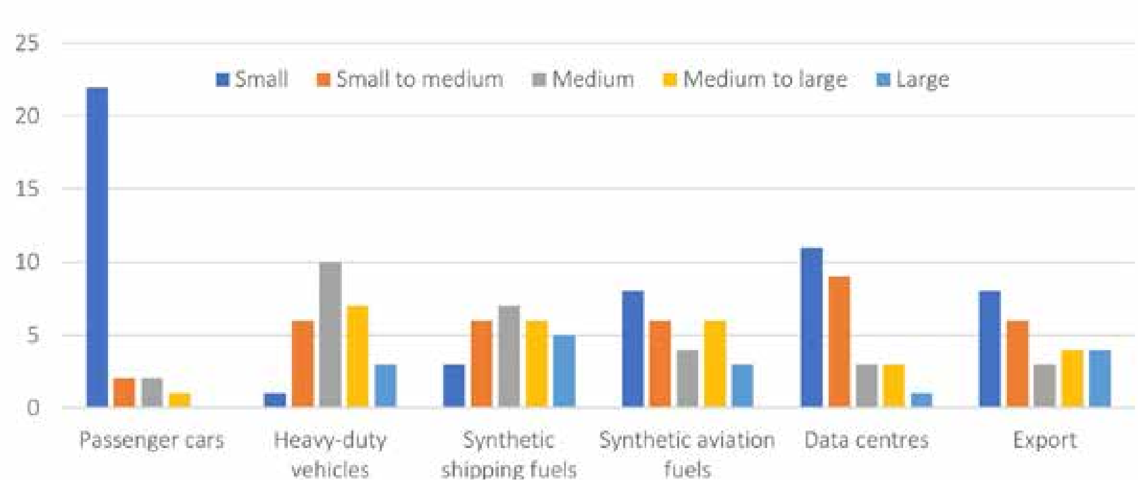
0
Small
Small to medium
Medium
Medium to large
Large
Electricity generation
Natural gas grid injection
Industrial feedstock
Domestic heating
Industrial heat
Demand side management


25
20
15
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5
0
Small
Small to medium
Medium
Medium to large
Large
Passenger cars
Heavy-duty vehicles
Synthetic shipping fuels
Synthetic aviation fuels
Data centres
Export

Q5. Are there any important market opportunities not captured by the previous question? Please specify.

11 responses:

- District heating linked to waste heat from H2 electrolysers and fuel cells
- The above are all potential opportunities for NI. We have answered for 2030-2035 but the potential picture for the 2040s will be very different.
- Electricity storage
- No
- Renewable energy storage
- Industrial processes
- As this is "before 2030" - the demand will be relatively low across above sectors but this will change by 2040. For Ireland, Hydrogen will be used for long term storage and electricity generation/DSM when required. Limited existing demand for industrial feedstock in Ireland but it will have a demand for H2. Aviation fuels more likely than Shipping as e-kero is a drop in fuel and does not require new engines. Likely cement/[Aluminium] industry will turn to H2 but likely to be competition from electrification.

- The potential for hydrogen to provide a source of dispatchable electricity generation should be explored as a means of decarbonising the power system whilst maintaining an adequate supply and demand balance. In particular, this policy approach is targeting a section of the electricity system which is currently supplied by conventional generation via fossil fuels, to ensure an effective transition to a net zero electricity system. Power-to-hydrogen technologies present opportunities to optimise the use of renewable electricity generation. The use of such technologies in Northern Ireland should be explored further including the potential benefits in relation to minimising dispatch down and use of hydrogen produced to decarbonise other sectors, such as transport. SONI is currently developing a new innovation & research strategy. This will focus on a number of big bet areas which we believe we need to explore over the coming years. As a part of this process we will develop a roadmap for exploring hydrogen as part of the energy system.

  SONI is also collaborating with NIE Networks on the Energia Hydrogen Trial. Powerto- hydrogen technologies present innovative opportunities to optimise the use of renewableelectricity generation. The use of such technologies in Northern Ireland should be explored further including the potential benefits in relation to minimising dispatch down (curtailment or constraint) and use of hydrogen produced to decarbonise other sectors, such as heat and transport. An excellent example of this potential is the hydrogen demonstration project at Long Mountain wind farm whereby installing an electrolyser behind the connection point means excess wind energy that would normally be wasted when dispatched down can instead be used to produce green hydrogen. This presents an excellent opportunity to utilise wind energy that would otherwise go unused, with the hydrogen produced being used to power a fleet of new double-decker hydrogen buses being locally manufactured by WrightBus. Further information can be found at https://www.energiagroup.com/renewables/long-mountainwindfarm/

  As demonstrated by the collaboration between Long Mountain and WrightBus, future hydrogen strategy in the coming years must focus not only on developing new uses and methods of generating hydrogen in Northern Ireland, but also in developing and supporting new markets and demand for hydrogen locally to ensure there is long term sustainability and viability. Please see SONI's consultation "Shaping Our Electricity Future" (https://consult.soni.ltd.uk/consultation/public-consultation-shaping-our-electricity-future) and the Tomorrow Energy Scenarios Northern Ireland paper (https://www.soni.ltd.uk/newsroom/press-releases/tesni-2020/) which provides further evidence to the above.

  - Medium sized fleet vehicles such as vans (An Post/ESB/AGC) etc.
  - Hydrogen for export

Q6. What policies do you feel will provide the greatest benefit to the Irish hydrogen industry? Please select all that apply and provide the anticipated impact.

Increased carbon tax:
o small (2)
o small to medium (3)
o medium (4)
o medium to large (8)
o large (11)

Renewable gas obligation:
o small (2)
o small to medium (3)
o medium (4)
o medium to large (12)
o large (6)

Hydrogen production subsidy:
o small (1)
o small to medium (1)
o medium (2)
o medium to large (4)
o large (20)

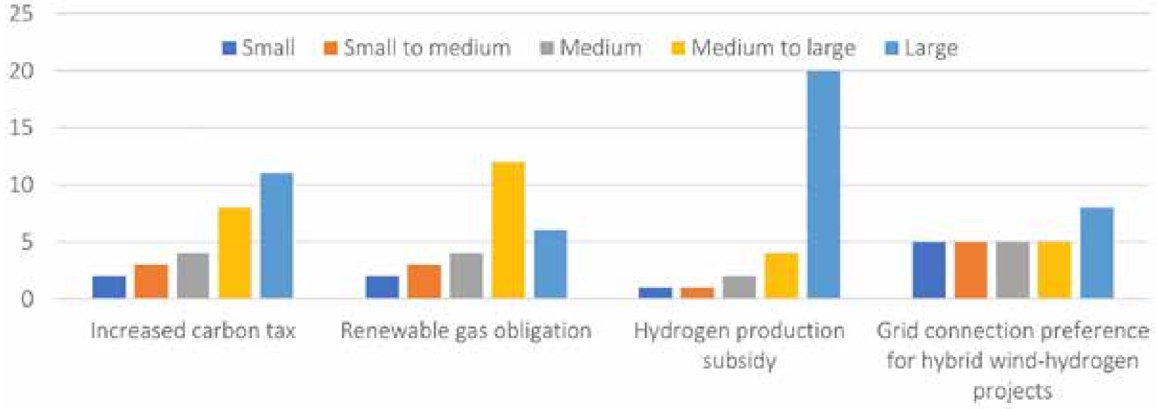
Grid connection preference for hybrid wind-hydrogen projects:
o small (5)
o small to medium (5)
o medium (5)
o medium to large (5)
o large (8)

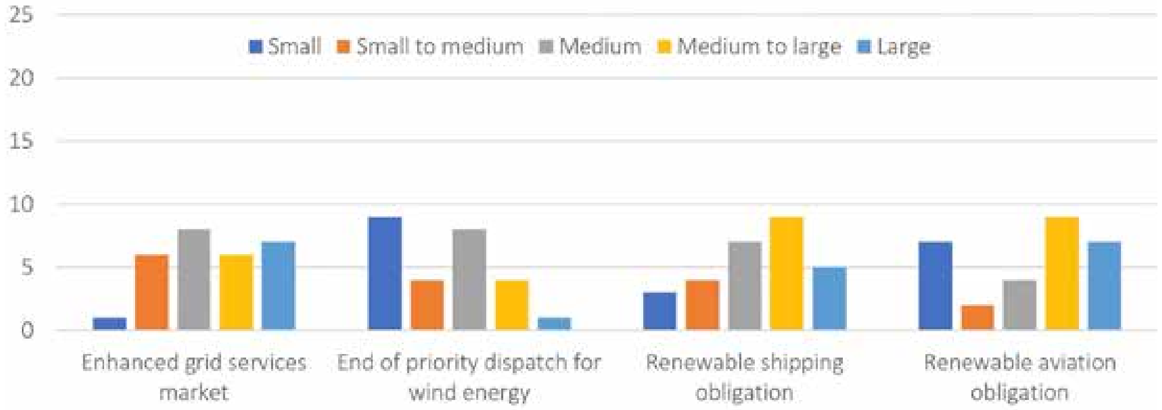
Enhanced grid services market:
o small (1)
o small to medium (6)
o medium (8)
o medium to large (6)
o large (7)

End of priority dispatch for wind energy:
o small (9)
o small to medium (4)
o medium (8)
o medium to large (4)
o large (1)

Renewable shipping obligation:
o small (3)
o small to medium (4)
o medium (7)
o medium to large (9)
o large (5)

Renewable aviation obligation:
o small (7)
o small to medium (2)
o medium (4)
o medium to large (9)
o large (7)





Q7. Are there any important policy mechanisms not captured by the previous question? Please specify.

11 responses:

- Making heat networks a regulated utility will complement the use of hydrogen for heat and power, by utilising waste heat from local H2 fuel cells and electrolysis, and by absorbing the more intermittent surpluses of renewable electricity that cannot finance electrolysers.
- None
- Specific storage targets and support for long term projects
- No
- Ambitious clean air targets for urban areas driving ZEV demand and industry moving to zero emissions
- Public financial support for hydrogen filling stations --> Large
- Renewable shipping and aviation are global rather than domestic policies so ROI has little influence - however huge impact if imposed.
- N/A
- Yes
- Hydrogen is an important consideration in the future of energy policy given that it has the potential for a broad range of applications and the potential to support coupling of a variety of economic sectors which will be a key element of developing pathways to decarbonising the generation, is the development of markets to utilise and create the demand to support this sector coupling.
- There must be a focus on cross-sector coupling as part of future hydrogen policy. Hydrogen can facilitate an integration of the gas and electricity systems and it will be key that this is properly managed. Appropriate measures and supports must be in place to ensure the most efficient solutions are found.

Q8. If the policies selected above were to be enacted, how many new jobs would your enterprise hope to create?

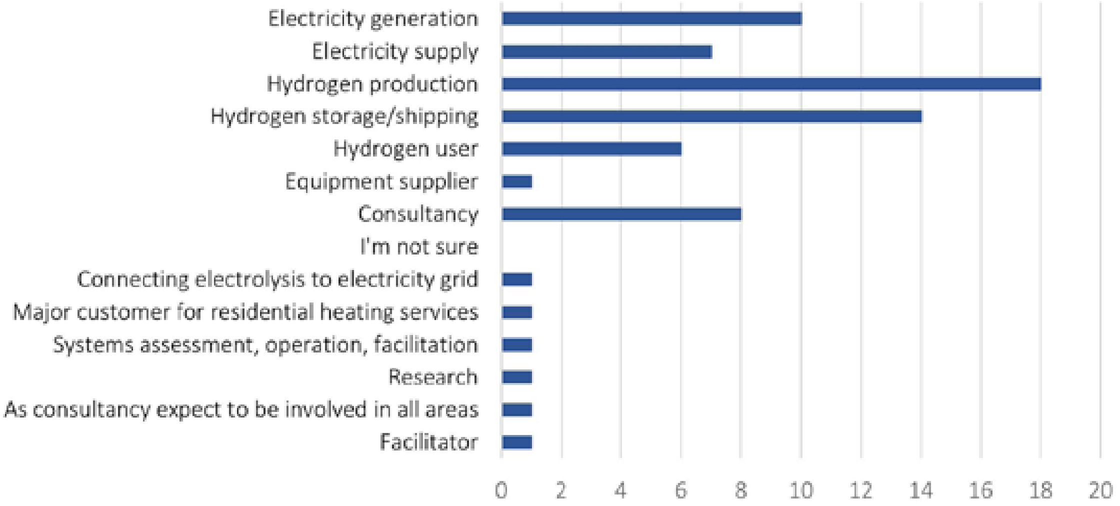
17 responses:

- No change
- 1-10
- 1-2 as part of larger global team in region of 5-10
- 5 (4)
- 5-10
- 10
- 10-20
- 20
- 30
- >50
- 80-200
- 100+ port-based jobs
- Difficult to say, probably 100s
- Not known

Q9. In which part of the hydrogen supply chain do you see your enterprise having a role? Please select all that apply.

29 responses:

- Electricity generation (10)
- Electricity supply (7)
- Hydrogen production (18)
- Hydrogen storage/shipping (14)
- Hydrogen user (6)
- Equipment supplier (1)
- Consultancy (8)
- I'm not sure (0)
- Connecting electrolysis to electricity grid to enable hydrogen production (1)
- Major customer for residential heating services, potentially via low carbon district heating and electric heat pump/boiler hybrids using hydrogen and metering heat rather than gas to more dwellings (1)
- Research (1)
- As consultancy expect to be involved in all areas (1)
- Facilitator (1)
- As electricity transmission system operator SONI will be responsible to assessing any reinforcements required on the transmission grid. We will also work with customers to facilitate the electrical connection to the electricity grid; As system operator SONI will be responsible for safely and securely managing the electricity demand/electricity generation from H2. We will also work with the regulator, the electricity distribution system operator and customers to operate the electricity market to procure energy and services from hydrogen power facilities to ensure a safe, secure and sustainable electricity system (1).



Q10. If you would wish, please provide more information on your enterprise's role in the hydrogen supply chain.

9 responses:

- Can provide more constant renewable electricity supply to electrolysers, by diverting surpluses of on site renewable generation to displacing the use of fossil fuels for boilers and to producing hot water for storage and later use.
- We are an early-stage project developer assessing alternative routes to market to facilitate decarbonisation of the electricity and energy sector.
- Research expertise
- Ambition to generate green hydrogen to be used by consumer to reduce carbon footprint
- Floating wind developer assessing hydrogen as a route to market
- Facilitation
- Establishing a hydrogen storage facility at the port for buses, taxi, small vans and potentially fuel cell for ferry services.
- Our objective is to stimulate collaborative research between industry, government and academia to accelerate the development of a hydrogen economy in Ireland with particular reference to collaborative offshore wind/hydrogen production/storage projects.
- As part of our role to plan and manage Northern Ireland's electricity grid, SONI will be responsible for providing connection offers to any hydrogen projects looking to connect to the high voltage electricity transmission grid, as well as manging the effects of any various activities in the hydrogen supply chain on the grid. During the transition it is essential that providing backup power for the variable renewable generation is complimented by flexible low carbon generation. Long term scenarios suggest that backup power could be provided by technologies including hydrogen. There are also opportunities for hydrogen electrolysers to provide system services on the grid. SONI continue to follow the GenComm Hydrogen pilot project which will enable Translink to explore the viability of hydrogen fuel as a solution for decarbonising their bus fleet. SONI are interested in this development since the power to hydrogen project provides additional electricity demand to the system; therefore reducing curtailment of renewable energy. There may also be opportunities in the longer term to manage network congestion issues, in partnership with the DSO.

Q11. With respect to the Irish Hydrogen industry, where do you see significant potential for job creation? Please select all that apply and provide the anticipated skill level.

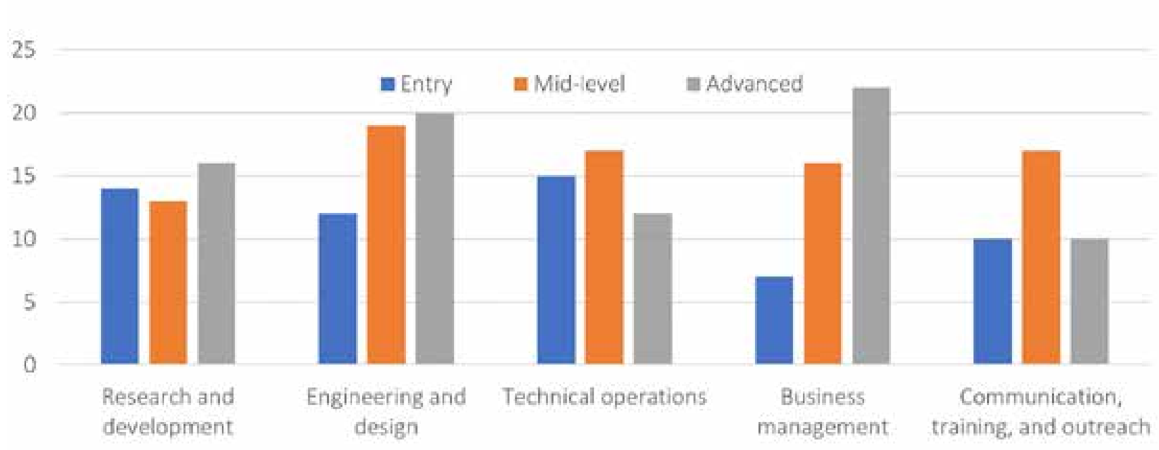
Responses:

Research and development:
    o entry (14)
    o mid-level (13)
    o advanced (16)

Engineering and design:
    o entry (12)
    o mid-level (19)
    o advanced (20)

Technical operations:
    o entry (15)
    o mid-level (17)
    o advanced (12)
Business management:
    o entry (7)
    o mid-level (16)
    o advanced (22)

Communications, training, and outreach:
    o entry (10)
    o mid-level (17)
    o advanced (10)



Q12. Has your enterprise experienced a knowledge, training, or skills gap related to your interest in hydrogen? If yes, please specify.

14 responses:

- Yes (8)
  - o A small gap; one person hired
  - o As a port operator, we need to upskill our knowledge of this sector
  - o Lack of detailed expertise – there will be a supply crunch in this area for a few years
  - o More staff needed that understand specifics of hydrogen
  - o Consultant knowledge of planning regulations and considerations to be applied in site selection
  - o Business model development for the Hydrogen economy
- No (5)
  - o Not immediately Hydrogen is still at an early stage there isn't that much advanced skills required yet.
- N/A (1)

Q13. Has your enterprise hired or begun the process of hiring specifically for hydrogen related roles? If yes, please specify.

14 responses:

- Yes (9)
  - o Ongoing recruitment for senior technical lead
  - o CEO, Policy & Strategy, Community Liaison, Planning, Admin
  - o 1 hire
  - o PhD-level research staff
  - o One person hired
- Not yet (1)
- No (4)

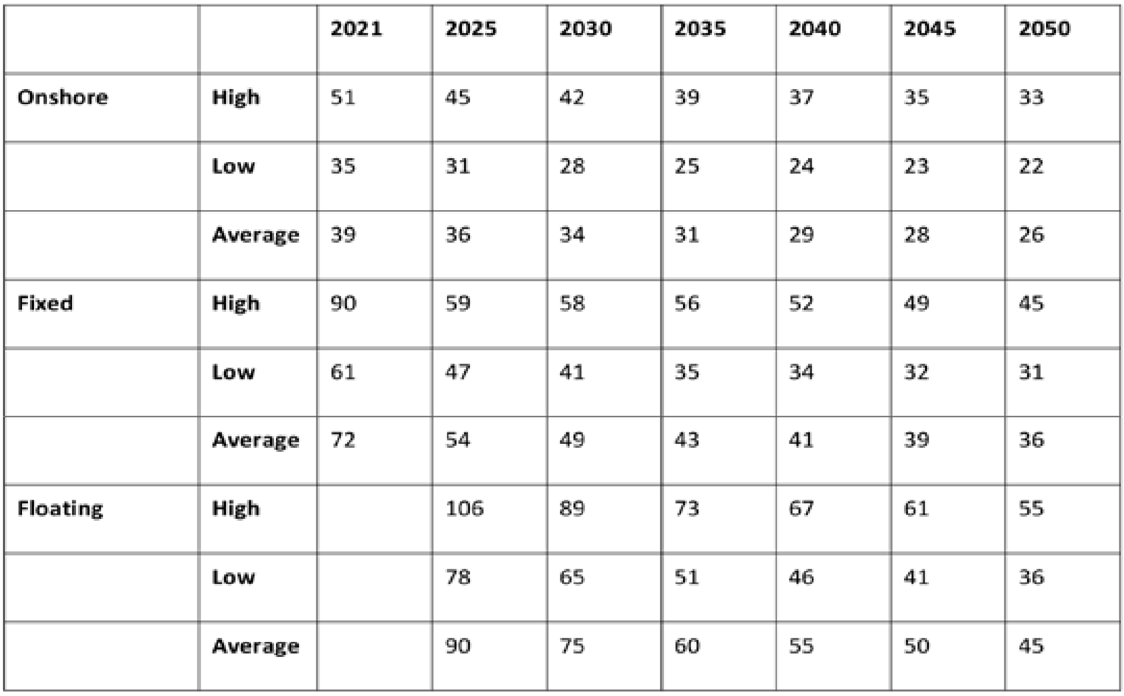
Q14. Is there anything you would like to add regarding the opportunities for the Irish hydrogen industry before 2030, and/or the steps required to capitalise on this opportunity?

14 responses:

- Start now to grow post 2030.
- I see renewable energy off Ireland's Atlantic Coast as our region's most significant economic opportunity in decades. Hydrogen will play a very significant role in this opportunity.
- The greatest blockage to achieving the potential of 'Green Hydrogen' is the foreshore/planning and consent process. It takes too long, generates too much uncertainty, nobody in Gov want to grab that nettle but it is a real hindrance to progress.
- 2021-2025 Govt should be supporting (grants, etc) for a number of demonstration projects relating to various opportunities, such as public transport (busses), power to gas, peaking plant, production at congested grid nodes, hybrid wind and solar projects. Govt should be supporting on developing internal markets and export markets for green H2.
- Carbon Tax and Government Support will be required to get this vital element of Net Zero off the ground.
- Large scale hydrogen storage will require industry and government collaboration. Geological storage will likely be critical.
- Actions needed now to incubate the renewable H2 industry so that it can form part of the solution to decarbonising Ireland's economy.
- Business case support through a tariff support scheme will be necessary to enable the economies of learning and scale to reduce the costs of hydrogen production from renewable energy sources. Without this it will be difficult for Green Hydrogen to compete against natural gas and to establish a viable offtake market.
- Grid charges need to be reduced at times of low power demand, to allow power to flow to electrolysers and from fuel cells located where their waste heat and oxygen have value.
- Huge opportunities for Ireland around green hydrogen given the wealth of renewable resources and industrial expertise.
- A collaborative approach is critical - a whole-systems approach should be taken in lieu of siloed electricity and other energy systems. Clear policy direction to developers and the wider hydrogen industry would bring clarity to the potential opportunity. This would reduce project development costs and WACC/financing costs. Focus on harder-to-abate sectors with a high decarbonisation impact in favour of meeting demand for hydrogen with minimal impact (e.g. focusing on 5% natural gas blends may prolong the dependence on fossil fuels). Five key areas for hydrogen use: power production and storage, aviation fuels, shipping fuels, fertilizer production.
- Still early days to say what technologies will dominate heat, power and transport.
- Concerted effort to produce PCEIs/demonstration projects.
- Collaboration between industry, academia and government is needed to accelerate innovative projects combining offshore wind and hydrogen production.
- Large scale hydrogen storage will require industry and government collaboration. Geological storage will likely be critical.

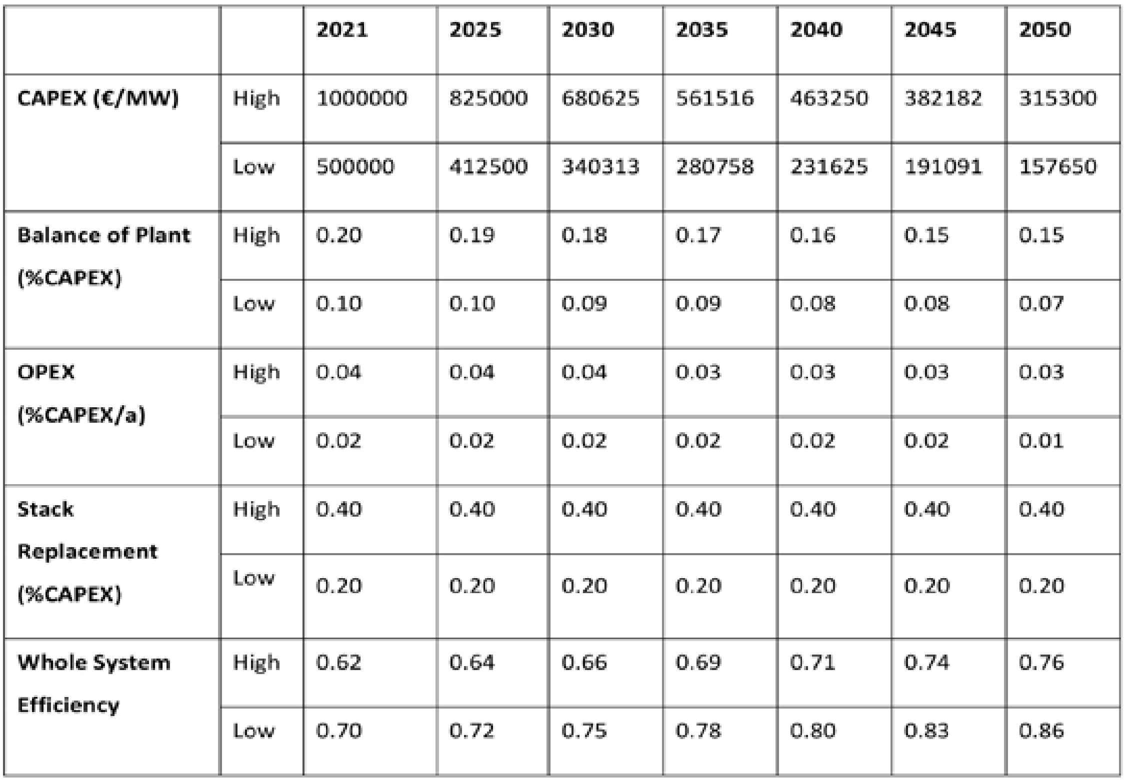
Appendix B: Hydrogen cost model

Table 1: Estimates for the LCoE of wind energy, adapted from Wiser et al. [3]. Figures are in 2020 €/MWh.



		2021	2025	2030	2035	2040	2045	2050
Onshore	**High**	51	45	42	39	37	35	33
	Low	35	31	28	25	24	23	22
	Average	39	36	34	31	29	28	26
Fixed	**High**	90	59	58	56	52	49	45
	Low	61	47	41	35	34	32	31
	Average	72	54	49	43	41	39	36
Floating	**High**		106	89	73	67	61	55
	Low		78	65	51	46	41	36
	Average		90	75	60	55	50	45

Table 2: Estimates of costs of the electrolysis system used to calculate the LCoH. Whole system efficiency is assumed to grow at 1.5% every 5 years, Balance of Plant and OPEX are assumed to fall 5% every 5 years, both in line with IRENA estimates [51]. Figures are in 2020 euros.



		2021	2025	2030	2035	2040	2045	2050
CAPEX (€/MW)	High	1000000	825000	680625	561516	463250	382182	315300
	Low	500000	412500	340313	280758	231625	191091	157650
Balance of Plant (%CAPEX)	High	0.20	0.19	0.18	0.17	0.16	0.15	0.15
	Low	0.10	0.10	0.09	0.09	0.08	0.08	0.07
OPEX (%CAPEX/a)	High	0.04	0.04	0.04	0.03	0.03	0.03	0.03
	Low	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Stack Replacement (%CAPEX)	High	0.40	0.40	0.40	0.40	0.40	0.40	0.40
	Low	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Whole System Efficiency	High	0.62	0.64	0.66	0.69	0.71	0.74	0.76
	Low	0.70	0.72	0.75	0.78	0.80	0.83	0.86

Table 3: Non-cost estimates used in constructing the LCoH model, Capacity factors are assumed to grow at 1.5% every 5 years, in line with IEA estimates [37].

Life	High	20	20	20	20	20	20	20
	Low	27	27	27	27	27	27	27
Discount Rate (%) **(Bottom-Fixed)**	High	0.060	0.060	0.060	0.060	0.060	0.060	0.060
	Low	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Capacity Factor (Fixed-Bottom) **(Floating)**	High	0.42	0.426	0.433	0.439	0.446	0.452	0.459
	Low	0.5	0.508	0.515	0.523	0.531	0.539	0.547
Capacity Factor (Floating)	High	0.450	0.457	0.464	0.471	0.478	0.485	0.492
	Low	0.550	0.558	0.567	0.575	0.584	0.593	0.601

The levelised cost of hydrogen (LCoH) is calculated as:

$$LCOH = \frac{\sum_{i=0}^{n} \frac{Costs\ in\ year\ i}{(1+Discount\ rate)^{i}}}{\sum_{i=0}^{n} \frac{kg\ of\ hydrogen\ produced\ in\ year\ i}{(1+Discount\ rate)^{i}}}$$

Table 4: Estimates used for the construction of Figure 6

Variable	**Value**		**Variable**	**Value**
CAPEX (€/MW)	675000		**Life (years)**	20
Balance of Plant (%CAPEX)	15%		**Discount Rate**	10%
OPEX (%CAPEX/a)	3%		**Whole System Efficiency**	62%
Stack Replacement (%CAPEX)	30%			

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An Roinn Breisoideachais agus Ardoideachais, Taighde, Nuálaíochta agus Eolaíochta
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