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Feasibility of Generation and Injection of Hydrogen into Ireland's Existing Gas Network Infrastructure

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Contents

List of Tables

List of Figures

List of Abbreviations and Acronyms

Acronym	Description
AE	Alkaline Electrolysis
AGI	Above Ground Installation
AHC	Australian Hydrogen Centre
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CCC	Climate Change Committee
CCUS	Carbon Capture, Utilization and Storage
CCGT	Combined Cycle Gas Turbine
CNGES	Compressed Natural Gas Energy Storage
CRU	Commission for Regulation of Utilities
DECC	Department of the Environment, Climate and Communications
DS	Distribution System
DSO	Distribution System Operator
DST	Decision Support Tool
DSU	Demand Side Unit
DS3	Delivering a Secure, Sustainable Electricity System
EHB	European Hydrogen Backbone
ETS	Emissions Trading System
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCP	Fuel Cell Plant
GHG	Greenhouse Gas
GNI	Gas Networks Ireland
GSF	Gas Safety Framework

GT	Gas Turbine
GW	Gigawatt
HGV	Heavy Goods Vehicle
HG2S	Hybrid Green Hydrogen Generation and Energy Storage
IEA	International Energy Agency
ISEM	Integrated Single Electricity Market
kg	Kilogram
kW	Kilowatt
kV	Kilovolt
LEL	Lumcloon Energy Limited
LHY	Liquid Hydrogen
MEC	Maximum Export Capacity
MMBTU	Metric Million British Thermal Unit
MT	Megatonne
MW	Megawatt
NG	Natural Gas
NOx	Nitrogen Oxides
NUIG	National University of Ireland, Galway
NWR	National Wildlife Refuge
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OS	Ordnance Survey
PEM	Proton Exchange Membrane
PM	Permanent Magnetic
P2G	Power to Gas
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
SEAI	Sustainable Energy Authority of Ireland
SEM	Single Electricity Market
SIR	Synchronous Inertial Response
SMR	Steam Methane Reforming
SNSP	System Non-Synchronous Penetration
TRL	Technological Readiness Level
TS	Transmission System

TSO	Transmission System Operator
UCC	University College Cork
UCDEI	University College Dublin’s Energy Institution
WLE	Wet Low Emissions

1 Executive Summary

This study investigates the potential to inject green hydrogen gas into existing gas network infrastructure as well as the possibility of developing a green hydrogen market in Ireland.

Information on the operation of the power and gas networks and the variety of issues that they are currently facing has been included to contextualise and highlight the need for hydrogen generation, injection and storage.

Detailed descriptions have also been provided on the current state of the global hydrogen industry, with focus on both Global and Irish progress towards the development of extensive hydrogen infrastructure. The challenges and benefits of hydrogen technology are examined extensively to provide a balanced summary of the path to hydrogen development in Ireland.

A range of hydrogen storage and generation technologies have been discussed. The individual merits of the technologies have been considered, as well as the specific use cases in which they would be most suitable.

Detailed descriptions of the markets (transport fuel, grid injection, wholesale) which would provide revenue for any future hydrogen projects have also been provided, along with the current competition in those markets. Also discussed are the development requirements which are necessary to complete an energy project, such as land, planning, and grid.

The conclusion of the study is that injecting green hydrogen into existing gas network infrastructure and developing a green hydrogen economy will substantially benefit GNI, the end-use consumer, and renewable energy developers in Ireland. It will support Ireland in becoming energy independent whilst also helping to ensure the security of supply of both gas and electricity. This will help Ireland to reach its GHG emission reduction targets while creating a reliable and sustainable power grid.

2 Introduction and Aim of the Study

Over the last decade, the generation and utilisation of green hydrogen has been the focus of significant amounts of research and development worldwide, both academically and commercially. This research has resulted in widespread technological advancements and the development of a variety of commercial pilot projects in various sectors.

Hydrogen is increasingly being seen as a missing link in Europe's energy transition. The Paris Climate Agreement and the European Union (EU) Green Deal have set the target of zero net emissions by 2050[1]. Green Hydrogen (produced via electrolysis using renewable energy) will be a key technology required to meet this ambitious goal. The flexible nature of hydrogen as an energy carrier allows for a multitude of purposes, such as decarbonising the gas network, transport fuel, industrial processes, coupling between the energy and gas sectors, and energy storage.

However, integrating hydrogen into the European economy will take significant investment from both the public and private sectors. The EU has signalled its commitment to advancing the hydrogen economy by issuing the "Hydrogen Strategy for a Climate-Neutral Europe" document in July 2020[2]. This detailed strategy highlights green hydrogen's benefits for the economy as well as its place in meeting the EU's climate goals.

Ireland's status as an island nation with relatively weak interconnection between its electrical grid and its European neighbours makes it particularly vulnerable to power outages due to a sudden imbalance in the ratio of generation to demand. This problem is made worse by the variable nature of many renewable energy sources such as wind and solar. Since Ireland has the highest level of onshore wind penetration in Europe, its electrical grid needs support infrastructure to ensure that it can cost-effectively handle this level of variability. This intermittent power problem is further compounded by the closure of many traditional generating plants within Ireland, which will have to be replaced by cleaner alternatives.

This feasibility study will examine the effects of hydrogen injection on the GNI gas network. It will also consider the benefits of using hydrogen to decarbonise hard to abate sectors like backup electricity generation.

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[1] European Green Deal, European Commission, December 2019, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[2] Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions. A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf?linkId=93338347

Another key aim is to explore the type of renewable generation/storage projects that could benefit from hybridisation with hydrogen injection and demonstrate to what level of hydrogen investment in Ireland could benefit the developer, consumer, and Gas Networks Ireland.

2.1 Introduction to Lumcloon Energy Limited

Lumcloon Energy Limited (LEL) has extensive experience in the power generation industry and can provide insight into the feasibility of potential projects in the Irish market due to previous experience from years of project development.

LEL is a leading developer of energy storage projects to enable the transition to a low carbon economy in Ireland. LEL has previously completed a pilot project using lead-acid batteries and flywheels to provide system services to the Irish grid. This project has led to the development of two 100 MW Li-ion battery plants that are now live and currently provide system services to the Irish grid. The project is currently the largest in Europe, Battery Energy Storage System (BESS), supporting the grid with system services in Ireland. LEL has a proven track record of delivering large, grid-scale energy development projects.

As LEL is an Irish company, it is ideally suited to take advantage of Ireland's unique position at the forefront of developing a national electrical grid with high levels of system non-synchronous penetration (SNSP) and low levels of traditional generation, supported by dynamic and innovative system services.

2.2 Analysis of the Current Irish Gas Networks and Electricity Grid

To consider the benefits of the generation and injection of green hydrogen for the Irish grid, an analysis of the current gas and electricity networks is required as a baseline.

The shortfalls and issues experienced in both the Irish gas and electricity transmission systems will be discussed, giving an insight into the areas in which hydrogen production and injection could improve their reliability.

2.2.1 Ireland's Gas Network Pipeline

The Irish gas network supplied 31% of Ireland's total energy demand in 2020[3] and currently supports 706,000 customers 24 hours a day annually, making it a crucial asset to energy production in Ireland. The gas network is separated into two systems: the transmission network (high pressure) and distribution network (low pressure), both owned by GNI. The two systems will be discussed separately as there are different roadblocks related to the injection of hydrogen into each gas network, depending on which network you wish to inject/transport hydrogen into. However, current research indicates that the gas network can withstand up to a 20% blend of hydrogen[3]. The process of acquiring planning permission for an injection point has been investigated in Section 6.1.3.

2.2.1.1 Transmission Network

The transmission network is composed of steel pipelines and is used to transport gas at high pressure (85-7bar)[4] from storage facilities into cities and towns. This system is where the most significant problems will arise when transporting hydrogen. This is because an embrittlement effect occurs due to hydrogen travelling at high pressures in a metal pipe. This concept is expanded upon in Section 3.3.4. It is important to note that a connection to the distribution network is favourable as the transmission network requires more expensive equipment due to the higher pressures. One of the scenarios favouring connecting to the transmission network would be if the volume of gas to be injected was larger than the capacity of the distribution network. This is because the transmission network has a much larger capacity due to the higher pressures the gas is transported at. The transmission network is also the current limiting factor for the purity of hydrogen allowed to be transported through the network, limiting the blend to 20% hydrogen content. Above this, more extensive modifications are needed for sensitive components such as gas turbines and compressors[3] [5]. In the case of turbines, this is due to the reactivity of hydrogen being much higher than natural gas. This causes the flame to form much closer to burner exit vents and a higher potential for flashback. Flashback is a process where the flame propagates upstream to the premixing zone,

[3] Ireland's Gas Network, Delivering for Ireland, Gas Networks Ireland, November 2021, https://www.gasnetworks.ie/docs/corporate/company/Irelands-Gas-Network_Delivering-for-Ireland_FINAL-file-as-published-11-11-2021.pdf
[4] Extending the Natural Gas Network, http://sta.ie/perch/resources/lessons/a4bglessoned.7.pdf
[5] Hydrogen integration in power-to-gas networks, Orfam Ahmad Gondal, January 2019, https://doi.org/10.1016/j.ijhydene.2018.11.164

resulting in significant hardware failure[6]. In the case of compressors, the problems are due to the molecular mass of hydrogen atoms; because of this, centrifugal compressors (the type used in the Cork compressor station[7]) must run at three times the fin speed-reducing in loss of efficiencies and more power draw[8].

Using retrofitted or more suitable compressors and turbines results in achieving a 30% hydrogen blend with negligible effects on the operating thresholds of the transmission network. Modern gas turbines have been shown to function normally with blends as high as 100% hydrogen. Another problem faced by the gas network is EU regulations; currently, Ireland is in breach of energy security standards[9]. This breach of policy is because initially, the primary source of natural gas used in Ireland came from Scotland through a cross-ocean transmission pipeline; this coupling of gas networks meant that Ireland's Risk Assessment would be analysed in conjunction with Britain. This enabled Ireland to reach acceptable levels of energy security. However, Ireland now fails to fulfil the current security standards due to Britain leaving the EU. The production and storage of hydrogen gas, as well as the transition to using hydrogen as a carbon-neutral energy source within the transmission network could help Ireland reach the necessary levels for the energy security standards by reducing reliance on foreign gas imports.

2.2.1.2 Distribution Network

Otherwise known as the "local" gas network as this is where gas is transported at much lower pressure (7bar-20mbar)[4] to individual customers such as family households. These pipes are constructed from polyethylene which does not suffer the same hydrogen embrittlement effect as steel. However, due to the calorific value of the hydrogen-natural gas blend being lower than that of pure natural gas, the volumetric flow rate of the gas must be increased to maintain a consistent energy supply. This pressure increase may require infrastructural development (for example, adjustments to the compression stations) to maintain safe operating conditions.

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[6]Overcoming technical challenges of hydrogen power plants for the energy transition https://www.nsenergybusiness.com/news/overcoming-technical-challenges-of-hydrogen-power-plants-for-energy-transition/

[7]GNI Network Development Statement 2011/12 – 2020/21 https://www.gasnetworks.ie/docs/corporate/gas-regulation/Network-Development-Statement-2011-12-2020-21.pdf

[8] Barton, M., Soriano, L., Stahley, J., Talakar, A., Siemens Energy, Under Pressure: The Challenges of Hydrogen Compression, Hydrocarbon Engineering https://assets.siemens-energy.com/siemens/assets/api/uuid:d985fced-fb7e-4881-a1b9-87cd6d7eac63/se-he-august2021-challenges-hydrogencompression-article.pdf

[9] Energy Security in Ireland 2020 Report, SEAI, 2020, https://www.seai.ie/publications/Energy-Security-in-Ireland-2020-.pdf

2.2.2 Grid Stability & Inertia

Traditionally, electricity generation at the Irish national grid scale was performed almost entirely by large spinning turbines, powered by either steam or gas combustion (with some hydro-powered turbines, too). These turbines were initially powered by burning coal, peat, oil, and natural gas, to generate energy, releasing significant amounts of CO2 and other greenhouse gasses. Modern electrical grids increasingly rely on renewable energy sources such as wind and solar power; this helps to reduce GHG emissions. Unfortunately, the proliferation of these intermittent and non-dispatchable power sources on the grid has reduced the stability and security of the electricity supply and increased the cost of energy for the consumer.

The stability of the electricity grid is determined over several time scales. The most important of these time scales is the first few seconds following a disturbance on the grid. A disturbance, in this case, is any imbalance between generation and consumption (or 'load'). As electricity grids traditionally have little or no formal energy storage capacity, the amount of electrical power generated must constantly be adjusted to meet the consumption demand. However, traditional fossil fuel burning generators provide what is known as synchronous inertia, which facilitates the smooth balancing of generation and demand in real-time.

This inertia assists grid stability on two different scales. Firstly, it provides resilience to the grid, allowing it to deal with the small rapid fluctuations that constantly occur as both generation and demand oscillate in unpredictable ways. These generators are all electromagnetically synchronised to the grid frequency of 50 Hz. The first observable effect of a power shortfall on the grid is that the generators will no longer be able to keep their turbines spinning at 50 Hz. However, the collection of large rotating masses on the grid will resist any change in rotational speed in unison. Their combined rotational inertia means any change to the grid frequency will happen slowly. If this inertia was not present, small rapid fluctuations in power on the grid could lead to a rapidly fluctuating grid frequency. This instability would damage equipment connected to the grid, potentially leading to more significant runaway oscillations that would require the grid to be shut down and restarted (blackout).

Secondly, when a significant and sudden imbalance between generation and demand occurs, such as when a generator suddenly trips off the grid (e.g., due to a mechanical failure), some of the rotational energy stored in the rotors of these large turbines will instantaneously be delivered to the grid to compensate for the loss of generation. This transference of energy has traditionally provided a brief time buffer sufficient for the grid's primary reserve to kick in and compensate for the power shortfall. If this buffer did not exist, any rapid change in demand or generation would lead to a runaway grid frequency change. This rapid change in rotational speed can easily damage large turbines. As a result, if the rate of change of frequency (RoCoF) exceeds a specific value, these turbines will automatically disconnect from the grid, leading to a domino effect and a system-wide blackout.

Most renewable generation such as solar and wind power is not electromagnetically synchronised to the grid (some older wind turbine designs were synchronised, but these have mostly been replaced by variable speed wind turbines, which can achieve much higher efficiency). As a result, a grid with a large fraction of its power coming from renewable sources becomes inherently unstable. In Ireland, the instantaneous percentage of the grid power provided by non-synchronous sources is known as the system non-synchronous penetration (SNSP). Currently, the instantaneous value of SNSP must always be limited to some value below 100% (though the target SNSP limit for the year 2030 in Ireland is 95%[10], the current limit is just 75%, regardless of how much renewable generation is available. This limiting factor is due to issues with the transmission grid itself and has led to the significant curtailment of renewable generation.

2.2.3 Renewable Harvesting & Intermittency

Efficiently exploiting renewable, sustainable, and green energy resources is one of Europe's most critical challenges today. The European Union has set ambitious energy and climate targets for 2030 and beyond as part of its *2030 Climate and Energy Framework*[11]. These include cuts of at least 40% in greenhouse gas emissions (from 1990 levels), at least a 32% share for renewable energy, and at least 32.5% improvement in energy efficiency[12]. As part of this challenge, Ireland aims to generate, on average, up to 80% of its electricity from renewable sources by 2030[13]. Renewable energy sources, e.g., solar and wind energy, are indigenous, plentiful, and sufficient to power our ever-increasing demand for more devices, technology, and transportation. However, the increased demand for electricity at peak times, the increased instantaneous penetration of the grid by non-synchronous sources (such as wind turbines and PV solar), and the intermittent and non-

[10] Shaping our electricity future roadmap, Eirgrid & Soni Group, November 2021, https://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf

[11] Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030, European Commission, January 2014, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0015

[12] Climate Action Targets, Caro, https://www.caro.ie/knowledge-hub/general-information/climate-change-policies-targets/climate-action-targets

[13] Climate Action Plan 2021, Department of the Environment, Climate and Communications, November 2021, https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/

dispatchable (*i.e.,* can't be controlled) nature of renewable energy sources is continuously leading to less stable electricity grids. This is particularly true in Ireland, whose isolated island grid is particularly vulnerable[14] [15].

The power output of traditional fossil fuel-powered generators is very reliable while fuel is available. Their control systems allow them to regulate their production and respond to small changes in demand in real-time. Large steam turbine-based power plants that behave in this way are known as base-load plants, and they have traditionally provided most of the power on a grid. Gas-powered combustion turbines can also rapidly increase their output significantly in response to sudden large changes in generation or demand. These plants are often kept running at low power output to provide a significant increase in power if needed rapidly. Such plants are known as peaking plants, and they are essential to ensuring the reliability of the grid. Both plant types are dispatchable as they can dynamically change their output, either automatically or in response to a request from the transmission system operator (TSO).

Most renewable generation is non-dispatchable. Both solar and wind power depend on atmospheric conditions that cannot be controlled. While the variation in the level of sunlight and the wind speed on a given day can be predicted with reasonable accuracy, the inherent volatility of the weather adds uncertainty to the level of power generated at any given time. This adds to the existing demand uncertainty, decreasing the grid's reliability. Furthermore, since the renewable generators have displaced dispatchable power plants on the grid, the ability of the system to respond to this more significant uncertainty has also decreased. This increases the stress on all dispatchable plants as they must now change their output much more often and by greater degrees. This also leads to an increased demand for peaking plants needed to enhance the grid's reliability at times of high SNSP. Unfortunately, peaking plants are relatively inefficient when running at low power output. This factor increases both the economic and environmental cost of operating the grid and partially offsets the benefits provided by renewable generation.

2.2.4 Peaking Power & Load Shifting

The electricity demand varies in a relatively predictable way for a typical day. The demand is highest both in the morning (roughly from 08.00-12.00) and the evening (roughly from 16.00-20.00) and

[14] The DS3 Programme, Eirgrid, SONI, http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Programme-Brochure.pdf

[15] Reconciling high renewable electricity ambitions with market economics and system operation: Lessons from Ireland's power system, F. Gaffney, J.P. Deane, B.P.Ó. Gallachóir, November 2019, https://doi.org/10.1016/j.esr.2019.100381

lowest at night (roughly from 02.00-06.00). Traditionally, a mix of base load plants and peaking plants would be used to meet this demand, as discussed in the previous section. However, EirGrid expects that most of the power on the Irish grid will soon come from renewable sources, particularly wind power.

Developing enough wind farms to meet the peak demand of the Irish grid is a significant challenge. Since wind speed is not correlated to electricity demand, even the most ambitious targets for future wind farm installations would still leave Ireland needing a backup power source in times of high demand and low wind speed. Similarly, at times of low demand and high wind speed, a significant power excess would be produced, which would need to be curtailed to avoid overloading the system. This will reduce to cost of electricity to almost nothing at times of low demand. To see a reasonable return on investment, wind farm operators will have to compensate for this loss of revenue by increasing energy prices during times of high demand. This will increase the cost of energy to the consumer.

The problems of variable load, intermittent supply and the resulting increase in energy costs can be addressed by adding storage to the electrical grid. The ability to store energy generated by renewable technologies is essential for the secure and stable operation of the electrical grid. Energy can be stored when excess renewable energy is available (either due to an actual surplus or an artificial surplus due to curtailment). This energy can be released back into the grid when there is a shortage of renewable energy. This is known as load shifting, and it can effectively reduce the volatility and uncertainty inherent in the use of renewable generation. The charging of the storage system during times of traditionally low demand will increase that demand and ensure that energy prices never fall too low to make renewable generation financially risky. Similarly, releasing that stored energy during times of high demand will reduce the requirement for fossil fuel-based peaking plants and their associated GHG emissions.

2.2.5 Island Grid & Transmission

The amount of inertia in an electrical grid is directly related to the size of the grid, i.e., the number of synchronised rotating masses connected to the grid. There has traditionally been an excess of inertia in large continental grids as so many synchronous generators are widely distributed across the grid. In this case, any single generator does not represent a significant fraction of the total generation on the grid. If a large generator suddenly trips off the grid, the large amount of inertia and reserve available can easily compensate for the power imbalance. However, for an island nation like Ireland, the relatively small number of generators on the grid has meant that synchronous inertia is relatively low. This also means that one large generator can represent a significant fraction of the total generation on the grid. Combining these two factors results in the Irish grid being relatively volatile and prone to frequency deviations. Therefore, the Irish grid is experiencing the grid stability issues associated with high levels of SNSP sooner and to a greater extent than continental European grids[16]. This makes Ireland the ideal test bed for technologies that aim to increase SNSP.

For example, as previously mentioned, the SNSP in Ireland is currently limited to 75% of the total generation. This is to maintain both the level of synchronous inertia and the amount of reserve power available above a certain minimum threshold required for grid stability. In 2020, Ireland already had to 'spill' over 1.4 million MWh of wind energy (representing 11,5% of total wind generation) to ensure the security of the electrical supply[17]. The TSO in Ireland has developed a range of system services in its DS3 (Delivering a Secure, Sustainable Electricity System) plan, which it believes are essential for the secure operation of the grid as we advance and for the gradual increase in the allowed level of SNSP. These services include the provision of synchronous inertial response (SIR) and various types of reserve capacity and balancing energy which operates over different timescales in the aftermath of a power imbalance. These problems will eventually have to be dealt with on larger, continental grids. Therefore, investing in the development of innovative technologies that facilitate these services in Ireland now will allow Irish companies to lead the way in the provision of the intelligent, stable, and renewable-powered grid of the future.

[16] Renewables in the European power system and the impact on system rotational inertia, L. Mehigan, Dlzar Al Kez, Seán Collins, Aoife Foley, Brian Ó'Gallachóir, Paul Deane, July 2020, https://doi.org/10.1016/j.energy.2020.117776

[17] Annual report confirms wind energy leads fight against climate change, Wind Energy Ireland, February 2021, https://windenergyireland.com/latest-news/5364-annual-report-confirms-wind-energy-leads-fight-against-climate-change

3 Injection of Hydrogen into the Existing Gas Networks

Natural gas accounted for 34% of primary energy in 2020 in Ireland. Primary energy includes the raw fuels used for transformation processes and generation processes[18]. In Ireland, 57% of the annual electricity is produced by natural gas, and on rare occasions, it can supply up to 80% of peak power demand[19].

As demonstrated in Section 2.2, several electricity and gas transmission issues need to be addressed to create a reliable and sustainable Irish gas and electricity network as we transition to a decarbonised system. Green hydrogen production and utilisation can be crucial in supporting this transition. This feasibility study investigates the initiatives described in the EU Commission's roadmap, including the generation of hydrogen with renewable energy resources and the repurposing of existing infrastructure. Furthermore, many European countries do not allow the injection of hydrogen into their existing gas networks. This creates an opportunity for research and pilot projects to demonstrate the feasibility of this concept. If more feasibility studies and projects are carried out, this will help to increase the chance of future projects succeeding, benefitting project developers

As mentioned previously, Ireland is experiencing several grid stability and reliability issues alongside being off course to meet ambitious GHG emission reduction targets[20]. According to the Sustainable Energy Authority of Ireland (SEAI), 27% of all energy-related CO2 emissions in Ireland came from the use of natural gas[21]. Although natural gas is a cleaner alternative fuel to coal, oil, or peat it remains a significant pollutant contributing to climate change, especially considering the impact of methane (a much more potent GHG than CO2[22]) leakages along the gas supply chain.

A potential solution to these grid issues would be to replace natural gas with green hydrogen. Adding H_2 into the pre-existing natural gas network would allow gas turbines around the country to run with reduced carbon footprints. Hydrogen could also be sold for use in vehicles, helping to abate the emissions of the Transport Sector. The costs of hydrogen transport can be minimised by using pre-existing gas distribution infrastructure (Transmission and Distribution Networks).

[18] SEAI Energy Use Overview https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/energy-use-overview/
[19] Investigation of the Multi-Point Injection of Green Hydrogen from Curtailed Renewable Power into a Gas Network, Ali Ekhtiari, Damian Flynn, Eoin Syron, November 2020, https://www.mdpi.com/1996-1073/13/22/6047
[20] EPA Assessment of Compliance https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/indicators--targets/
[21] CO2 Emissions, SEAI, https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/co2/
[22] US EPA, The importance of Methane https://www.epa.gov/gmi/importance-methane#:~:text=Methane%20is%20more%20than%2025,trapping%20heat%20in%20the%20atmosphere.

3.1 Global Progress on Hydrogen Projects

The last decade has seen exponential investment growth in green hydrogen production and utilisation worldwide[23]. This increase in investment can be seen in Section 3.1.1, as the number and size of hydrogen projects seem to be increasing. Of the 5000km of hydrogen pipelines currently operational worldwide, more than 90% can be found in Europe and the US[24]. Most are closed systems owned by large hydrogen producers, concentrated near industrial consumers. However, developments involving repurposing natural gas pipelines can significantly reduce the cost of establishing national and regional hydrogen networks[24]. Academic institutions worldwide are pushing these technologies to the forefront of solutions that can support the transition to a decarbonised gas and electricity transmission system.

3.1.1 Pilot Projects

This section will discuss some examples of pilot projects which are currently in either development or operation internationally that utilise or generate green hydrogen.

3.1.1.1 Europe's Grouped Action

In July 2020, several European gas transmission system operators (TSOs) came together to produce a vision document for the European gas sector[52] to tackle its role in the energy transition. Hydrogen can enable a reduction in emissions throughout Europe by offsetting the use of natural gas whilst maintaining a framework like what is used today. It can already use existing gas pipelines and can be blended in higher percentages with minor modifications and costs compared to other alternatives. This vision document focuses on linking demand sites, such as industrial clusters, with areas of peak hydrogen generation to establish an initial demand for hydrogen and then concentrate on building up regional areas around these critical hubs. The paper concluded that such a continent-wide network would cost between €27 – €64 billion, with completion possible by 2040 and an annual demand of 1,130 TWh expected[25].

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[23] Deloitte Will hydrogen be the surprise of this decade? https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/articles/will-hydrogen-be-the-surprise-of-this-decade.html

[24] IEA (2021), Hydrogen, IEA, Paris https://www.iea.org/reports/hydrogen

[25] Euro pipeline proposal brings to the demand side, Columbia Threadneedle, Sharon Vieten, September 2020, https://www.columbiathreadneedle.co.uk/en/inst/insights/euro-pipeline-proposal-brings-hydrogen-to-the-demand-side/

3.1.1.2 Gasunie using the Dutch Natural Gas Networks

The Dutch company "Gasunie Transport Services" (GTS) operates the 12km Yara-Dow hydrogen pipeline in the Netherlands, with a throughput capacity of 4kt/yr, commissioned in November 2018[26]. Gasunie stated that the planned national hydrogen infrastructure would be the first large-scale retrofit of natural gas pipelines, using existing channels for 85% of the backbone to save substantially on costs. With an estimated price tag of €1.5 billion, the projects are scheduled for completion in 2027. For it to be reused, the 1200km long, 36inch diameter pipelines would need to be cleaned and prepared (according to the HyWay27 report). In 2019, the Dutch government established a National Climate Agreement[27], a policy targeting 3-4GW of electrolysis capacity by 2030. It also published a strategy on hydrogen in 2020[28]. The 12km pipeline commissioned in 2018 prompted a consortium of gas grid operators in Europe to propose the European Hydrogen Backbone (EHB) initiative in 2020 (updated in 2021) that envisions 39,700km of pipelines across 21 countries by 2040. 69% of the pipeline will consist of repurposed natural gas networks, and 31% will be newly built hydrogen pipelines[29].

3.1.1.3 HyDeploy hosted by Keele University, UK

A trial currently being carried out in the UK, known as HyDeploy, is currently testing the viability and safety of injecting 20% hydrogen blend by volume into the normal gas supply[30]. HyDeploy is being hosted at the Keele University in Staffordshire. Approximately 6 million tonnes of CO_2 could be saved each year, equivalent to taking around 2.5 million cars off the road if the 20% blend is applied[31]. The current phase of HyDeploy is set to finish in 2023

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[26] The Netherlands to refit natural gas network for pure hydrogen, Cristina Brooks, July 2021, https://cleanenergynews.ihsmarkit.com/research-analysis/the-netherlands-to-refit-borderstraddling-natural-gas-grid-for.html
[27] Dutch National Climate Agreement https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands
[28] Dutch Hydrogen Strategy https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen
[29] European Hydrogen Backbone. https://www.ehb.eu/page/publications
[30] What is Hydeploy, HyDeploy, https://hydeploy.co.uk/faqs/what-is-hydeploy/
[31] HyDeploy project could open door to larger scale hydrogen projects, Jeffrey McDonald, January 2020, https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/electric-power/010920-hydeploy-project-could-open-door-to-larger-scale-hydrogen-projects-sources

3.1.1.4 Germany's National Hydrogen Strategy

Germany has shortlisted 62 hydrogen projects with a total capacity of 2GW for IPCEI (Important Project of Common European Interest) state aid on May 28th, 2021.[32] These projects were selected from 230 proposals. The German energy ministry has selected 50 projects, including electrolyser projects with a combined capacity of over 2GW and hydrogen pipelines with a length of 1700km. The transport ministry has selected the remaining 12 projects to develop and produce fuel cell systems and vehicles. These projects combine for over 400MW electrolyser capacity, being: Lingen (300MW), Rostock (100MW), and offshore Heligoland (28MW). Vattenfall's proposal for a 100MW electrolyser was also shortlisted.

3.1.1.5 Avacon Injection in Germany

Avacon has begun injecting 20% hydrogen blends into the German gas network for the first time as of December 2021.[33] The injection of a hydrogen blend to a sub-grid in Saxony-Anhalt, Germany, will be implemented in steps. The joint project of Avacon and the German Technical and Scientific Association for Gas and Water (DVGW) intends to demonstrate that it is technically possible to inject hydrogen into existing gas networks at a significantly higher percentage than previously envisaged in the DVGW's technical rules (10% by volume[34]). As part of the approval process, all home appliances have been tested at 23% hydrogen (laboratory tests show that many household appliances can be operated with mixtures of up to 30%[35]).

3.1.1.6 New Jersey Hydrogen Generation and Blending

JERA Americas has announced plans to blend hydrogen at its Linden Cogeneration plant in New Jersey[36]. Linden Cogen will take Bayway Refinery produced hydrogen, containing fuel gas, and blend it with natural gas used to power the 172MW Linden Cogen Unit-6 gas turbines. Modifications will enable up to a 40% hydrogen blend. The New Jersey Resources Corp. has begun construction on a

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[32] Germany shortlists 62 hydrogen projects with 2 GW capacity for IPCEI state aid, S&P Global, May 2021, https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/electric-power/052821-germany-shortlists-62-hydrogen-projects-with-2-gw-capacity-for-ipcei-state-aid

[33] 20 percent hydrogen in the German gas network for the first time, Marvin Macke, October 2021, https://www.eon.com/en/about-us/media/press-release/2021/20-percent-hydrogen-in-the-german-gas-network-for-the-first-time.html

[34] Hydrogen Research Projects, DVGW, October 2020, https://www.dvgw.de/medien/dvgw/leistungen/publikationen/dvgw-h2-wasserstoff-forschungsprojekte-broschuere-en.pdf

[35] Hydrogen Central, Avacon German Gas Network https://hydrogen-central.com/eon-avacon-dvgw-20-percent-hydrogen-german-gas-network/

[36] JERA Americas Announces Hydrogen Fuel Blending Plans in Supports of Net Zero CO_2 Goals, July 2021, https://www.businesswire.com/news/home/20210727005884/en/

green hydrogen project in Howell, New Jersey[37]. The project uses electricity from a nearby solar farm to generate green hydrogen, which is then be injected into the company's gas distribution system as of October 2021.

3.1.1.7 Korea, Hanwha Energy Hydrogen Fuel Cell Plant

An excellent example of a large-scale hydrogen fuel-cell power plant is Hanwha's plant in the Daesan Industrial Complex in Korea (see Figure 1)[38]. Lumcloon Energy has worked extensively with Hanwha and has gained significant insight into their state-of-the-art fuel cell plant (FCP).

Figure 1: Fuel Cell Power Plant in Daesan Korea

Hanwha has demonstrated that it is technically possible to build a large-scale FCP. However, the financial viability depends on the cost of the hydrogen. Hanwha's plant runs on by-product hydrogen created by an adjacent petrochemical plant they own. Since this hydrogen is essentially free, the plant is not a realistic example for use in Ireland.

3.1.2 Research

Research and testing of hydrogen grid injection is taking place all over the world.

A study by Cardiff School of Engineering shows the viability of Power to Gas (P2G) injection systems in Great Britain. The results showed that producing hydrogen from electricity can reduce wind

[37] Hydrogen Pilot Projects advance, evolve at gas utilities, Tom DiChristopher, Bill Holland, Tim Siccion, August 2021, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hydrogen-pilot-projects-advance-evolve-at-gas-utilities-65942022

[38] Hanwha's Groundbreaking Power Plant Shows How Hydrogen Can Fuel a 'Circular Economy', FuelCellsWorks, August 2020, https://fuelcellsworks.com/news/hanwhas-groundbreaking-power-plant-shows-how-hydrogen-can-fuel-a-circular-economy/

curtailment and decrease the overall cost of operating the Great Britain gas and electricity network. It was found that if you allow 5% of gas demand at a specified node to be injected as hydrogen (assuming enough electrolyser capacity is available for this) which is produced from wind curtailment, it reduces wind curtailment by 62% on a typical low electricity demand day and by 27% on a high demand day with high wind energy availability[39]. Injecting hydrogen without constraint would eliminate wind curtailment, as all previously wasted energy would now be used to produce hydrogen.

As of March 2021, Portgás started investigating the technical feasibility of injecting hydrogen into the gas distribution network[40]. In line with the national strategy for decarbonization of various sectors of the economy, INEGI supports developing technologies for producing, storing, and using green hydrogen. Today, the reinforcement of Portgás' partnership with INEGI has led to the development of a laboratory and test benches to test hydrogen injection into the natural gas distribution network[41]. The laboratory is currently operational and is performing tests to simulate and observe the conditions of the metallic distribution and supply networks of Portgás upon hydrogen injection, including all its components (piping, sensors, seals, valves).

The Australian Hydrogen Centre (AHC) was established in 2019 to create detailed feasibility studies investigating the delivery of 10% renewable hydrogen blends[42]. The AHC plans on building upon the Hydrogen Park South Australia and Hydrogen Park Gladstone projects to deliver their Low Carbon Vision of a 10% blend renewable gas network by 2030 and full decarbonisation by 2050. The AHC's development, supported by the Australian Renewable Energy Agency (ARENA) grant, has accelerated the completion of comprehensive studies on the decarbonisation of gas consumption in Victoria and South Australia. Plans have also been established to inject 10% renewable hydrogen into selected regional towns. Their project timeline proposes completing a state-wide 10% renewable gas blend and feasibility studies for state-wide 100% renewable gas conversion in South Australia and Victoria in Q1 2022.

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[39] Role of power-to-gas in an integrated gas and electricity system in Great Britain, Cardiff School of Engineering, https://doi.org/10.1016/j.ijhydene.2015.03.004

[40] Portgás studies the feasibility of hydrogen injection in the natural gas distribution network, with collaboration from INEGI, INEGI, March 2021, http://www.inegi.pt/en/news/portgas-studies-the-feasibility-of-hydrogen-injection-in-the-natural-gas-distribution-network-with-collaboration-from-inegi/

[41] Portgás and INEGI create a laboratory to simulate hydrogen injection into the natural gas network, INEGI, April 2022, http://www.inegi.pt/en/news/portgas-and-inegi-create-a-laboratory-to-simulate-hydrogen-injection-into-the-natural-gas-network/

[42] Investigating hydrogen networks through industry and government collaboration, Australian Gas Infrastructure Group, https://www.agig.com.au/australian-hydrogen-centre

3.1.3 Policies for Injection into Existing Gas Networks

In July 2020, the EU Commission issued a strategic roadmap for the European hydrogen sector. The roadmap discusses the importance of hydrogen in Europe in the coming decades to decarbonise its economy and the importance of using and repurposing its existing pipeline infrastructure to enable this transition[43].

The US Department of Energy announced its Hydrogen Program Plan in 2020[44] to accelerate research, development, and deployment of hydrogen and related technologies in the United States. The plan promotes the applicability of hydrogen in comparison to other fossil resources. The objective of the Hydrogen Program Plan is to research, develop, and validate hydrogen related technologies such as fuel cells and gas turbines. The plan also addresses institutional and market barriers and will attempt to ultimately enable adoption across multiple applications and sectors.

On 4th November 2021, the United Arab Emirates (UAE), represented by the Ministry of Energy and Infrastructure, announced its Hydrogen Leadership Roadmap[45]. This comprehensive national blueprint supports low-carbon domestic industries, aiding the country's net-zero ambition. The roadmap will aim to establish the country as a competitive exporter of hydrogen. The UAE has become the first country in the Middle East and North African region to announce a strategy to achieve net-zero GHG emissions by 2050.

Japan became the first country in the Asia Pacific region to adopt a focused approach to developing its hydrogen economy when the government released its "Basic Hydrogen Strategy" in 2017. Today, it continues to lead the way in the sector. 11 companies in Japan, including hydrogen station operating businesses, automobile manufacturers, and financial investors, jointly established Japan H2 Mobility in 2018. The number of companies has increased to 26 as of 2021. Japan H2 Mobility launched 24 more hydrogen stations in Japan in the fiscal year 2020-21 (April-March) as part of the Ministry of Economy, Trade and Industry's target to install 160 hydrogen stations in the fiscal year

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[43] A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020, https://knowledge4policy.ec.europa.eu/publication/communication-com2020301-hydrogen-strategy-climate-neutral-europe_en

[44] Department of Energy Hydrogen Program Plan, U.S. Department of Energy, November 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

[45] UAE announces Hydrogen Leadership Roadmap, reinforcing Nation's commitment to driving economic opportunity through decisive climate action, WAM, November 2021, http://wam.ae/en/details/1395302988986#:~:text=The%20Hydrogen%20Leadership%20Roadmap%20comprises,well%20as%20other%20priority%20UAE

2020-21[46]. Of the total 152 hydrogen stations in Japan as of 2021, Japan H2 Mobility accounted for 63 of these[47]. Japan's end goal by 2030 targets 1,000 operating hydrogen stations nationwide.

The United Kingdom, Ireland's closest neighbour and our only means of importing and exporting natural gas, has developed a comprehensive green hydrogen implementation roadmap. The UK government have introduced their UK Hydrogen Strategy to implement a £240 million Net Zero Hydrogen Fund[48]. The UK government currently supports hydrogen innovation through several mechanisms, including the HySupply competitions, Industrial Fuel Switching competition, and Hy4Heat programme[48]. Supporting technical improvement and commercialisation of new hydrogen technologies will remain a key priority as the UK government develops the £1 billion Net Zero Innovation Portfolio. This fund, as outlined in the UK's Ten Point Plan, was established to enable acceleration of commercialisation of low-carbon technologies and systems for net zero emissions. Hydrogen project developers have to date also been able to access government co-investment through the £315 million Industrial Energy Transformation Fund, £170 million Industrial Decarbonisation Challenge and £10 million Green Distilleries Fund, all of which support deployment of low carbon technologies, including hydrogen. The Net Zero Hydrogen Fund is designed to provide initial co-investment for new low carbon hydrogen production to de-risk private sector investment and reduce the lifetime costs of low carbon hydrogen projects. The Hydrogen Business Model provides longer-term revenue support to hydrogen producers to overcome the cost gap between low carbon-hydrogen and higher carbon fuels to enable producers to price hydrogen competitively and help attract private sector investment in hydrogen projects.

The UK government is considering whether to support the blending of low carbon hydrogen into the current gas network. This blending would help with the initial development of the hydrogen economy in the UK. The 'Ten Point Plan' set commitments to complete necessary testing of blending up to 20 per cent hydrogen into the gas grid by 2023[49]. The Energy White Paper has also noted the ambitious intentions to enable up to 20 per cent hydrogen blending on the networks by 2023 but is subject to trials and testing. Safety demonstrations such as HyDeploy and FutureGrid are underway

[46] Japan H2 Mobility aims to launch 24 more hydrogen stations in 2020-21, S&P Global, April 2020, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/042420-japan-h2-mobility-aims-to-launch-24-more-hydrogen-stations-in-2020-21

[47] Japan JHyM to add four new hydrogen stations, H2Bulletin, 10th May 2021, https://www.h2bulletin.com/japan-jhym-to-add-four-new-hydrogen-stations/

[48] UK Hydrogen Strategy, Secretary of State for Business, Energy & Industrial Strategy, August 2021, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

[49] The Ten Point Plan for a Green Industrial Revolution, HM Government, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

to explore the potential for blending at distribution and transmission network pressures and investigate the impacts on end-use. The current gas system is not currently equipped to accommodate hydrogen. Consequently, the UK government is working closely with key delivery partners to assess the regulatory, physical and system changes required across the gas market to facilitate blending.

The 'Ten Point Plan' outlined that over £4 billion of private investment could be unlocked between 2020 and 2030, positioning the UK hydrogen sector to deploy projects at scale in the 2030s and supporting the growing global market. The new UK Infrastructure Bank (UKIB) launched in June 2021 will provide leadership to the market in developing new technologies, including hydrogen, particularly in scaling early-stage technologies that have moved through the R&D stage. UKIB will have an initial £12 billion of capital and will invest in local authority and private sector infrastructure projects. It will also provide an advisory function to help develop and deliver projects. The investments described above will likely initiate further private investment and will accelerate the progress towards a net-zero economy. The UK hydrogen 2020s roadmap can be seen in Figure 2.

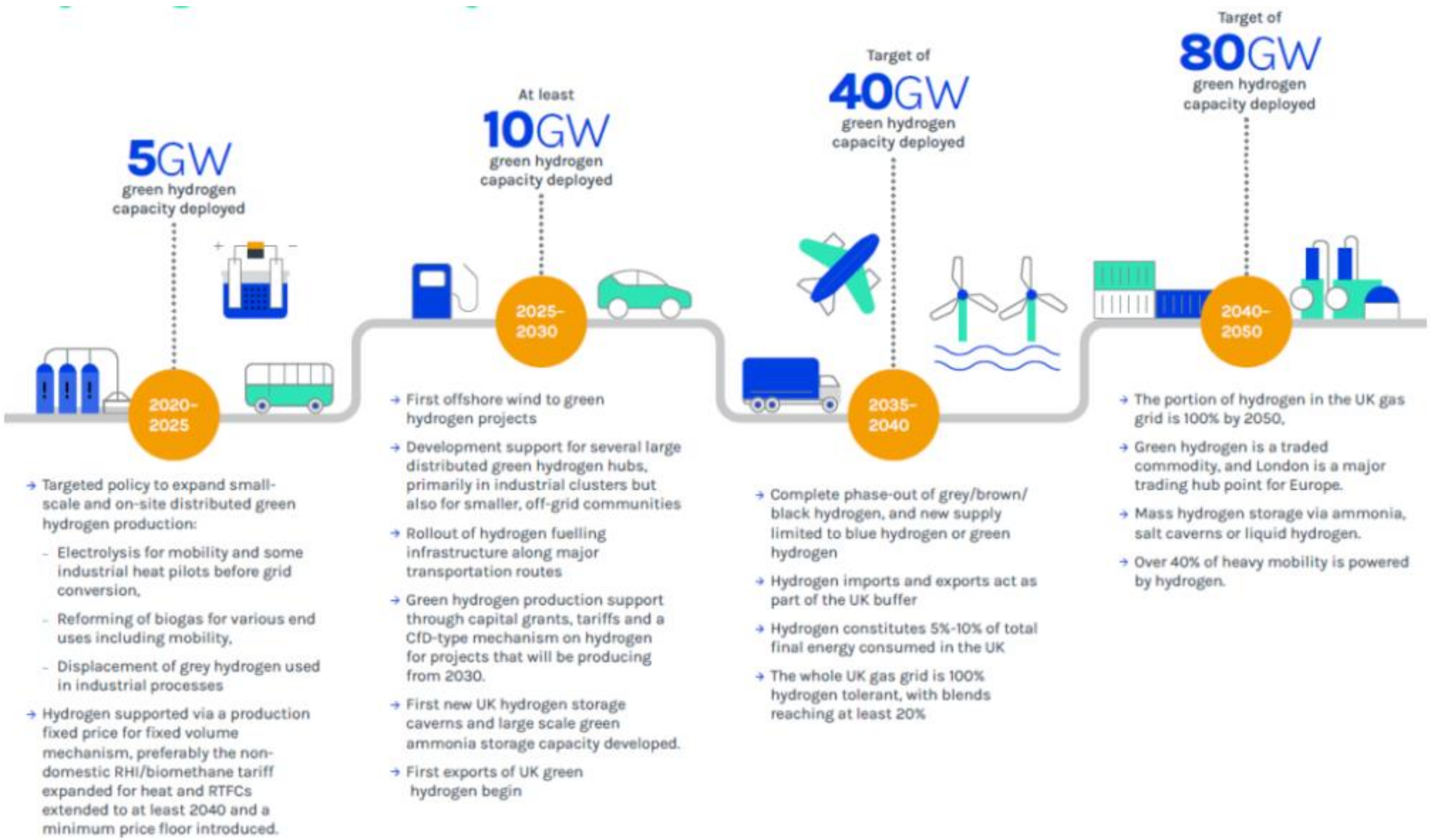

Figure 2: Rollout plan for a UK hydrogen economy[50]

[50] UK Government Must Implement Hydrogen Roadmap Now if Net Zero Is to Be Achieved, FuelCellWorks, February 2021, https://fuelcellsworks.com/news/uk-government-must-implement-hydrogen-roadmap-now-if-net-zero-is-to-be-achieved/

3.2 Irish Progress on Hydrogen Projects

Countries worldwide emphasise national strategies and incentives for energy developers to enhance their green hydrogen economy. These governments see green hydrogen as a viable method of decarbonizing their electricity, transport, and heating sectors. Many private and public development companies have taken interest and have demonstrated pilot projects to generate, store, and transport green hydrogen at a utility scale. Ireland is currently behind in terms of hydrogen investment and development compared with other countries and bodies worldwide.

Ireland's political leaders have created a set of roadmaps designed to bring the country back on track without negatively affecting economic prosperity. As a first step, Ireland's coalition government agreed to annual 7% GHG emissions cuts until 2030[51]. Meeting our Climate Action Plan targets for 2030 and 2050 will require significant commitment and financial investments from the public and private sectors. Hydrogen could potentially be one of these investments that will enable Ireland to reach our climate goals

3.2.1 Gas Network Irelands Climate Goals

Gas Networks Ireland (GNI) has set ambitious climate goals, including zero net carbon emissions by 2050, as outlined in its *Vision 2050, A Net Zero Carbon Gas Network for Ireland* document. More specifically, GNI aims to achieve the following:

- Hydrogen deployment; a zero CO2 emissions, combustible, and flexible fuel source.
- Implementing power to gas (P2G) that uses renewable electricity to split water into hydrogen and oxygen[52].

The abatement of emissions from the natural gas sector is a critical step toward achieving Ireland's GHG emissions reduction targets. This will require a significant change in how GNI provides services to the citizens of Ireland. GNI has set a goal of decarbonizing its gas supply by 20% before 2030 and 50% by 2050.

[51] Ireland's National Energy and Climate Plan 2021-2030, Department of the Environment, Climate and Communications, 15th June 2020, https://www.gov.ie/en/publication/0015c-irelands-national-energy-climate-plan-2021-2030/
[52] Vision 2050, Gas Networks Ireland, https://www.gasnetworks.ie/vision-2050/

Ireland is a very suitable location to implement green hydrogen production due to the large amounts of wind generation. However, because of the issues associated with the Irish grid infrastructure, much of the renewable wind energy cannot be used and is curtailed. This curtailment presents an ideal opportunity to establish grid-connected green hydrogen production facilities in Ireland by using this energy to generate the hydrogen.

3.2.1.1 Climate Action Plan Actions

In conjunction with GNI's Vision 2050 document, progress towards the development of renewable gas in the gas grid in Ireland is currently in progress[53]:

- The Department of Environment, Climate and Communications (DECC) will establish secondary legislation establishing GNI's renewable gas registration scheme by Q2 2022.
- A completed assessment of the impacts on network operation, integrity, and end users' appliances will be carried out by GNI by Q4 2022, which assesses the technical feasibility of safely injecting green hydrogen blends into the gas grid.
- The DECC is currently assessing the potential for energy system integration between the electricity and gas networks, including the production, storage, and use of green hydrogen.

For hydrogen use in heavy commercial transport such as buses, a pilot project by the National Transport Authority will be carried out. This will review the performance of hydrogen fuel cell double-deck buses and is set to be published by Q4 2022. To support the development of renewable gas, such as biomethane or hydrogen, as a transport fuel in the transport sector, the CRU is engaging with relevant stakeholders regarding the renewable gas registry to support certification requirements for grid-injected renewable gases in the transport sector. The registry is presumed to be established by Q4 2022[53].

A study reviewing the profile, sustainability, and supply of transport fuels in Ireland (such as biofuels, advanced biofuels, e-fuels, synthetic fuels, biogas, and green hydrogen) is currently

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[53] Hydrogen and Ireland's National Gas Network, GNI, 2022, https://www.gasnetworks.ie/vision-2050/decarbonisation-by-sector/electricity/Hydrogen-and-Irelands-National-Gas-Network.pdf

being developed by the Department of Transport (DOT) with the proposed output of a research report including recommendations for sustainable biofuels policy development.

3.2.2 Pilot Projects

There are a limited number of green hydrogen pilot projects in Ireland as adoption of the technology in Ireland is still in the early stages. This section will discuss the pilot projects currently in development in Ireland.

3.2.2.1 SSE Consortium, Galway Hydrogen hub

In April 2022, a consortium including SSE renewables and the port of Galway has unveiled plans for Ireland's first Hydrogen Valley. The consortium plan to develop a flagship demonstrator project at Galway harbour for the production (from renewable resources) and supply of clean hydrogen fuel for public and private vehicles. This hub is expected to be fully operational by the second half of 2024[54].

3.2.2.2 Aghada 50MW Electrolyser, Co. Cork

A 50MW electrolyser is due to be built by EI-H_2 in Aghada, County Cork by 2023[55]. This project will aim to produce approximately 20 tonnes of green hydrogen per day for the commercial market once operational. It has been announced that the project will cost €120 million upon completion and is forecasted to avoid 63,000 tonnes of carbon emissions each year. The P2G plant enables the production of green hydrogen to be added to existing natural gas supplies, which will aid in abating carbon emissions.

3.2.2.3 H-Wind Project

The H-Wind project is led by UCC MaREI Research Centre and co-funded by Science Foundation Ireland, GNI, DP Energy, ESB, and Equinor ASA. The project will develop green

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[54] Galway sets out stall for hydrogen hub, BusinessPlus, 15th April 2022, https://businessplus.ie/news/galway-hydrogen-hub/

[55] Energy company plans €120m hydrogen facility near Cork harbour, Kevin O'Sullivan, May 2021, https://www.irishtimes.com/business/energy-and-resources/energy-company-plans-120m-hydrogen-facility-near-cork-harbour-1.4574726

hydrogen using offshore wind[56]. The project will last three years and will be completed by 2024. The primary focuses of the project are:

- Utilizing green hydrogen as the interface between offshore wind energy, gas network markets, electricity system markets, and developing new markets for zero-carbon green hydrogen.
- Ensuring the delivery of the EU strategy on energy system integration and helping with the government's 2050 targets.
- Large-scale hydrogen production from offshore wind farms by developing hydrogen hubs for the Irish, Celtic, and Atlantic Seas, along with focuses on hydrogen storage and transportation.
- Research into the customer value chain, policy recommendations, hydrogen safety procedures, and scalable optimized offshore wind concepts.

3.2.2.4 GENCOMM[111]

GENCOMM will validate the maturity of hydrogen technologies by implementing three pilot plants that link the three primary northwest European renewable sources (solar, wind, and bioenergy) with energy storage and the primary forms of energy demand (heat, power, and transportation fuels). GENCOMM aims to produce a "Decision Support Tool" to provide a roadmap for northwest European communities to transition to renewable, hydrogen-based energy. The project aims to:

- Empower communities to implement hydrogen-based primary energy sources to satisfy their energy demand sustainably.
- Stimulate the uptake of renewable hydrogen-based technologies by successfully running three demonstration facilities.

[56] H-Wind Project, MaREI, https://www.marei.ie/new-h-wind-project-to-advance-development-of-hydrogen-energy-in-ireland

3.2.3 Research

Efforts to research the implementation of hydrogen into the gas network and enable end-use applications from renewable hydrogen are currently taking place. Certain institutions such as UCDEI and GNI are carrying out studies to resolve hydrogen implementation issues.

Gas Networks Ireland (GNI) and researchers from University College Dublin's Energy institution (UCDEI) are currently studying the effects of hydrogen blend fuel in Irish homes and pipelines. These tests use the facilities at UCDEI's Integrated Energy Lab and GNI's new hydrogen innovation facility in west Dublin[57].

NUI Galway is the leading university in Ireland in the field of green hydrogen research (Dr Rory Monaghan and Dr Pau Farras). Below is a summary of relevant projects in recent years.

- GREEN HYSLAND; FCH-03-2-2020; Dr Farràs and Dr Monaghan as partners; 01/2021 to 12/2026; €20M. NUIG's role is to study green hydrogen's socioeconomic and technoeconomic consequences in Ireland.
- FLOWPHOTOCHEM (www.solar2chem.eu); H2020-NMBP-25-2019; Dr. Farràs Coordinator; 05/2020 to 04/2024; €7M. NUIG will model and simulate the production of solar green hydrogen-based fuels and chemicals.
- SEAFUEL (www.seafuel.eu); INTERREG Atlantic Area programme; Dr. Farràs Lead Partner; 12/2017 to 11/2020; €3.6M. The project will demonstrate the feasibility of wind and solar-powered green hydrogen production on island communities in Spain and Ireland.
- GenComm (http://nweurope.eu/gencomm); INTERREG North-West Europe programme; Dr Monaghan WP leader; 03/2017 to 09/2021; €9.3M. The project demonstrates green hydrogen supply chains in Northern Ireland, Scotland, and Germany. NUIG's role is to optimise the hydrogen supply chains for economic and environmental performance.
- HyLIGHT; Dr Monaghan Coordinator; 04/2021 to 03/2024; €1.6M. Science Foundation Ireland and industry-funded project to devise a hydrogen roadmap and strategy for Ireland.

[57] Can Ireland warm homes and cook dinners with hydrogen? Gas Networks Ireland, November 2021, https://www.gasnetworks.ie/corporate/news/active-news-articles/hydrogen-ucd/

- Sustainable Energy Authority of Ireland (SEAI); Dr. Rory Monaghan; 03/2020 to 09/2023; €1.5M combined. The SEAI have funded three research projects which investigate hydrogen integration with wind energy in Ireland.

3.3 Challenges

Ireland is taking steps towards implementing green hydrogen into the power and transport sector. However, there are several issues slowing the implementation of green hydrogen injection into the Irish natural gas pipelines, which are discussed below.

3.3.1 Incomplete Policy

Ireland doesn't currently have a hydrogen strategy. However, GNI has published its "Hydrogen and Ireland's national gas network" document[58]. It outlines that the Department of the Environment, Climate and Communications (DECC) will develop a policy and regulatory roadmap for green hydrogen injection into the gas network as part of the Climate Action Plan 2021 and will be delivered by Q1 2023. Upon completion of the roadmap, the role of green hydrogen will be to abate emissions in hard to decarbonise sectors such as heavy commercial transport, high-temperature process heating, and heavy industry.

Asset management requirements for hydrogen blending and injection facilities, as well as other gas network assets, will need to be developed for to ensure that hydrogen-related assets on the gas network meet the necessary safety standards and operational requirements over their life cycle. The CRU has set out a code of operations to govern the relationship between GNI and the gas shippers (companies that buy and sell gas and arrange for the transportation of gas through networks owned by gas transporters) on the gas network. This code of operations outlines regulatory compliance, capacity arrangement, nominations (requests to move gas from one location to another under contract) and allocation arrangements, balancing, shrinkage, gas specification and quality, and other market arrangements. Clauses related to hydrogen blending will need to be added to the code of operations to govern how hydrogen is injected into the gas network and transported to end-

[58] Hydrogen and Ireland's national gas network, Gas Networks Ireland, 2022, https://www.gasnetworks.ie/vision-2050/decarbonisation-by-sector/electricity/Hydrogen-and-Irelands-National-Gas-Network.pdf

users. Physical limitation such as the percentage of gas flows permitted, pipeline capacity and storage arrangements will have a bearing on the new code rules.

3.3.2 Storage and Transport of the Hydrogen

One of Ireland's most significant barriers to developing a functioning hydrogen economy is storage. Hydrogen's unique physical properties present issues when trying to store or transport it. It is necessary to ensure high levels of safety to avoid possible leaks due to the flammability of hydrogen while also keeping it in the tightest possible space despite hydrogen having a large volume per unit of energy in its gaseous state. However, new and innovative ways of storing hydrogen are still emerging. The most commonly known methods include compression, liquefaction, and trapping hydrogen in other materials.

Another issue that could arise is losing the ability to import natural gas from the United Kingdom. Research and investment are being carried out to inject blends of up to 20% green hydrogen into the gas network pipelines in the UK. Suppose research and development of this type of infrastructure are implemented in the UK. In that case, this could result in the two countries using gas with incompatible compositions, which would remove the option of gas trade. This could also be seen as a benefit, as if both Ireland and the UK were to use a similar gas blend, trade would resume with the possibility of Ireland being able to export pure hydrogen to the UK for use in their gas network. This would be preferable to the current situation of exclusively importing pure natural gas at the moment.

3.3.3 Safety of Hydrogen Transportation

The CRU oversees the Gas Safety Framework (GSF) in Ireland and is responsible for the safety regulations regarding the gas network. All natural gas undertakings are required to be licensed by the CRU[59]. A safety case must be submitted to the CRU in order to apply for a license. This safety case must outline how the risks are being managed for the specified natural gas undertaking. The CRU currently licenses GNI to transmit and distribute natural gas in Ireland. If an incident occurs involving a death, hospitalisation, property damage in excess

[59] CRU Gas Safety Framework https://www.cru.ie/professional/safety/gas-safety-framework/

of €6,348.69, or if GNI believes there is valuable information to be gained from the incident, a report will be submitted to the CRU

Hydrogen may only be injected into the gas network if a safety case outlining the risks involved with such a process and how they will be managed is submitted to the CRU. The process will include completing an "As Low as Reasonably Practicable" risk assessment. Evidence of competency of the contractors and employees involved in such a project should also be developed by GNI to support the safety case. GNI has commenced the development of a safety case for hydrogen, which will ultimately require review and acceptance by the CRU.

3.3.4 Hydrogen Embrittlement of Transmission Lines

The gas network infrastructure in Ireland consists of transmission and distribution pipeline systems. The distribution network transports gas at 7bar to 20mbar and is made of polyethylene. Hydrogen embrittlement will be one of the biggest roadblocks when considering the injection of hydrogen into the gas network. However, extensive studies by the International Gas Union Research Conference found that high-density polyethylene piping used in the distribution network shows no degradation with pure hydrogen flowing for up to 10 years[60]. However, hydrogen embrittlement of steel (like in the transmission network) is a well-studied issue. The pipes are usually made from steel alloys that transport gas at pressures between 85 bar and 7 bar for transmission networks. Hydrogen can cause brittleness of steel alloyed pipes, which can affect the failure resistance of the pipe. This has consequences for the safety and lifetime of the pipeline. The small size of the hydrogen atom allows it to diffuse through the lattice structure of the material[61], leading to effects such as hydrogen-induced cracking and in-bulk dissipated damage. Suppose the pipeline has also been operating under fluctuating pressures. In that case, the pipe wall is more sensitive to diffusion degradation than a pipeline of the same material that has been run under constant pressure. Another concern raised regarding transporting hydrogen in existing gas grids is the propensity of

[60] Using the Natural Gas Network for Transporting Hydrogen – Ten Years of Experience, Henrik Iskov, Stephan Kneck, 2017, https://arkiv.dgc.dk/sites/default/files/filer/publikationer/C1703_IGRC2017_iskov.pdf
[61] Hydrogen embrittlement of steel pipelines during transients, Zahreddine Hafsi, Manoranjan Mishra, Sami Elaoud, 2021, https://doi.org/10.1016/j.prostr.2018.12.035

hydrogen to leak. However, several studies have concluded that leakage rates would not be high enough to be a significant concern[62].

3.3.5 Loss of Energy Density

Hydrogen is less energy-dense than most hydrocarbon fuels (nearly three times less dense than methane). This difference in energy density reduces the energy deliverable by the natural gas pipeline that contains hydrogen blends. This effect is nonlinear and depends on the energy density by volume and the flow properties of hydrogen. As hydrogen is less compressible than natural gas, as the ratio of hydrogen rises, increased pressures must be applied to deliver the same amount of energy using the same pipelines. This problem means that to generate the same amount of energy that natural gas produces, 3.2 times more hydrogen (by volume) is needed[63]. Higher pressure transportation of gas is required because of this. This issue does not necessarily imply that the cost spent on hydrogen will be 3 times more than natural gas, however. Figure 3 shows the energy delivery of pipelines at low (0.5 bar) and intermediate (5 bar) pressure levels, with increasing levels of hydrogen injection as a percentage of the energy delivery of pure methane. In order to manage the reduced energy delivery in gas networks, either peak energy demand would need to be reduced (which isn't a favourable option) or higher flow rates (causing more significant pressure drops and higher compression requirements) would be higher needed. The effects of increased pressure must be considered, such as increased embrittlement effects and the safety concerns of high-pressure combustible gas.

[62] Blending Hydrogen into Natural Gas Pipeline Networks, A Review of Key Issues, National Renewable Energy Laboratory, 2013, [Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues (nrel.gov)]

[63]Sofoklis, S. and Makridis. (2016). Hydrogen storage and compression. https://arxiv.org/ftp/arxiv/papers/1702/1702.06015.pdf

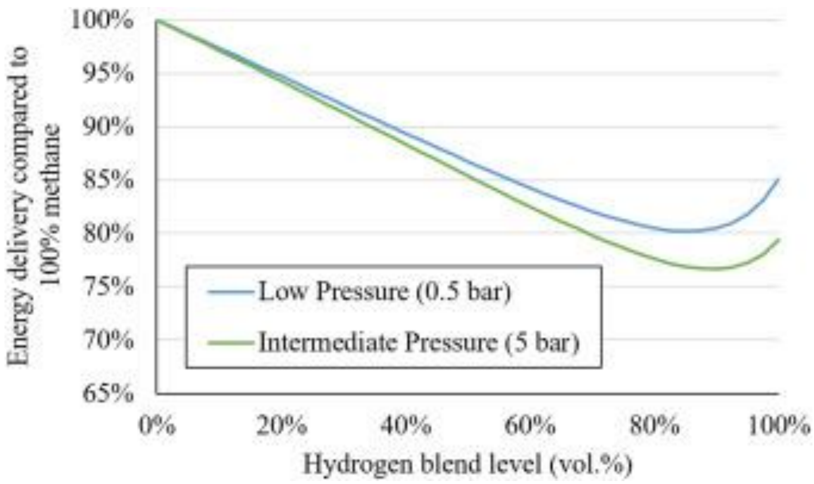

Figure 3: Graph displaying the effect of hydrogen blend level on the energy delivery of gas pipelines (based on the relationships described in [64])

3.3.6 End-use Applications

Further safety concerns arise when considering hydrogen in the home, particularly regarding leakage and risk of ignition. Hydrogen also burns differently than hydrocarbon fuel types. Hydrogen combustion is efficient for converting fuel into heat energy; however, this brings about several safety and engineering challenges. For example, hydrogen has a higher risk of ignition than natural gas, and, as with natural gas, it may be necessary to add an odorant to hydrogen to improve detectability. It may also be required to add a colourant as, unlike natural gas, a pure hydrogen flame is almost invisible[65]. Multiple studies have considered the effects hydrogen would have on the performance of household appliances, notably the NaturalHy project[64]. Since hydrogen ignites with almost any air-to-fuel ratio, electrical equipment must be entirely spark-proof and insulated. Saying this, it has been found that end-use appliances will only suffer from relatively minor issues as most modern appliances (such as stovetops, fireplaces, tumble dryers, etc.) should be capable of burning hydrogen blends of between 20 - 50 vol%[5] with minimal technical adjustments. This is unlike home gas boilers which fail at relatively low hydrogen blends. Above this level, appliances would likely need adjusting or replacing, which would be a major undertaking.

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[64] Safe operation of natural gas appliances fuelled with hydrogen/natural gas mixtures (Progress obtained in the naturalHy-project), NaturalHy, 2007, Steady state analysis of gas networks with distributed injection of alternative gas | Elsevier Enhanced Reader

[65] Injecting hydrogen into the gas network – a literature search, Health and safety Laboratory, 2015, Injecting Hydrogen into the Gas Network- A Literature Search | Hydrogen Knowledge Centre (h2knowledgecentre.com).

3.3.7 Cost of Electrifying Natural Gas-fired Heating Appliances in Buildings

There are benefits to using hydrogen over electrifying a home as over longer distances, electricity is more expensive to transport (not accounting for efficiency losses when producing hydrogen). Another benefit to using hydrogen in a home is that minimal hardware retrofitting is required. New appliances must be purchased to convert from a “gas-powered” to an “electricity-powered” home (for heating and cooking); however, the same gas-powered appliances can be used for lower hydrogen blends.

3.4 Benefits

Development of green hydrogen production, storage, and injection into the existing natural gas networks in Ireland has numerous advantages for GNI, the Irish consumer, and renewable energy developers. This would help to bring Ireland to the forefront of the green hydrogen economy, maximize and store Ireland’s vast wind resources, address the local TSO's stability and reliability needs, and take advantage of the country’s existing gas pipeline infrastructure.

3.4.1 Hydrogen for Industrial Processes and High-Temperature Heat

Fossil-based hydrogen has supplied industrial processes for decades. With an expansion of green and blue hydrogen production in the near future, an opportunity will present itself to lower the carbon footprint of these processes. Whilst this is the more expensive alternative currently, prices of green hydrogen will decline as economies of scale increase for both renewable energy and hydrogen infrastructure.

Over 50% of all hydrogen produced globally is used for ammonia production. Typically, hydrogen is produced on-site at ammonia plants from a fossil feedstock via Steam Methane Reforming (SMR). This hydrogen will then be reacted with nitrogen to produce ammonia via a large-scale Haber-Bosch process. The vast majority of this ammonia is then used for producing fertiliser. Therefore, with ammonia’s dependency on hydrogen and the continuous worldwide need for this process, hydrogen demand (particularly the green variety) is likely to continue. The global green ammonia market was valued at $2.91 billion in 2021 and is projected to reach $29.01 billion by 2027 at a compound annual growth rate of 46.70%[66]. Other potential uses for industrial processes include the petrochemical industry, metal manufacturing, electronics, power generation, and steel production.

3.4.2 Hydrogen for Wind Curtailment

As an island network, Ireland currently has one of the highest renewable wind penetrations in Europe, only exceeded by Denmark. The level of wind penetration by country can be viewed in Figure 4. Ireland currently has 4.5 GW of onshore wind,[67] 11.4% of which is curtailed on average each year[68]. With plans to develop more wind generation both on and offshore in Ireland moving into 2030 (Approximately 10 GW[10]), the amount of curtailed energy is also expected to increase.

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[66] Green Ammonia Market – Global Industry Analysis and Forecast (2022-2027), MMR, https://www.maximizemarketresearch.com/market-report/global-green-ammonia-market/115753

[67] Wind energy supplied record high of 53% of electricity demand in February, Wind Energy Ireland, March 2022, https://windenergyireland.com/latest-news/6344-wind-energy-supplied-record-high-of-53-of-electricity-demand-in-february

[68] National Energy and Climate Plans for the island of Ireland: wind curtailment, interconnectors and storage, David Newbery, November 2021, https://doi.org/10.1016/j.enpol.2021.112513

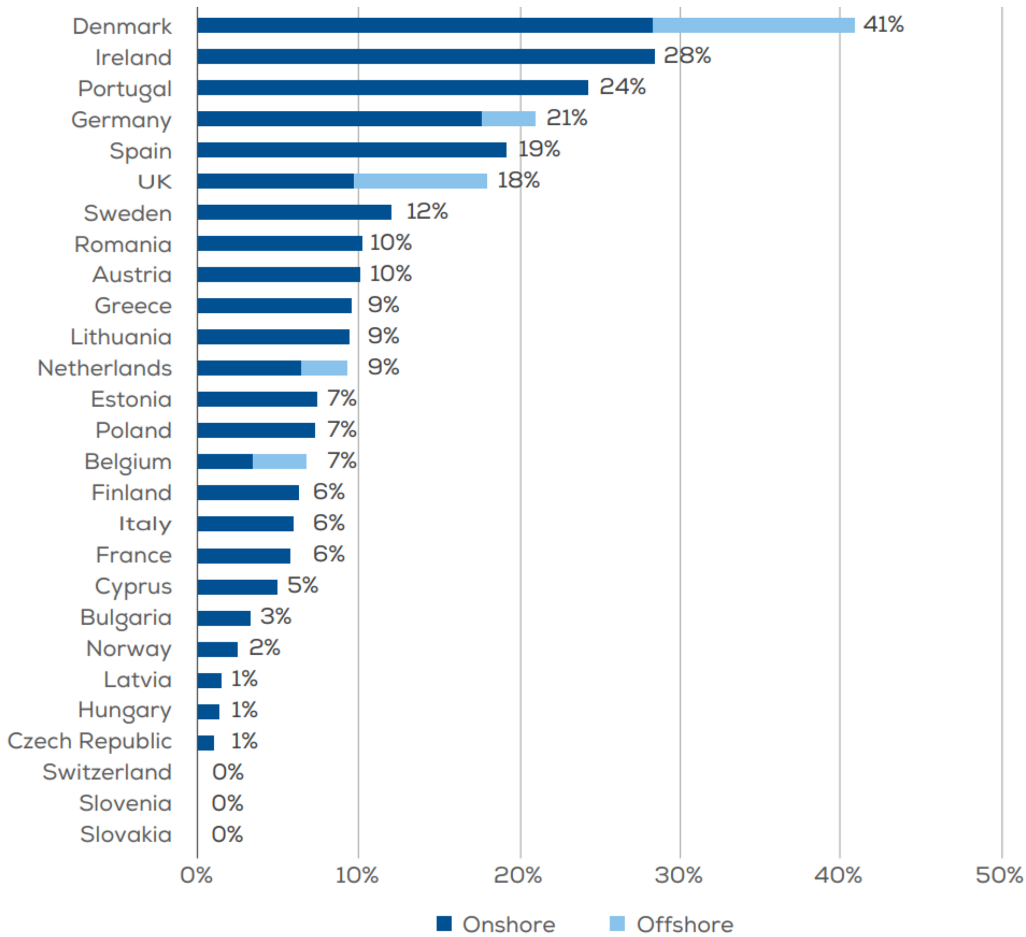

Figure 4: Relative level of wind penetration on the electrical power grid of EU nations (2018)[69].

Whilst most Renewable Energy Sources generate intermittently, hydrogen can facilitate supply/demand balancing, enabling 'time-shifting' via storage mechanisms. Using this same mechanism, electrical grid capacity constraints can also be mitigated. In addition, any excess power generated at peak production times (e.g., particularly windy/sunny days), which would typically be wasted, can instead be used to power electrolysers, generating renewable hydrogen.

Many of Ireland's large wind farms may be suitable for on-site electrolysis, like the GenComm project at Long Mountain. Another option would be to connect electrolysers to the grid rather than directly to a wind farm, allowing access to the electricity system through the integrated single electricity market (ISEM). Such electrolysers could also provide ancillary services to the electricity grid, further increasing the grid's reliability.

[69] Wind energy in Europe in 2018, Wind Europe, 2018, https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf

3.4.3 Reduced Investment in the Irish Electricity Transmission Network Infrastructure

The Irish electricity transmission grid is currently under strain, resulting in locations where renewable energy generation development is inadvisable due to grid constraint issues. EirGrid (Irish TSO) presented this conclusion in the "Shaping Our Electricity Future" roadmap and determined that significant investment in the Irish transmission grid will be needed to counteract these constraint and congestion issues. Below is a table representing the CAPEX investment proposed by EirGrid to reinforce the system[70].

Category	Ireland(€M)	Northern Ireland (£M)
Current and future programme	2,117	140
Shaping Our Electricity Future	1,103	134
Total	3,220	274

Table 1:Transmission network reinforcement investment needed for 2030 in Ireland, shaping our electricity future roadmap

Here we can see that the Irish TSO forecasts over €3.2 billion in investment into the electrical transmission grid by 2030 to enable a reliable and decarbonised transmission network. Injecting hydrogen into the existing infrastructure can be seen as a good investment in this context. This is because we are essentially coupling these two transmission networks by injecting hydrogen into the gas network using curtailed energy. This would enable the existing gas network to compensate for at least some of this projected investment needed by the electricity transmission network.

3.4.4 Transport

The transport sector could benefit massively from hydrogen production in Ireland. Average emissions from road transport in the 2015-2019 period in Ireland averaged to be 11.6MtCO_2 (Reduced to 9.7MTCO_2 in 2020)[71]. If hydrogen production is implemented in Ireland, the market for hydrogen fuel-cell based vehicles can be established, supporting the decarbonisation of the Irish transport economy. In Ireland, buses are the most commonly

[70] Shaping our electricity future, EirGrid, SONI, November 2021, http://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf
[71] Environmental Protection Agency Transport Statistics. https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/transport/

used mode of public transport, followed by trains. The transition to zero-carbon bus and train fleets in Ireland will likely require a mixture of electric and hydrogen-powered buses/trains. A transition of the Dublin metropolitan PSO bus service to low/zero emissions is currently being researched by the National Transport Authority (NTA). A pilot of hydrogen fuel cell double-deck buses is being carried out to review performance, with findings to be published by Q4 2022. Implementing a hydrogen economy in Ireland would ensure that the energy required to power the public transport fleets is sourced from renewable energy. This would abate emissions in the transport sector in Ireland. This sector contributes to 40% of energy-related GHG emissions prior to the Covid-19 pandemic in Ireland[72] (reduced to 17.9% during the Covid pandemic due to reduced workforce travel; however, this can be expected to return to a significant share as the Irish workforce returns[73]).

Hyundai has already delivered 46 heavy-duty trucks to Switzerland as of July 2021 and plans to deploy a further 1600 vehicles in the country by 2025. The Port of Rotterdam and Air Liquide have created an initiative to deploy 1000 fuel cell trucks by 2025, and a joint call signed by over 60 industrial partners aims for up to 100,000 trucks by 2030. According to the IEA's Net-Zero by 2050 Roadmap to have a global carbon-neutral energy sector, it is projected that by 2030 more than 15 million hydrogen fuel cell vehicles will be needed. Based on current and announced capacity, the IEA estimates that fuel cell manufacturing could enable a stock of 6 million FCEVs by 2030, satisfying around 40% of Net Zero Emissions in the global energy sector by 2050[24].

3.4.5 Long Duration Storage in Existing Gas Pipelines

Using gas pipelines as long-duration energy storage systems can be effective. The cost of hydrogen storage can be significantly reduced by storing it in pre-existing gas pipelines.

Existing natural gas infrastructure can be utilized to perform two steps in the compressed natural gas energy storage (CNGES) process: 'charging' by raising the pressure of the gas through existing compressors and 'storing' by utilizing an underground field, aboveground vessel, or a flowing pipeline. The third step, 'discharging', can be deployed by installing new

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[72] CO_2 Emissions, SEAI, https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/co2/

[73] Latest emissions data, EPA, https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/latest-emissions-data/https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/latest-emissions-data/

expander generators at existing pressure reduction stations, thereby harnessing available pressure differentials to produce electricity.

It is a cheaper option to use CNGES than compressed air energy storage (CAES) when you have access to pre-existing gas compression and transport infrastructure. CAES consists of the same process steps, but projects will typically involve the development of entirely new infrastructure for all three of the process steps. CNGES avoids the cost of two of the three process steps by integrating with existing infrastructure.

To deploy CNGES at a pipeline for long-duration energy storage in channels, the charging process transforms electrical energy into potential energy (higher pressures) and kinetic energy. For CNGES, this process occurs at natural gas compression stations. CNGES requires electrical motor-driven compressors. The controls are adapted to increase the compressor load (increasing pressure) during times of off-peak demand or during clean energy peaks, all while decreasing its load during demand peaks. This operation utilizes variations in electricity prices to minimize the costs for the system.

Storage can occur at either a closed volume (such as underground storage or aboveground cylinders) or a flowing pipeline. A flowing channel differs from other energy storage forms in that gas continuously enters and exits the system at its endpoints. The amount of hydrogen possibly stored corresponds to the energy that can be converted to electricity from the inventory of gas accumulated inside the volume of the pipeline between the minimum pressure at the end of discharge (minimum line pack) and the maximum pressure at the end of charge (maximum line pack). The maximum line pack is set to a pressure below the maximum allowable operating pressure of the pipe. The minimum line pack is set to a value above the minimum pressure needed to deliver the required gas flow. Underground and aboveground storage can be connected directly to the pipeline to increase storage capacity incrementally. The pressure in these storage facilities is usually higher than the maximum operating pressure of the pipeline to maximize energy density.

The discharging process transforms the stored energy back into electricity. Expander generators can be used at pressure reduction stations to convert the energy from the gas flow as its pressure reduces. A complementary technology to expander generators is permanent magnetic (PM) generators. These PM generators can be integrated directly onto the shaft by affixing magnets to their surface, replacing traditional induction motors or used to produce expander generators. The function of a PM generator is to convert the mechanical energy generated by a turbine into electrical energy. PM generators also boast efficiencies of up to 98%, such as the PM manufactured by ABB[74]. The power output depends on the gas flow rate, temperature, and the pressure differential. The gas flow rate depends on the natural gas demand at the low-pressure end of the pipeline.

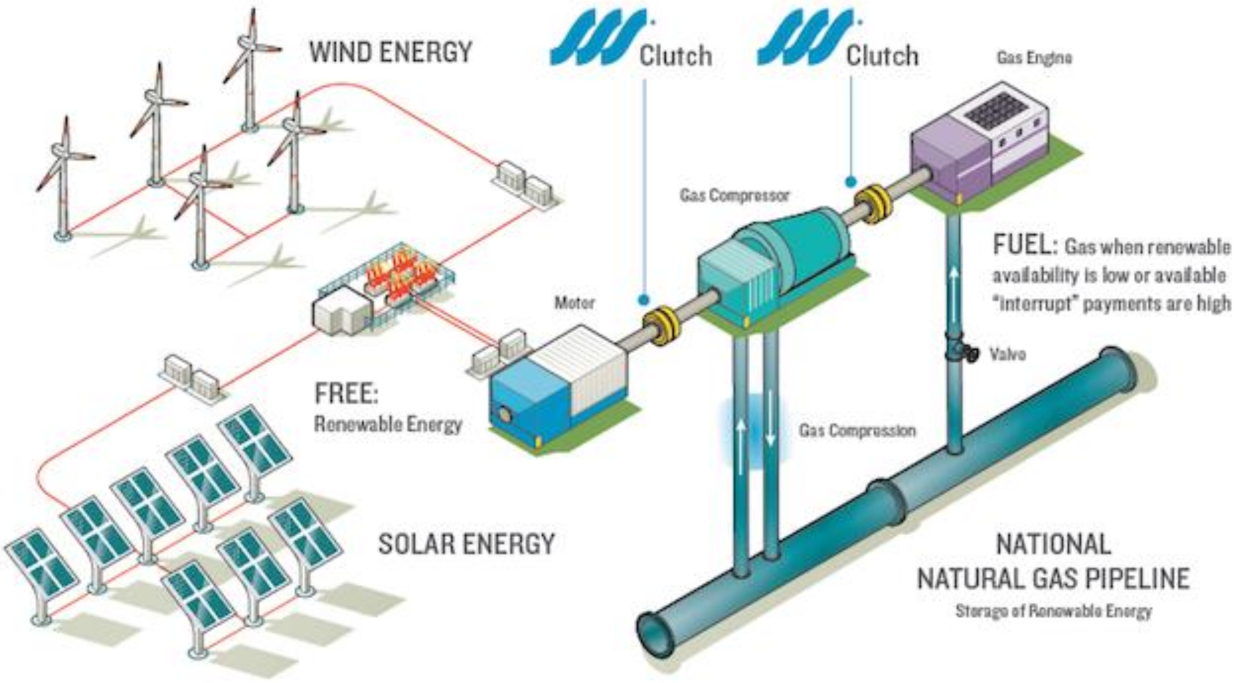

Figure 5: Diagram showing the use of cheap renewables for compressed gas storage in gas pipelines[75].

3.4.6 Importing and Exporting Hydrogen

As part of their Green Deal Vision, Hydrogen Europe proposed the target of a total of 80GW of electrolyser capacity (more than is currently installed worldwide) amongst the EU and its neighbouring countries[76]. This hydrogen plan suggests that areas of high renewable potential, whose hydrogen production potential would significantly outweigh their domestic demand,

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[74] ABB, High speed permanent magnet generators, https://new.abb.com/motors-generators/generators/generators-for-wind-turbines/permanent-magnet-generators/high-speed-permanent-magnet-generators

[75] Robb, D., Could the Pipeline Network Solve the Renewable Storage Problem? https://www.renewableenergyworld.com/storage/could-the-pipeline-network-solve-the-renewable-storage-problem/#gref

[76] Europe partners set to beat 2030 green hydrogen capacity target, Reuters, https://www.reuters.com/business/energy/europe-partners-set-beat-2030-green-hydrogen-capacity-target-says-eus-timmermans-2021-11-29/

such as Portugal, Southern Spain and Northern Africa could produce hydrogen and export it to countries which consume more than they could produce domestically.

Even today, we see first-mover projects focused on future regional clean energy transfer. Air Products & Chemicals have recently announced plans to build one of the world's largest green hydrogen production plants, with over 4GW of wind and solar power being used to produce 650 MTs of green hydrogen per day[77]. This hydrogen is likely to be exported worldwide, particularly to the EU and other climate-leading countries, in the form of hydrogen or ammonia.

Australia is already exporting hydrogen in its liquid form to Japan[78]. The first Liquid Hydrogen (LHY) tanker was launched at the beginning of 2022, operating between Australia and Japan. Such systems are being compared to, and are competing with, chemical storage options, e.g., ammonia. Suppose LHY is eventually deemed to be the preferential method and becomes mainstream. In that case, LHY systems and storage will become much more widespread.

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[77] Exploring opportunities in the Northern Ireland energy transition, NUI Galway, https://www.nweurope.eu/media/13425/hydrogen-exploring-opportunities-in-the-northern-ireland-energy-transition-march-2021.pdf

[78] World's first hydrogen tanker to ship test cargo to Japan from Australia, Reuters, 21st January 2022, https://www.reuters.com/business/environment/worlds-first-hydrogen-tanker-ship-test-cargo-australia-japan-2022-01-20/

3.5 Discussion of Possible Implementations for Hydrogen Injection in Ireland

Compressed gas storage is the most suitable hydrogen storage technology in the context of injecting hydrogen into the gas network. Typical storage pressures range from 30 bar (the pressure at which many electrolysers operate) to 700 bar (the pressure required for storage onboard hydrogen fuel cell cars). High-pressure hydrogen storage is a highly developed, mature, and commercially available technology with a TRL of 9.

One of the ways to use hydrogen is direct injection into the natural gas network. The energy content per volume of H2 is one-third that of natural gas, so injection must be carefully managed to maintain gas quality. The amount of H2 that can be mixed with natural gas depends on the network composition, flow rate and other parameters, including the structure of the pipeline network, end-use and legislation. The laws of the individual EU member states regulate the amount of hydrogen in the H2/NG mixture. However, it varies considerably from one country to another, and there is no single European position.

GNI is currently embarking on its first studies of H2 injection in the Irish gas grid. From a technical perspective, the following H2 blend limits (by volume) are estimated to be achievable for Ireland: 10% in the transmission system and 20%-100% in the distribution system (higher figures for newer grids). However, the end-use appliances that would burn the NG-H2 blend impose their own limits in the following ranges: 5% for unmodified gas turbines, 60% for specially modified gas turbines, 20% for unmodified domestic/commercial boilers, and up to 100% for new hydrogen-burning domestic boilers[5].

As an isolated electricity system with high penetration of non-synchronous renewable generation, Ireland is likely to encounter the challenges of electricity system decarbonisation before many other countries and regions in the EU. Being one of the first countries to find themselves in this situation makes Ireland an essential testing ground for technologies that facilitate the integration of non-dispatchable renewable energy like solar and wind. Curtailment and constraint of electricity generated by wind is already an issue in Ireland. With a government target to produce up to 80% of electricity from renewables by 2030, this problem will likely grow if not adequately addressed. Most of this growth in renewable energy in Ireland is likely to come from wind, both on and offshore. Though the challenge of increasing wind generation capacity to decarbonise the electricity grid is significant, Ireland's offshore wind potential far exceeds its current peak electrical demand. Estimates of this potential vary from 35-75 GW[79], making Ireland a potential future renewables superpower, with the ability to export energy to the rest of Europe in the form of electricity or electro fuels.

This huge renewable potential can also be used to take advantage of the country's modern gas grid. The network transports gas around the country for heating and power generation. Most of this fossil fuel gas is currently being imported from the UK, but there remains an excellent opportunity to decarbonise the network with indigenous biomethane and hydrogen gas sources.

There is currently a significant shortage of electricity supply in Ireland. The CRU has forecasted a need for 2GW of new natural gas generation to support the transition to a decarbonised generation fleet before 2030 [80]. This added to the nearly 4.5 GW [81] of existing gas feed conventional generation in Ireland, means that the injection of hydrogen into existing gas pipeline infrastructure can assist the decarbonisation of up to 6.5 GW of generation in Ireland by 2030. Of course, the blends of hydrogen in the gas network would have to be suitable for the current turbine technology, although initially running using a mixture of mainly natural gas could allow the prolonged operation of traditional turbine plants. Newly developed plants could transition towards 100% hydrogen as the hydrogen economy develops in Ireland. In the context of Hydrogen combustion turbines in Ireland, it's a tough market to break into due to the finite number of contracts available and the cheaper cost of natural gas as a fuel compared to hydrogen. The implementation of green hydrogen production and utilisation in Ireland would be assumed to bring these prices closer, encouraging the development of renewable hydrogen-burning turbine technology in Ireland.

With regards to the progress on the decarbonisation and expansion of renewables into Ireland's heat sector, Ireland comes last in the EU with only 6.3% of heat supplied by

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[79] Wind Energy Ireland 2021 Final Report, Wind Energy Ireland, July 2021, https://windenergyireland.com/images/files/revolution-final-report-july-2021-revised.pdf

[80] Shaping our electricity future, Eirgrid, SONI, November 2021, http://www.eirgridgroup.com/site-files/library/EirGrid/Shaping_Our_Electricity_Future_Roadmap.pdf

[81] All Island Generation Capacity Statement, Eirgrid, SONI, 2020, https://www.eirgridgroup.com/site-files/library/EirGrid/All-Island-Generation-Capacity-Statement-2020-2029.pdf

renewable energy[82]. The rollout of 600,000 heat pumps by 2030[83], powered by Ireland's abundant wind energy, is a government priority. Still, studies by the UK Climate Change Committee (CCC) in its 2020 Carbon Budget highlight the challenges of pursuing a heat pump-only heating strategy. While this will be cost-effective in most cases (the CCC estimates that heat pumps are the most cost-effective option for most homes), retrofitting all current homes and upgrading electricity distribution systems will be prohibitively expensive. Also, adopting a heat pump only strategy means that there needs to be significant over-capacity of power generation (mostly of polluting gas peaking plants) to ensure heat availability in all weather conditions. The CCC has shown that using a hybrid heat pump and hydrogen systems is the most efficient solution as hydrogen can be used during peak demand hours when electricity costs are high[84]. Because of the energy storage and system flexibility provided by hydrogen, it requires much less over-capacity. The SEAI is currently conducting a similar study for Ireland. Hydrogen can also decarbonise industry as it can attain higher temperatures than heat pumps allowing it to be used for the more intensive heating operations needed by industry. This is especially true for processes which require direct contact with a flame, such as kilns or furnaces[84].

When hydrogen is combusted, it releases no carbon dioxide (CO_2); consequently, any addition of hydrogen to the natural gas grid will result in lower CO_2 emissions at end-use. Provided the hydrogen is produced in a low carbon manner, through steam-methane reforming (SMR) with carbon capture and storage (CCS) or through electrolysis of green hydrogen, the produced hydrogen can be used as a replacement fuel which reduces CO_2 emissions. Furthermore, the coupling of the electricity and gas networks could shift some of the variability caused by intermittent renewables on the electricity grid onto the gas grid.

82 Energy In Ireland, SEAI, 2021, https://www.seai.ie/publications/Energy-in-Ireland-2021_Final.pdf
83 National Development Plan 2021-2030, Government of Ireland, https://assets.gov.ie/200358/a36dd274-736c-4d04-8879-b158e8b95029.pdf
84 Committee on Climate Change, Hydrogen in a low-carbon economy, https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

4 Hydrogen Generation, Storage, and Utilisation in the Irish Energy Sector

The injection of green hydrogen and natural gas blends into Ireland's existing gas network infrastructure would become the foundation of developing a green hydrogen economy in Ireland. This implementation would allow renewable developers and consumers to utilise green hydrogen. From a developer's point of view, hydrogen production and storage markets will open. The following section examines the technologies that could be used to generate, store, and utilise hydrogen in Ireland.

4.1 Hydrogen Generation Technologies

Power-to-gas is an important area of interest for decarbonisation while also increasing flexibility in energy systems. It has the potential to absorb renewable electricity at times of excess supply and provides backup energy in the form of gas at times of excess demand; this is long-term load shifting. By integrating power-to-gas with the natural gas grid, it is possible to exploit the grid's inherent line pack flexibility (storage of gas in pipeline) for load-shifting and storage. Furthermore, if the gas injected into the gas grid is low-carbon, such as hydrogen from renewable P2G, then there will be an overall reduction in GHG emissions from the gas grid. Before storing and utilising green hydrogen, we should first produce it in Ireland, as importing grey hydrogen would not make sense due to the high cost compared to natural gas and the increased carbon footprint compared to green hydrogen. Grey hydrogen is focused on here as this is the cheapest hydrogen found today. Grey hydrogen is produced from steam-methane reformation without carbon capture. This increases its carbon footprint while directly linking its price to that of natural gas. Producing our own green hydrogen also has the benefit of increasing energy independence and security of supply. Below are a number of technologies that could be developed in Ireland to produce green hydrogen.

4.1.1 Steam-Methane Reforming

The most common hydrogen production method currently is steam-methane reforming. This process involves heating methane from natural gas with steam in the presence of a catalyst, which produces carbon monoxide, hydrogen gas, and carbon dioxide. Even though this process can produce large quantities of hydrogen, the injection and capital costs are higher than just using natural gas. The carbon cost is higher due to the leakage of methane, carbon dioxide, and carbon monoxide throughout this process outweighing what is released when using natural gas.

4.1.2 Electrolysers

Electrolysis of water uses electricity to split water into its constituent elements, hydrogen and oxygen. This is done by immersing two inert electrodes in water and applying a potential of at least 1.23 V between them. At the positive electrode (anode), oxygen gas is evolved, and the electrons liberated in this process are passed to the anode.

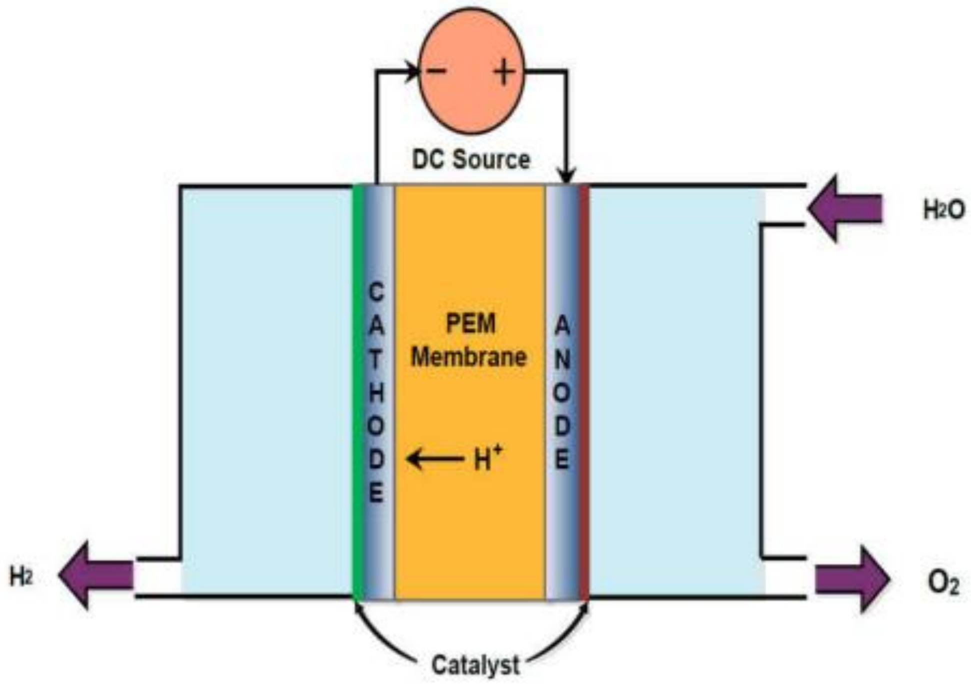

Figure 6: Fundamentals of PEM Electrolysis[85]

Hydrogen gas is evolved at the negative electrode (cathode), with the required electrons flowing from the anode to the cathode through an external circuit.

[85] Hydrogen Production by Water Electrolysis, Mamoon Rashid, Mohammed Khaloofah Al Mesfer, Hamid Nasem, Mohd Danish, February 2015, https://www.researchgate.net/publication/273125977_Hydrogen_Production_by_Water_Electrolysis_A_Review_of_Alkaline_Water_Electrolysis_PEM_Water_Electrolysis_and_High_Temperature_Water_Electrolysis

Electrolysis is one of the most critical technologies for future sustainable hydrogen production. Today most of the world's industrial hydrogen demand (around 70 million tonnes annually) is produced from natural gas and coal by processes which emit significant amounts of carbon into the atmosphere. An electrolyser operating at the average carbon intensity of France's electricity grid (50-70 gCO_2/kWh in 2020 according to the European Environmental Agency[86]) produces hydrogen with a carbon footprint of 2.6-3.6gCO_2/gH_2. However, an electrolyser using electricity at the global average carbon intensity (475gCO_2/kWh according to the IEA[87]) would produce hydrogen with a carbon footprint nearly three times higher than an unabated natural gas reformer[86]. However, when coupled with Renewable Electricity Sources (RES), Electrolysis creates sustainable and pure hydrogen.

Electrolysis as a process breaks down a feedstock of water into its components, hydrogen and oxygen, via the input of electricity. The technology features two electrodes separated by an electrolyte forming an individual electrolyser cell. These cells are then combined to form stacks and adapted to specific demands or applications. Different electrolyte compositions can be used, including alkaline electrolysis (AE) and proton exchange membrane electrolysis (PEM). AE is the most mature technology and well suited to large-scale projects. However, many projects opt for PEM designs as they operate more flexibly and are more responsive, thus helping with managing RES power. Innovations such as membrane-free electrolysers are also under investigation.

PEM electrolysers consist of a proton-conducting solid polymer electrolyte that facilitates the transfer of protons (H^+ ions) from the anode to generate hydrogen at the cathode. As well as being more suitable for flexible operation than traditional AE, PEM electrolysis produces more pure hydrogen. Though presently PEM is not as mature a technology as AE, PEM electrolysis projects with a capacity of greater than 10 MW are now commercial. PEM electrolysis as a technology has a TRL of 9. Although, improvements to cost, efficiency, and stack lifetime in the next decade are likely to be significant as the technology is manufactured and deployed at scale.

[86] Hydrogen, IEA, November 2021, https://www.iea.org/reports/hydrogen
[87] IEA, Global Energy & CO2 Status Report 2019, https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions

While this process seems relatively straightforward, achieving a practically useful reaction rate is challenging as the decomposition of water is not energetically favoured, *i.e.,* energy must be added to force the reaction to happen. This unfavorability typically leads to either impractically slow reaction rates or low electrical efficiency. The electrical efficiency of the process can be improved by selecting appropriate catalytic metals for the electrodes and by careful control of the solution's pH. Unfortunately, these catalytic metals are typically expensive noble metals that significantly increase the process's cost. The cost of the electricity needed to produce hydrogen is also a significant drawback.

As a result of these difficulties, electrolysis is not typically used in the industrial production of either hydrogen (typically produced from natural gas in the steam reforming process) or oxygen (typically produced by the fractional distillation of liquefied air), except when very high purity gases are required. Recently, however, there has been renewed interest in water electrolysis for hydrogen and oxygen production. This is because the predominant processes for their production release significant amounts of CO_2 into the atmosphere. If the electricity for electrolysis comes from renewable sources (*e.g.,* wind and solar PV), then the only gases outputted by that process are hydrogen and oxygen. The promise of hydrogen and oxygen production without any GHG emissions has driven significant interest in hybridising electrolysis plants and renewable generators.

The development of electrolyser projects worldwide has increased substantially over the past couple of decades. Figure 7 shows the number of P2G projects that began operation each year since 1990. Considering the relatively small number of projects in the 1990s, increasing interest in P2G can be seen throughout the 2000s and 2010s. A breakdown of new electrolyser technology types per year is also shown. Alkaline and PEM technologies are the most common as shown, with alkaline electrolysis present in most early projects. PEM technologies have been increasing in popularity in recent years. Figure 7 indicates the countries in which all completed, operational, and planned projects are located. Germany leads in all categories, hosting over a third of all identified P2G projects.

Electrolysers have reached enough maturity to scale up manufacturing and deployment to significantly reduce costs, reflected in three consecutive years of record capacity deployment in 2018, 2019, and 2020. Close to 70MW of electrolysis became operational in 2020, bringing the total installed capacity to almost 300MW. Europe has 40% of the global installed capacity. Thanks to the stimulus of policy support from numerous hydrogen strategies in the last few years and the prominence of electrolytic hydrogen in the Covid-19 recovery packages of countries such as Germany, France, and Spain, it will likely remain the dominant region. Electrolysis capacity deployment is expected to accelerate in the upcoming years. This acceleration is looking to break the barrier of 1GW of total electrolysis capacity already this year thanks to the high number of projects currently under development. Total installed electrolysis capacity could reach 54-91GW by 2030, with electrolytic hydrogen production ranging from 4.9Mt to 8.3Mt.

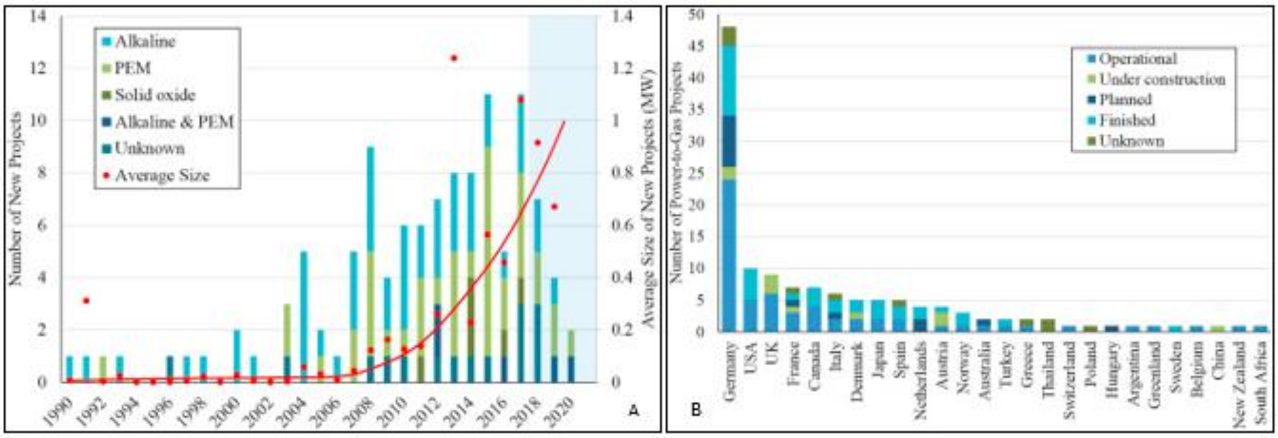

Figure 7: Showing A) Timeline of Power-To-Gas projects going into operation & B) The locations of P2G projects by country[88]

4.1.2.1 Cell Structure

Each reaction component must be optimised to overcome the problems discussed in the previous section and efficiently produce hydrogen and oxygen from water. While electrolysis can occur in pure water, its naturally low conductivity will require extra energy to push electrical current through the water. However, if a water-soluble electrolyte is added, the conductivity of the water can rise significantly. Ideally, this electrolyte will disassociate into positively charged cations and negatively charged anions. The anions can move quickly

[88] Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling?, Renewable and sustainable energy reviews, 2018, https://www.sciencedirect.com/science/article/pii/S1364032118306531

towards the anode and neutralize the build-up of positively charged H^+ there (left over from the splitting of water and the evolution of O_2).

Similarly, the cations rush towards the cathode and neutralize the build-up of negatively charged OH^- there (left over from water splitting and the evolution of H_2). These effects can significantly increase the efficiency of the electrolysis process. Strong acids or bases (such as H2SO4 or NaOH) are used as electrolytes due to their high conductivity. Solid electrolytes, typically polymer membranes through which ions can pass, can also be used. These require unique catalytic layers to be deposited on either side of the membrane.

Electrodes are typically machined to incorporate flow fields and facilitate the optimum distribution and flow of water across their surface. The electrodes will typically be composed of a low-cost conductive metal with nanostructured electrocatalysts. Electrocatalysts facilitate increased reaction rates at lower voltages which significantly increase the electrical efficiency of the electrolysis process. However, these catalysts are usually made from expensive noble metals and thus are used sparingly in high surface area configurations (*i.e.,* nanostructures) to minimise the financial cost of the process.

4.2 Hydrogen Storage

The choice of a hydrogen storage solution depends on a variety of factors, including the application for which the hydrogen will be used, high or low-pressure requirements, the energy density of hydrogen, the quantity of hydrogen stored, the duration of storage, local resources available such as waste heat or cheap electricity, the geology of the area, scale of the project, maintenance costs, and safety. This section will compare the different storage methods with these factors in mind.

4.2.1 Purification of Green hydrogen before Compression

Before hydrogen enters the compressor, it must be purified. This is a multi-step process. In the first step, hydrogen is catalytically deoxidized, eliminating all traces of oxygen. In the second part, the hydrogen is cooled, which causes approximately 95% of the moisture to condense. This moisture is then drained away by a condensate trap. Subsequently, the hydrogen is ready to enter the compressor, where it gradually compresses. Finally, the hydrogen is cooled once more and dehumidified, then stored in pressure vessels. It is then moved to the gas pipeline network or transported to end-users. If the hydrogen was to be stored in metal hydride, this purification process becomes unnecessary as metal hydride, by function, purifies hydrogen.

4.2.2 Compression of Hydrogen for Storage and Transport Purposes

The multi-stage reciprocating compressor is one of the most integral components of the entire system. It is used to compress hydrogen which then travels to storage tanks, gas pipelines, or cisterns. It is envisaged to use an oil-free and gas-tight compressor to ensure the high quality of the supplied hydrogen without losses on the equipment itself. To ensure deliveries within the P2G system, an outlet pressure behind the compressor of 80 bar is assumed. If hydrogen is to be used as a fuel for vehicles, it is necessary to use a compressor with an outlet pressure of 300 bar for buses and trucks and 700 bar for cars. The first case is a single-stage multi-piston compressor. In the second case, it is necessary to use a multi-stage and multi-piston device. This step can be skipped entirely if solid or liquid hydrogen storage is required, subsequently moving straight to storage in metal hydride or being replaced with the liquefaction process, respectively. The units are designed for a broader range of operations, including rapid load changes (depending on the output of the electrolyser) or high efficiency at part load.

4.2.3 Gas Storage

Compressed hydrogen is a storage method where the hydrogen is stored at pressures from 350bar to 700bar to reduce volume. This can be done on many different scales, from small containers to large vats and even underground caves. If the gas is being stored and converted back to electricity on-site, the need for large volumes of storage capacity increases. As opposed to having a small buffer tank and injecting the gas directly into the transmission network, an energy generating plant would require an enormous storage volume. One option is to have multiple large steel tanks. A less expensive but more geographically dependent solution would be to store the H_2 in naturally occurring caverns[89]. Storing hydrogen in underground salt caverns is a proven technology that the petrochemical industry has used since the early 1970s. Today, there are four hydrogen salt cavern sites operational: three in the US and one in the UK. Several pilot projects are under development in Europe.

A recent example of this is the "Green Hydrogen @Kinsale" project being developed by ESB and dCarbonX[90]. Investigations are underway into the feasibility of storing large amounts of green hydrogen (3TWh) in retired natural gas reservoirs off the coast of Ireland. The use of pre-existing gas reservoirs is very advantageous since there would only be a small infrastructural retrofit required to make the site usable for hydrogen instead of natural gas. Kinsale Head, for example, is already connected to the Irish gas network, so minimal new development would be required to bring the site online. In the context of high-volume storage in Offaly, a feasibility study could investigate potential sites with proximity to both caverns and electrical infrastructure. Another solution that could become viable would be to export hydrogen to centralised storage sites like Kinsale. This would be dependent on government development policies regarding hydrogen infrastructure and whether they favour local storage or larger sites like retrofitted gas fields. A significant advantage of such a development in the context of transitioning to clean energy is that it could reintroduce displaced workers to the power industry without the need for substantial changes to their current skillsets. Operating a Hydrogen transmission system is highly similar to the existing natural gas pipeline process and reusing gas reservoirs would create new jobs. Unless there is cheap energy easily accessible, the cost of compressing hydrogen gas can be quite high. Compressed hydrogen has higher maintenance costs than metal hydride but is still lower than LHY due to the cost of liquefaction. Underground storage of hydrogen is nearly always cheaper. The only instance where it is not economical is when small quantities of gas are stored in large caverns, making the investment for cushion gas (cushion gas is the volume of gas needed to maintain pressure within a storage reservoir) large compared to hydrogen stored. Compressed gas storage has safety risks associated with high-pressure storage because of the possible over-pressurisation, or if there is a leak, rapid release of hydrogen vapour, and the combustion of

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[89] 2020 grid Energy Storage Technology Cost and Performance Assessment, Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle, Pacific Northwest Laboratory, December 2020, https://www.pnnl.gov/sites/default/files/media/file/Hydrogen_Methodology.pdf

[90] ESB, dCarbonX explore large-scale hydrogen storage in County Cork, Ireland, Molly Burgess, August 2021, https://www.h2-view.com/story/esb-dcarbonx-explore-large-scale-hydrogen-storage-in-county-cork-ireland/

hydrogen due to it being a reactive gas. This means metal hydride is the safest form of storage. Still, there is no reason why safety measures cannot ensure the secure storage of compressed gaseous or liquid hydrogen with steps taken such as tank location.

4.2.4 Solid Storage

Metal hydride is currently one of the only solid methods of hydrogen storage. It operates due to the chemical reaction between a specific type of alloy and hydrogen, causing a chemical bond to be formed, which alloys with the hydrogen and bypasses the compression stage. However, to extract the hydrogen, a continuous heat source is required. It is only suitable for relatively small (less than 1,300kg[91]) quantities of hydrogen, whereas compressed gas storage becomes more economical for larger amounts of hydrogen. However, if a waste source of heat is available or high-pressure hydrogen is needed, it could still be economical. This is a good option for stationary storage as metal hydride's high volumetric density allows for a small footprint. Metal hydride is most efficient when used in the case of low-pressure hydrogen production, but a high-pressure gas is needed for storage. It is also a good choice if purifying hydrogen is a necessary function, as this is inherent in this gas storage method. There is very little cost difference between compressed gas and metal hydride storage when considering small quantities of hydrogen. There is little difference between the cost of metal hydride alloy versus a pressure vessel. Metal hydride is the safest form of hydrogen storage as a source of continuous heat is required to release the hydrogen-metal bond.

4.2.5 Liquid Storage

If the purpose of the hydrogen is for cryogenic applications, then liquid hydrogen storage is the only option. Hydrogen turns into a liquid when cooled to a temperature below -257.87°C. This is achieved within the industry using a liquefaction plant. Liquid storage of hydrogen can be helpful for long-distance transport when using trucks. Automobile transportation of metal hydride is not feasible, however. This is because metal hydride storage has much more weight than liquid storage, making automobile transport a lot more expensive. Liquid hydrogen is

[91] Technical and economic assessment of methods for the storage of large quantities of hydrogen, J.B. Taylor, J.E.A. Alderson, K.M. Kalyanam, A.B. Lyle, L.A. Phillips, 1986, https://doi.org/10.1016/0360-3199(86)90104-7

very dense however, meaning one truck filled with liquid hydrogen can equate to roughly 20 trucks carrying gaseous hydrogen.

Another benefit of storing liquid hydrogen is that for higher capacities, the boil-off rate decreases, as it is inversely proportional to vessel size. The cost of liquefaction is the primary constraint with liquid hydrogen storage. However, liquid hydrogen becomes more economical than gaseous storage in pressure vessels because of its cost efficiencies at higher volumes. When transporting over longer distances, liquid is the most suitable storage method. As the storage time increases, liquid storage also begins to make more sense economically than above-ground compressed gas storage and metal hydrides. However underground cave storage is just as viable for longer storage times. It's also essential to note maintenance costs for liquid hydrogen will be higher than, say, metal hydride due to the complicated liquefaction plant versus a metal hydride with no moving parts. Liquid hydrogen has similar safety concerns as the other storage methods. If a leak were to occur in liquid hydrogen storage, it would emit more hydrogen than its gaseous counterpart. Liquid hydrogen will also vaporise quicker; however, in open areas, hydrogen diffuses quickly, making the chance of combustion low[92].

4.2.6 Summary of Storage Methods

Underground storage is suitable for large quantities of gas or long-term storage for pressures between 350-700 bar. Liquid hydrogen is suitable for large quantities of gas, long term storage, low electricity costs, or applications requiring liquid hydrogen. Compressed gas is suitable for small quantities of gas, high cycle times, or short storage times. Metal hydride has its use for low pressure hydrogen production, while its high volumetric density allows for stationary storage[93].

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[92] The high-throughput highway to computational materials design, Stefano Curtarolo, Gus L. W. Hart, Marco Buongiorno Nardelli, Natalio Mingo, Stefano Sanvito, Ohad Levy, February 2013, https://doi.org/10.1038/nmat3568
[93] Technical and economic assessment of methods for the storage of large quantities of hydrogen, J.B. Taylor, J.E.A. Alderson, K.M. Kalyanam, A.B. Lyle, L.A. Phillips, 1986, https://doi.org/10.1016/0360-3199(86)90104-7

4.3 Utilization of Hydrogen

Hydrogen can be stored in pressure vessels or injected into the natural gas network. In addition to storage, hydrogen can also be used in fuel cells, internal combustion engines (both stationary and non-stationary applications), and as a raw material for industrial operations. Hydrogen can also be utilized in the transport sector. Assuming a high share of renewable energy sources and thus frequent energy fluctuations in the transmission network, the excess electricity can be used to produce hydrogen that can be either used immediately or put into long-term storage. Alternatively, excess hydrogen can be stored for export to international markets.

4.3.1 Hydrogen to Power

There are several ways to convert hydrogen gas into electricity. The first option is to use a gas turbine or engine to create power via hydrogen combustion. Another option is to feed the hydrogen gas into an array of fuel cells, which use chemical reactions to combine oxygen and hydrogen, producing electricity.

4.3.1.1 Hydrogen Fuel Cells

Fuel cells are a technology which converts the chemical energy of hydrogen, or other fuels, into electrical energy[94]. They are essentially electrolysers working in reverse, but instead of splitting water to form H_2 and O_2, fuel cells combine H_2 and O_2 to make water, producing electricity. They will output power for as long as fuel (in this case, hydrogen) is supplied. There are a variety of different types of fuel cells, but Proton Exchange Membrane (PEM) is one of the most common due to its high efficiency (currently 60%) and relatively low operating temperature (100°C) [95]. Like electrolysers, fuel cells consist of two electrodes sandwiching an electrolyte. Hydrogen is fed to one electrode (anode), and air is fed to the other (cathode). The hydrogen is separated into protons and electrons by a catalyst at the anode before the protons travel across the electrolyte membrane to combine with the oxygen, forming water. The electrons also participate in this reaction, but they travel through an external conductor

[94] Fuel Cells, Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/fuelcells/fuel-cells
[95] Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications, Raluca-Andrea Felseghi, Elena Carcadea, Maria Simona Raboaca, December 2019, https://doi.org/10.3390/en12234593

instead of across the electrolyte. These moving electrons result in current flow across the electrodes. This is the same technology used by hydrogen-powered vehicles.

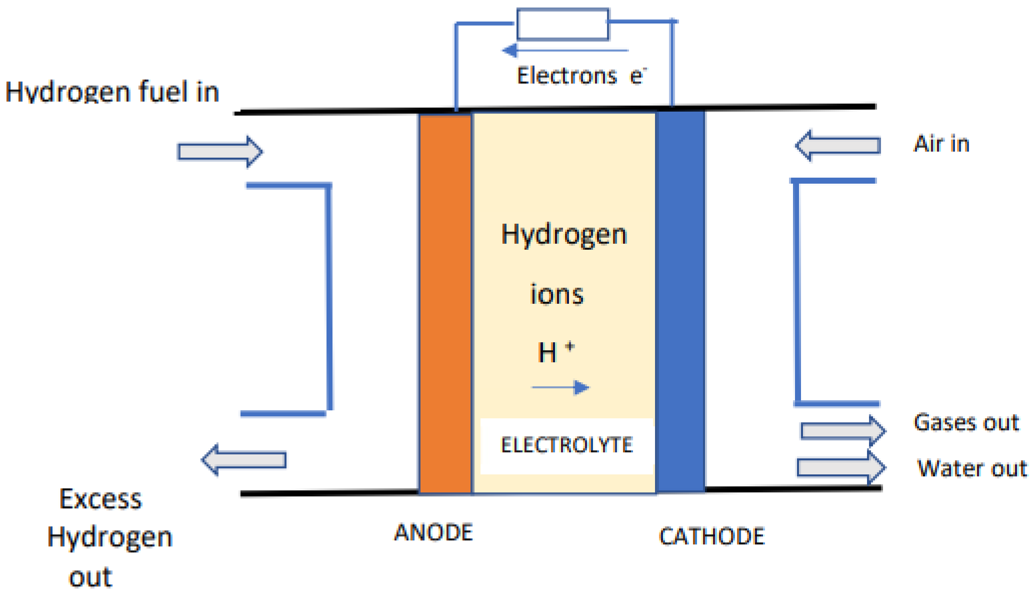

Figure 8: Schematic diagram of hydrogen fuel cell[96]

Individual fuel cells only produce small voltages, but they can be connected in series to increase this value depending on the application. No CO_2 is produced during operation. Water and heat are the only by-products of this process. The recent global interest in using hydrogen as a long-term energy storage medium means there will be a significant increase in the deployment of fuel cells.

4.3.1.2 Gas turbine

A gas turbine is a heat engine that stores mechanical energy on a shaft by expanding a gaseous working medium. This stored mechanical energy is then used to drive a generator producing electrical energy. This is what provides most of Ireland's current power generation. The basic criterion for the distribution of gas turbines is whether the turbine burns fuel directly in the combustion chamber. If so, they are defined as combustion turbines.

[96] A Review of Development in Electrical Battery, Fuel Cell and Energy Recovery Systems for Railway Applications A Report for the Scottish Association for Public Transport, David Murray-Smith, November 2019 https://www.researchgate.net/publication/337991572_A_Review_of_Developments_in_Electrical_Battery_Fuel_Cell_and_Energy_Recovery_Systems_for_Railway_Applications_A_Report_for_the_Scottish_Association_for_Public_Transport

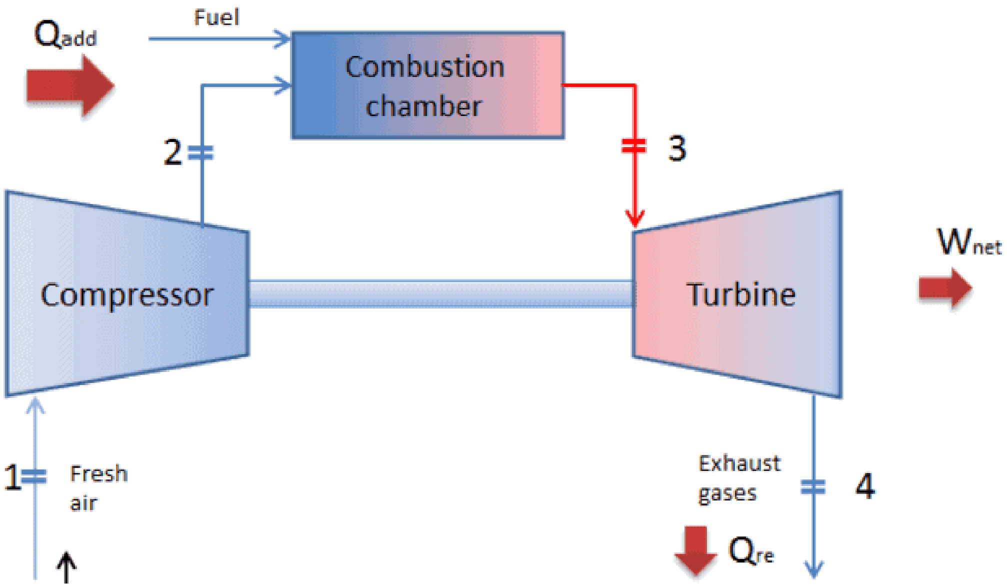

Figure 9: Diagram of open Brayton cycle[97]

If the turbine does not contain a combustion chamber and hot gas is fed directly to the turbine blades, it is defined as an expansion turbine. The closed Brayton cycle in Figure 10 shows this. We also distinguish between two basic types of turbines according to the direction of flue gas flow. They are radial turbines and axial turbines. Radial turbines are used in connection with a predominantly single-stage radial compressor as low power backup sources. Axial turbines are used for their high outputs as sources of electricity or for energy-intensive industrial applications and drives of high-power machines.

[97] What is Brayton Cycle, Nick Connor, May 2019, https://www.thermal-engineering.org/what-is-brayton-cycle-gas-turbine-engine-definition/

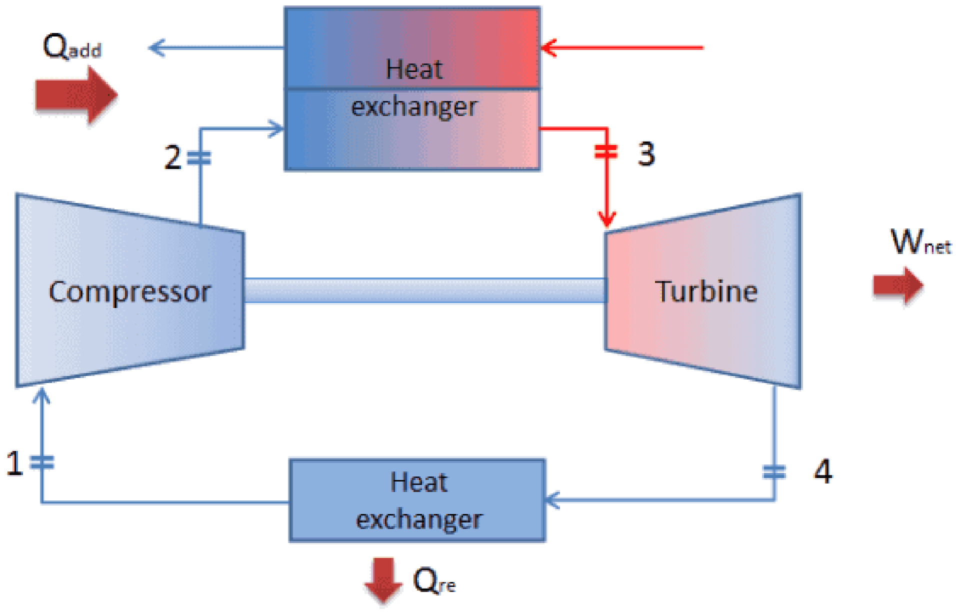

Figure 10: Diagram of Closed Brayton cycle

4.3.1.2.1 Combustion Fuels

Solid, liquid, and gaseous fuels can all drive gas turbines. Chemical and mechanical purity is essential for all types of fuels. In the 1950s and 1960s, experiments were performed with solid fuel, but due to several complications, this intention was abandoned. The solid fuel tested was finely ground coal dust. The disadvantage was the high amount of ash and the associated erosion of the blades and flow parts of the combustion chamber and turbine. Today, liquid and gaseous fuels are mainly used.

The use of liquid fuels is prevalent today. The basic requirement is a good mixing of fuel and air, mainly due to the low viscosity of the fuel. Gaseous fuels are usually the most suitable option for most applications. The advantage is the easy mixing of gaseous fuel and air. Natural Gas is among the most frequently used gaseous fuel. Hydrogen enrichment of natural gas has become very widespread in the last few years. Hydrogen produced from renewable sources can thus become a future successor and a substitute for natural gas, which is mainly found in mining. When changing the combustion from natural gas to hydrogen, no fundamental change in the unit's design is necessary.

The main problem with the combustion of pure hydrogen is the formation of high amounts of undesirable nitrogen oxides. However, even this problem is technically solved, and most manufacturers are now adapting their machines to pure hydrogen.

4.3.1.3 Hydrogen Turbines

For the burning of hydrogen, there are limitless gas turbines available on the market. Many types of turbines are now ready to burn a mixture of natural gas with up to 70% hydrogen. One of the turbines ready to burn 100% hydrogen is Siemens SGT-A65[98].

The Siemens SGT-A65 (formerly the Industrial Trent) can burn 100% hydrogen using a Wet Low Emissions (WLE) burner that keeps NOx at 25 ppm. It is a three-shaft, axial-flow, aero-derivative gas turbine that produces 60 to 71 MW depending on its configuration and is suitable for flexible peaking and combined cycle applications. The SGT-A65 includes a two-stage low-pressure compressor with variable inlet guide vanes. It has a high overall pressure ratio and high thermal efficiency. In addition, the low-pressure compressor boosts the airflow so that the power level is held at a firing temperature low enough to reduce NOX outputs. While still high enough to give good cycle efficiency. The intermediate-pressure compressor has eight stages and three rows of variable stators. The high-pressure compressor has six stages, with no variable stators. The overall pressure ratio is 34.1:1 for the 50 Hz dry low emissions configuration.

Furthermore, the SGT-A65 incorporates a series of staged pre-mix, lean-burn combustion cans that allow the GT to simultaneously achieve low NOx and CO. Eight combustors are incorporated into a single module. The SGT-A65 has a five-stage low-pressure turbine, a single-stage intermediate-pressure turbine, and a single-stage high-pressure turbine. Each of these turbines drives its own compressor. The SGT-A65 low-pressure stages 4 and 5 have a larger gas path area and a lower exit Mach number than the Trent aero version. The gas turbine can generate full power in less than 8 minutes from start-up without the need for auxiliary systems to maintain the unit in an operationally ready standby mode. In the event

[98] Feasibility of Power-to-X Projects, Dr. Volkmar Pflug, June 2019, https://ec.europa.eu/info/sites/default/files/03.04_-_presentations_-_siemens_-_feasibility_of_power-to-x_projects.pdf

of a shutdown, the unit can be restarted at any time to restore power quickly, as it has no hot-lockout restrictions.

4.3.2 Hydrogen for Heavy Industry

Ireland has limited options for use in heavy industry. The biggest opportunity available would be the utilisation of hydrogen in petroleum refining by selling it to Whitegate Refinery, Ireland's only oil refinery. However, the most significant opportunities will be found by exporting hydrogen. Other exportation markets include ammonia production and methanol production. The industry sector demand for hydrogen was 51Mt in 2020, with chemical production consuming around 46Mt. Roughly three-quarters were used for ammonia production and one-quarter for methanol. The remaining 5Mt was consumed to reduce iron ore directly to metal in the steelmaking industry. Only 0.3Mt of 2020 demand was met with low-carbon hydrogen, mainly from a handful of large-scale Carbon Capture, Utilization and Storage (CCUS) plants, small electrolysis units in the chemical subsector, and one CCUS project in the iron and steel subsector[24].

Expectations from the Net Zero Emissions by 2050 Scenario show total hydrogen demand from industry to expand 44% by 2030, with low-carbon hydrogen becoming increasingly important[99]. Hydrogen production as an export will be discussed further in Section 5.

4.4 Technology Comparison

Security of supply has traditionally been provided by a mixture of baseload CCGTs and peaking OCGTs, with both operating on fossil fuels like Natural Gas (NG) or Distillate Fuel Oil. An alternative solution must be found as Ireland moves away from carbon-intensive generation. Each technology mentioned above has both advantages and disadvantages, but none can solve the problem individually.

Gas Turbines running on 100% hydrogen can provide the same services as the old generation, but they suffer from the same fundamental issue: inefficient operation. This wasn't a huge issue for older generations due to the low cost of natural gas compared to hydrogen. A

[99] IEA Net Zero Emissions By 2050. https://www.iea.org/reports/net-zero-by-2050

hydrogen fuel cell, combined with a synchronous condenser, could provide the same services and have a much faster response time with significantly higher operating efficiency.

One of the main drawbacks of the water electrolysis process is its high-cost relative to other hydrogen production methods such as steam reforming. The primary source of this cost is the electricity needed to produce the hydrogen, which costs significantly more than the quantity of natural gas required to produce an equivalent amount of hydrogen by steam reforming. While the *direct energy efficiency* of an electrolysis plant (up to 80% for large modern plants)[100] is similar to that of a steam reforming plant, the electrical energy used in the electrolysis process typically comes from a generator with its own energy inefficiencies, which can make the *roundtrip efficiency* of the process relatively low.

The inefficiency and excess cost associated with electrolysis may be justified if excess renewable energy is available that would otherwise be wasted. This 'free' energy would allow the electrolysis process to compete with the dominant hydrogen production techniques while significantly reducing the resulting greenhouse gas emissions. This, in turn, could enable green transport by facilitating affordable hydrogen fuel for fuel cell-powered vehicles. However, the initial inefficiency in energy use for electrolysis is compounded by losses during the storage and transportation of the produced hydrogen. Further energy losses occur as the hydrogen is consumed in the fuel cell. As a result, the overall energy efficiency of using electrolysis to produce hydrogen to fuel cars is very low. The hydrogen can also be burned directly in a gas turbine to generate electricity when needed, but this is also a very energy inefficient process. More efficient and cost-effective use of any excess renewable energy can be made by using more efficient energy storage technologies such as batteries.

The primary component of the running cost for a fuel cell plant would be the hydrogen cost. In the case of hydrogen being supplied by an on-site electrolyser, the cost would be coupled with the cost of electricity. Since the plant would then sell the power generated back to the grid, the profit margin would rely almost entirely on the roundtrip efficiency of the plant vs the change in the cost of electricity over the day.

[100] 2007 Final Technical Report, European Commission, 2007, https://cordis.europa.eu/docs/projects/files/ENK5/ENK5-CT-2001-00536/103966621-6_en.pdf

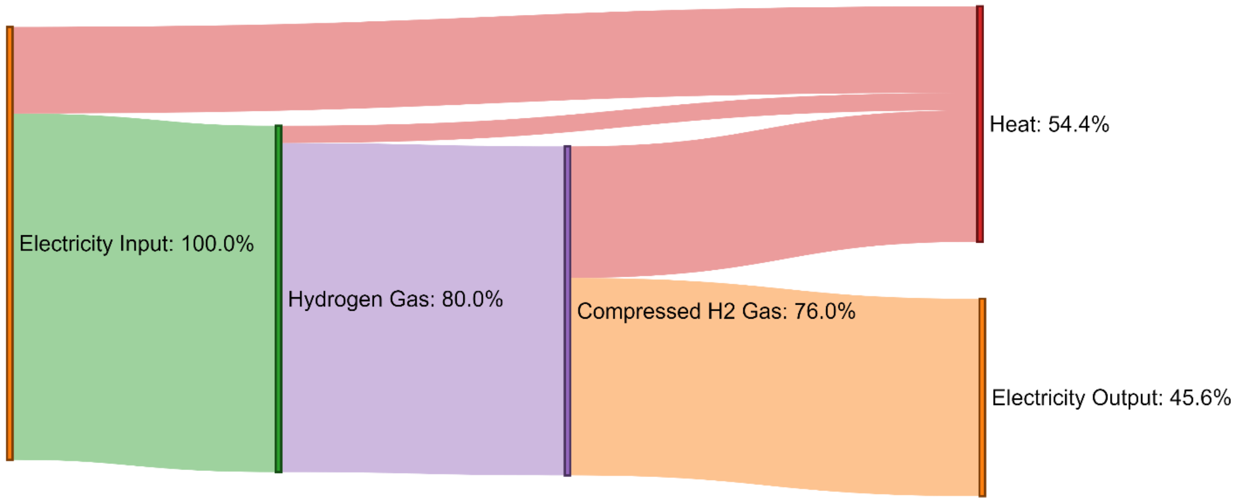

Figure 11: Hydrogen Fuel Cell Plant Efficiency, the current best-case scenario

If 20-35%[101] of the energy is lost during electrolysis, 5-20%[102] is lost during compression, and 40%[103] is lost by the fuel cells, the roundtrip efficiency of the process (described in Figure 11) is 31-45%. This means that unless the electricity could be sold for more than double the buying price, unsubsidised energy arbitrage would not make any profit.

On average, the most considerable difference in electricity value is approximately a factor of two, meaning the break-even point for a plant would be 50% efficiency. Any plant with an efficiency of less than this would not be profitable. Arbitrage could potentially become viable if the plant could secure a power purchase agreement (PPA) with a wind farm, allowing it to generate hydrogen using heavily discounted electricity. The other sources of revenue would be system services and capacity payments.

The plant could also generate revenue from system services, but the profits would be much lower than a comparable Battery Storage System which could provide the same services at a smaller cost due to greater efficiency. Similarly, the plant could generate revenue via capacity payments. However, they would not be able to win any of the Irish capacity auctions due to

[101] Overview of the PEM Silyzer Family, Siemens Energy, September 2020, https://4echile-datastore.s3.eu-central-1.amazonaws.com/wp-content/uploads/2020/10/10132733/20200930-SE-NEB-PEM-Electrolyzer-and-Applications_EW.pdf
[102] DOE Hydrogen and Fuel Cells Program Record, Monterey Gardiner, July 2009, https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf
[103] Fuel Cell Technologies Office, U.S. Department of Energy, https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

the high cost of building and running the plant. It would be outcompeted by Open Cycle Gas Turbines (OCGT), which could provide the same capacity to the grid with much lower bid prices due to more favourable economics. Natural Gas turbines have an unlimited supply of fuel from the national network. Natural gas is much cheaper than the equivalent energy cost of electricity (needed to create hydrogen). Advances in fuel cell and electrolyser technology would increase efficiency and make Fuel Cell Plants a more attractive solution for Ireland. There is continual research going on around the world into these technologies, and commercial plant efficiencies will gradually increase.

The only way for a Hydrogen Fuel Cell Power Plant to generate significant revenue would be to provide DS3 System Services. A similarly sized BESS could produce much greater profits while providing the same services to the grid, making Electrolyser and Fuel Cell combinations economically unattractive under current policy conditions. However, potential changes in hydrogen policy due to updated European and Irish energy targets could result in the subsidisation of hydrogen generation plants, which would allow FCPs to compete with Batteries[104].

In this context, hydrogen storage would be dependent on location; this is because if there is a suitable underground cave for the storage of hydrogen, it would be the most sensible choice.

[104] Fit for 55, European Council, https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/

5 Markets

The main issue with using hydrogen production, storage, and combustion for energy arbitrage is that even under perfect conditions, the energy lost in the process will be much greater than the potential gains earned by buying low and selling high. Unless specific subsidies are put in place to incentivise the use of hydrogen in gas turbine peaking plants as a method of moving away from natural gas, there is no economic incentive to do so due to the inefficiency of these plants. Therefore, it makes sense financially to exclude hydrogen combustion to produce electricity and instead sell the hydrogen itself rather than convert it to electrical energy using a turbine or fuel cells. It would directly compete with far more efficient and mature technologies like Battery Energy Storage Systems (BESS) or conventional fossil fuel peaking plants by selling electricity. Hydrogen itself is a much more profitable resource than the electricity it can produce. This is due to the relative scarcity of hydrogen in the available markets and the growing demand for its use as an alternative fuel. Large scale hydrogen production is still in its infancy and is in very short supply. However, there is a growing market for hydrogen in transport applications (trains, trucks, ships, and aviation) as well as heat, power, and industry, which will rapidly increase demand both in Ireland and abroad.

5.1 Hydrogen Gas Market

Historically, global hydrogen demand has consisted of industrial uses like oil refining, ammonia production, methanol production, and steel production. These are all pre-existing markets that green Hydrogen producers could potentially take advantage of. In Europe, the industry holds 90% of the market share of hydrogen use. The main consumers within the industry are the chemical industry (63%), refineries (30%) and metalwork (6%)[95].

The Irish market for Hydrogen is set for major growth due to an influx of hydrogen fuel cell vehicles. Such vehicles are already in use worldwide and will soon reach Ireland as well. Since the market is currently small, it isn't easy to project future hydrogen fuel values. A solution to this issue would be to look at the prices in a location like California[105], where hydrogen vehicle adoption has already been adopted, and the market has had a chance to stabilise.

[105] Stations, California Fuel Cell Partnership, https://cafcp.org/stations

"The average price of hydrogen for a light-duty fuel cell electric vehicle (passenger car) in California is $16.50 per kilogram, according to the 2019 Joint Agency Report.[106]"

The projected hydrogen costs shown in Figure 12 show that while hydrogen for consumers starts at a rate much higher than the equivalent cost of diesel, the cost rapidly approaches parity. This reduction can most likely be explained by the economies of scale and technological advances in hydrogen generation. This price projection can be used to approximate the future Irish market.

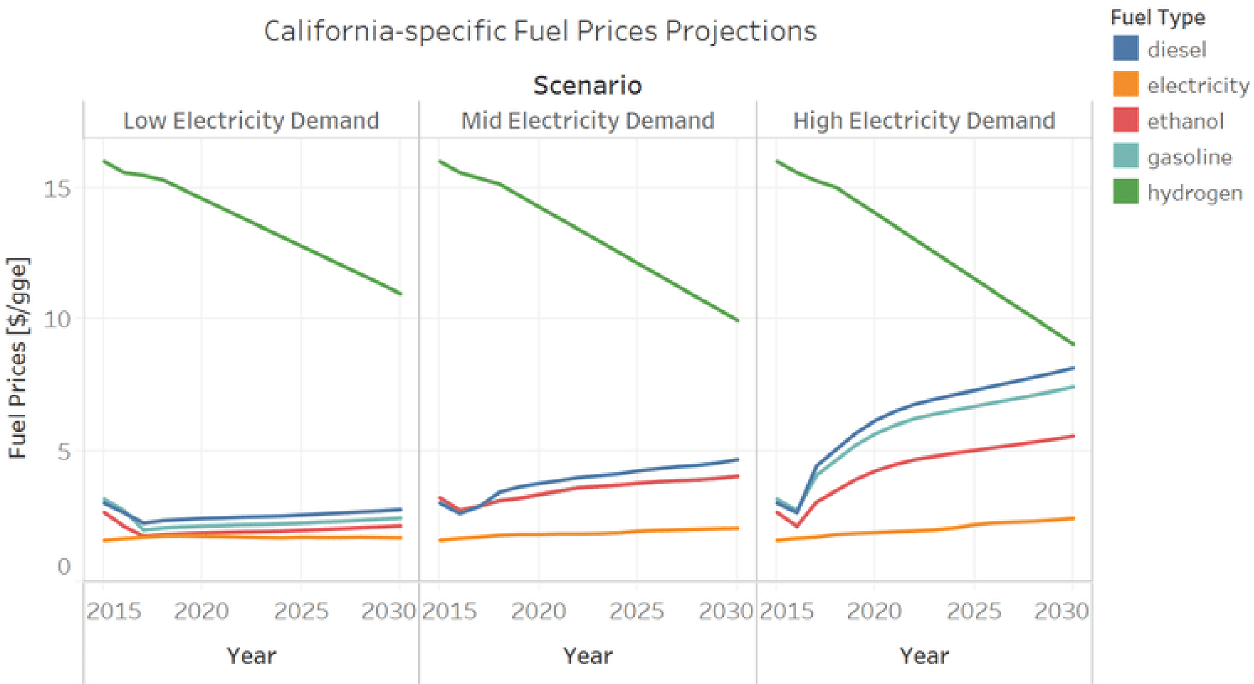

Figure 12: Projected Fuel Cost in California[107] (gge, gallon of gasoline-equivalent)

Similarly, the cost of producing green hydrogen is comparable to other more carbon-intensive methods. This figure shows that as research increases and policies are implemented, green hydrogen will begin to approach the price of more carbon-intensive fuels.

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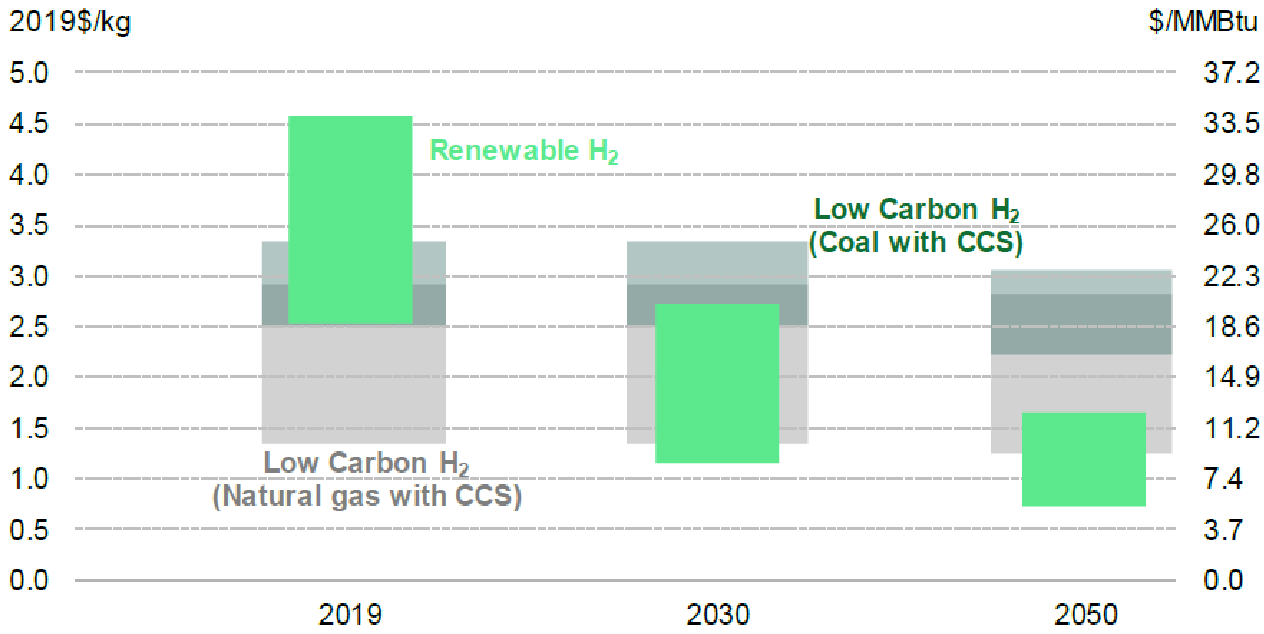
[106] Joint Agency Staff Report on Assembly Bill 8: 2019 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California, Gavin Newsom, December 2019, https://www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-039.pdf

[107] Light-Duty Vehicle Attribute Projections (Years 2015-2030), Eleftheria Kontou, Aaron Brooker, August 2018, https://www.researchgate.net/figure/California-Fuel-Price-Projections_fig7_327164223

Figure 13:Forecast global range of levelized cost of hydrogen production from large projects[108].



Source: BloombergNEF. Note renewable hydrogen costs based on large projects with optimistic projections for capex. Natural gas prices range from $1.1-10.3/MMBtu, coal from $30-116/t.

Connection to the national gas pipeline will allow for more project flexibility. For example, if there is decreased demand for hydrogen, it will not restrict the provisional use of hydrogen for system services. The hydrogen market in Ireland is at its nascent stage, and the national policy framework on alternative fuels is under constant active revision. GNI, as a public utilities company in Ireland, has the vision of a net-zero carbon gas network by 2050. There are many gas pipelines in Ireland of high enough quality to accept up to 20% hydrogen[109]. The experience gained from research and pilot projects being carried out both domestically and internationally should strongly stimulate hydrogen market growth in the country as time goes on.

[108] BNEF Hydrogen Economy Outlook. https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf
[109] Hydrogen and Wind Energy Report.

5.2 Electrolyser Competition

This competition analysis focuses on large hydrogen generation projects and may exclude some smaller projects. There are only three developments to note in Ireland, the first of which (Aghada) will be the largest hydrogen production plant in the country once built.

- A 50MW electrolyser is due to be built in Aghada, County Cork by 2023. It will cost €120m to construct and remove 63,000 tons of carbon emissions each year from Irish Industry[110].
- A 0.5MW electrolyser is in development in Antrim, Northern Ireland, under the project name GENCOMM[111].
- An electrolyser in Firlough, County Mayo is scheduled to be operational by early 2025. Although the power of the electrolyser has not yet been specified, the developers claim that it will produce enough hydrogen to power the ongoing requirements of 1000 fuel cell heavy goods vehicles[112].

5.3 Electrolyser as a Demand Side Unit

The operation of electrolysers can be managed when coupled with suitable hydrogen storage facilities. This means energy grid management services can be provided by flexing the output of the electrolyser, which can act as an additional revenue stream for the system. There is expected to be an exponential growth of global electrolyser capacity onstream in the relatively near term as larger, more substantial projects are approved.

5.3.1 Current System Services Market for Demand Side Units in Ireland

System services can currently be procured with a 1-year rolling contract within the DS3 programme. EirGrid's DS3 programme for system services will phase out sometime between April 2023 and April 2026, and the services procurement is supposed to be auctioned. Among many reasons why Ireland's competitive process will be difficult to implement is the selective

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[110] Irish Examiner, Ireland's first green hydrogen facility is planned for Cork Harbour, Alan Healy, May 2021, https://www.irishexaminer.com/business/companies/arid-40297886.html

[111] GENCOMM: GENerating energy secure COMMunities through Smart Renewable Hydrogen, Interreg North-West Europe GenComm, https://www.nweurope.eu/projects/project-search/gencomm-generating-energy-secure-communities/?tab=&page=3

[112] Press, Mercury Renewables, https://mercuryrenewables.ie/press/

choice of system services that can lead to different volume procurement of each service and create undesired issues in the grid. It is assumed that categories of services will be bundled for the procurement process; however, there are currently no insights on how this auction market will look. Nevertheless, the fast response of HG2S as a Demand Side Unit (DSU) makes it suitable for the provision of many system services. These services range from short to long response time and short to long duration. They also encompass both frequency and voltage control services.

the DS3 system services that a HG2S project can provide are:

1. Frequency regulation (FFR, POR, SOR, TOR1, and TOR2)
2. Reactive power (SSRP)
3. Voltage regulation (DRR)

Announced back in 2015 as interim arrangements, most of these tariffs increased by 5.3% (in 2017) and are currently known as regulated arrangements. This trend can continue as the Irish power grid needs more and more system services due to Government policies and ambitious plans to add at least 3.5 GW of offshore wind, 1.5 GW of solar, and increase onshore wind capacity by up to 8.2 Gw by 2030.[113] To accommodate a high level of renewables (an average of 70% of total generation), the total budget for system services will need to be increased from the current € 235 million to € 750 million.[114]

5.4 Hydrogen for Transport

Hydrogen for transport is already beginning to be implemented in certain locations around the world with the commercialisation of fuel cell vehicles. Hydrogen's primary use for transport however will be for heavy goods vehicles (HGV), buses, and possibly commercial aviation in the near future.

[113] Climate Action Plan 2019 To Tackle Climate Breakdown, Government of Ireland, https://assets.gov.ie/25419/c97cdecddf8c49ab976e773d4e11e515.pdf.

[114] 'Financial Implications of High Levels of Renewables on the European Power System, European Commission, March 2020, https://eu-sysflex.com/wp-content/uploads/2020/05/Task_2.5-Deliverable-Report_for_Submission.pdf.

5.4.1 Trucks

Fuel Cell (FC) trucks have historically been ignored by Original Equipment Manufacturers (OEM) and have only recently begun to appear. FC technology is favourable for moving heavier/larger vehicles. Whilst BEVs are becoming the primary choice for the passenger vehicle space, they are ineffective for goods transportation. The batteries needed to move HGVs leaves the range/capacity of the vehicles lower than required, which, when coupled with long charging times, means they are not ideal for commercial use. Their hydrogen counterparts can boast ranges over 1000km[115] for several of the models released to date and fast refuelling times similar to those of diesel fuelled trucks.

Initial interest began with Nikola; a public relations led company formed in 2016, issuing positive sustainable trucking and mirroring Tesla's approach in the BEV market. The company has secured investment from many prominent industry leaders such as Bosch, GM and Iveco.

However, today's market is led by Hyundai with the world's first mass-produced unit called the 'XCIENT'. It carries 32kg of hydrogen and has an approximate range of 400km. Real-world applications are being supplied with these trucks now. Hyundai, alongside Swiss company H2 Energy, have collaborated to bring the supply of trucks to the Swiss market. 1,600 units will be running on Switzerland's roads by 2025[116].

5.4.2 Buses

Interest and investment in FC buses have steadily increased since their conception. Due to their return to base operation, FC buses' infrastructure needs are initially more straightforward to deploy than FC trucks. Although they are not in mass production yet, they have reached a high level of technical maturity. FC buses have an average range of 300 to 450km[117]. They face increasing competition from BEV buses but have the advantages of longer range, reduced refuelling times, and the ability to operate on challenging, hilly routes

[115] Daimler Truck Berlin Presentation. https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Presentations.xhtml?oid=47382817#prevId=47466466

[116] Hyundai Xcient, Autoindustriya, https://www.autoindustriya.com/truck-bus-news/hyundai-xcient-truck-can-go-400-km-on-32-kg-of-hydrogen.html

[117] Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe, Roland Berger, September 2015, https://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.PDF

due to their weight. Most cities will likely see a mix of technologies within their fleets in the future.

Many countries and projects have introduced FC buses to cities, and they are seen as the most thoroughly tested application for hydrogen mobility in the EU. After the success of the CUTE and HyFLEET: CUTE projects from 2006 to 2009, the commercialisation of FC buses has been perceived as viable. Today, further projects are being delivered. Key amongst these are JIVE, JIVE2, and The H2Bus Consortium. With these combined, they expect to deploy well over 1,000 FC buses along with the supporting infrastructure.

In the UK, both London and Aberdeen have already had two of the world's longest running hydrogen bus fleets. Both locations are expanding their hydrogen-powered bus fleets in a vote of confidence in the technology.

5.4.3 Aviation

Aviation is currently responsible for 3.6% of EU greenhouse gas emissions[118]. An independent study commissioned by Clean Sky 2 and Fuel Cells & Hydrogen 2 Joint Undertakings (FCH 2 JU) on the potential of using hydrogen for aviation was presented in June 2020. It explained that hydrogen could feasibly power short-range aircraft by 2035.

The two main uses of hydrogen for aviation are hydrogen propulsion and synthetic fuels. Hydrogen propulsion uses combusted hydrogen through modified gas-turbine engines, or the hydrogen can be converted into electrical power that complements the gas turbine via fuel cells. Using both creates a highly efficient, hybrid-electric propulsion chain powered entirely by hydrogen. Hydrogen can also be used as a synthetic fuel generated exclusively through renewable energy. The hydrogen produced using renewable electricity is combined with carbon dioxide obtained via Direct Air Carbon Capture (DACC) to form a carbon fuel with net-zero GHGs.

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[118] Quiet and green: Why hydrogen planes could be the future of aviation, Jonathan O'Callaghan, European Commission, July 2020, https://ec.europa.eu/research-and-innovation/en/horizon-magazine/quiet-and-green-why-hydrogen-planes-could-be-future-aviation

ZeroAvia is planning to commercialize hydrogen propulsion technology by 2024[119]. As of December 2021, United Airlines expects to purchase 100 of ZeroAvia's 100% hydrogen-electric engines. These engines could be retrofitted to existing United Express planes as early as 2028. With an investment of approximately $150 million, ZeroAvia is centred around implementing its technology in turboprops by 2026 and regional jets by 2028.

[119] ZeroAvia Sets 2024 Target for First Passenger Hydrogen Flight, Linnea Ahlgren, October 2021, https://simpleflying.com/zeroavia-sets-2024-target-for-first-passenger-hydrogen-flight/on

6 Discussion of an Innovative Green Hydrogen Solution

The generation, storage, and utilisation of green hydrogen have undoubtedly positively impacted Ireland concerning decarbonisation. Although the above sections make hydrogen seem promising, a green hydrogen production and storage facility in Ireland would not be financially viable from a renewable energy developer's point of view. This primarily results from the lack of a hydrogen market in Ireland. However, a facility that can effectively participate in current Irish energy markets would certainly create an opportunity for a financially feasible project.

To develop a cost-effective and sustainable solution/facility to advance the clean hydrogen economy in Ireland, Lumcloon Energy would propose combining state-of-the-art electrolyser technology, battery energy storage, and system service provision. These innovative technologies, coupled with existing infrastructure, can significantly increase the grid's stability, enable a higher level of renewable penetration (i.e., a higher fraction of renewables on the grid), and contribute to greening Ireland's gas network. Therefore, this innovative system will significantly reduce Ireland's greenhouse gas emissions and provide a pioneering demonstration of how this can be achieved across the EU. Below is a diagram displaying a high-level overview of the conceptual processes and end markets in which a facility like this will incorporate.

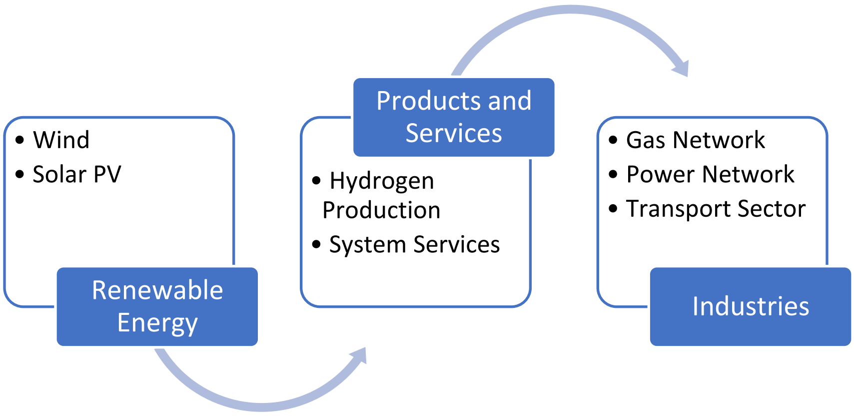

Figure 14: Conceptual Processes for end Markets

The proposed facility would be able to address several grid decarbonisations issues along with participating in several markets. These include:

- Coupling of electricity and gas networks to:

  - Reduce curtailment of renewable energy, therefore facilitating an increase of penetration on the electrical grid
  - Decarbonise the natural gas network through the blending of green hydrogen
- Hybrid Green Hydrogen Generation and Storage (HG2S) system of Electrolyser coupled with BESS will participate in EirGrid's (Irish Transmission System Operator) DS3 system services[120] market, Capacity Market, and act as a demand side unit for Wind Balancing Services. This provides valuable low-cost solutions which avoids the need for extensive infrastructural development of the transmission system. This further helps to reduce curtailment and stabilise the electrical grid and market, allowing for further integration of renewables such as wind and solar. The system will provide the following DS3 system services:
  - Frequency: FRR, POR, SOR, TOR1 and TOR2
  - Voltage: DRR
  - Reactive power: SSRP
- Green hydrogen produced by the plant will be injected into the gas network in accordance with Gas Networks Ireland's requirements.
- Green hydrogen will be sold on the wholesale market for transportation and other use.

6.1 Early-Stage Development Requirements

Several processes must be executed to progress the project towards the construction/operational stage, namely planning permission, grid connection, and gas connection. Securing these will enable progression past early-stage development. The requirements below explain how to secure each of these processes.

6.1.1 Planning Permission

Obtaining planning permission for a hydrogen project would be very similar to the process required for applying to build a natural gas-fired turbine. Both deal with highly flammable gases; while NG plants don't hold significant fuel reserves as they are connected to the gas

[120] DS3 Programme, Eirgrid, http://www.eirgridgroup.com/how-the-grid-works/ds3-programme/

transmission network, a hydrogen plant would include a large amount of fuel storage. The volume and duration of hydrogen storage could lead to novel issues when obtaining planning permission. Since there is no real precedent set for large scale hydrogen generation and storage in Ireland, open communication and cooperation with the relevant planning authorities would be necessary to facilitate any hydrogen project development. Obtaining planning permission for BESS development is a topic that Lumcloon Energy is very familiar with.

6.1.2 Grid Connection

The process for obtaining a grid connection for a Hydrogen generation plant which both imports electricity to power an electrolyser and exports electricity from a fuel cell plant or turbine, would be like that of a BESS (both import & export capability). If hydrogen production were the plant's sole purpose, an import connection would be the only requirement. This would likely result in a more straightforward connection process.

Once the relevant safety measures have been taken and planning permission has been obtained, obtaining a grid connection should be relatively straightforward. Again, open communication with the relevant authorities will be necessary.

The ECP-2 application system for connecting to the grid prioritises large generation/storage methods powered by renewables such as the BESS/Electrolyser discussed in this study. Proof of planning permission (with relevant council) must be provided, ensuring that the project has planning permission within the timeframe of the ECP-2 connection offer. This is sent along with a fee to the DSO (Distribution System Operator) for applications with MEC (maximum export capacity) smaller than 40MW or to TSO (Transmission System Operator) for applications larger than 40MW[121]. The CRU (Commission for Regulation of Utilities) also advised the SEM committee that successful participants should also be awarded grid connections for the 2024/25 T-3 capacity auction due to the imminent danger of generation shortages. It is uncertain whether this will apply to future capacity auctions[122].

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[121] Ruleset for Enduring Connection Policy Stage 2, ESB, Eirgrid, August 2020, https://www.eirgridgroup.com/site-files/library/EirGrid/ECP-2-Ruleset-Final.pdf

[122] Ireland Region Level 1 Locational Constraints for the 2024/25 T-3 Capacity Auction, Karen Trant, March 2021, https://www.cru.ie/wp-content/uploads/2021/03/CRU21030a-CRU-Direction-to-EirGrid-re-T-3_Final.docx.pdf

6.1.3 Gas Connection

Obtaining a gas connection is imperative as it would be one of the primary ways of transporting and selling the generated hydrogen. However, the existing gas line will need to be modified to allow for hydrogen injection. This can be done using an above-ground installation (AGI) and a hot tap. Hot tapping is a method of connecting to a gas line without requiring it to be depressurised. This reduces cost and GHG emissions since the process does not release gas into the atmosphere or interrupt service during maintenance[123]. An AGI is an above-ground construction surrounding the injection point, used for maintenance and servicing. Gas Networks Ireland targets a zero-carbon national gas network by 2050, with hydrogen making up a portion of the demand[52]. This show of interest in developing hydrogen projects by GNI should incentivise new Power to Gas (P2G) projects in the future. However, whilst there are currently no hydrogen policies, the novelty of these technologies cause hesitancy in the advancements of these types of projects. The legislation must most likely be created before any projects can connect. GNI registers and issues certificates to Irish producers that inject renewable gas into the gas network. However, certificates are only issued for biomethane and must be updated to accommodate hydrogen-related certificates. By tracking the commercial transactions of hydrogen through the supply chain, Ireland's Renewable Gas Registry will help establish trust in the market and confidence in the renewable gas sector.

In 2018 GNI updated their connection policies to include renewable gas (biogas) injection. These policies provide a good outline of what the future hydrogen injection process will look like. The connections policy governs the rules used by GNI to calculate and offer a network connection to customers. A hydrogen connections policy, including entry tariffs, will need to be developed for approval by the CRU to facilitate the connections of a hydrogen gas facility to the gas network. The renewable gas connection policy from GNI has multiple stages. The first step is to complete a network analysis to identify the most suitable, economical way to connect to the gas network. This is based on capacity, distance, pipe pressure, and environmental factors. A report must then be submitted to GNI specifying the most suitable connection option. This step has no associated fees. The second stage is making an application

[123] Using Hot Taps for In Service Pipeline Connections, Environmental Protection Agency, October 2006, *https://www.epa.gov/sites/default/files/2016-06/documents/ll_hottaps.pdf*

for the previously specified gas connection. Transmission System (TS) connections are usually more expensive than Distribution System (DS) connections due to more extensive equipment requirements and higher gas injection pressure requirements. The benefit of TS injection is the significantly larger volumes of gas that can be injected per unit of time compared to the DS.

The application process for a direct pipeline connection comes with a €10,000 fee. It requires the provision of; Decision on the point of connection and site boundaries indicated by OS maps, proof of planning permission application, proof of landowner consent, details on maximum hourly quantities along with estimated annual production, daily supply point capacity, minimum annual production levels, and high-level timeline details.

Stage 3 begins once the application has been approved. At this point, a more detailed network analysis is performed by GNI, which provides the maximum hourly quantity allocated, along with a quotation of costs. This stage requires a percentage payment of the total costs of installation. Once the offer has been signed, there will be a 24-month period within which the design must be complete and necessary equipment to be purchased for the project's injection process. A complete detailed design must be submitted to be compared against the Functional Specification Requirements set out by Gas Networks Ireland, along with planning permission being granted for the project. The last step is to be granted a connection offer where the final balance of costs must be paid.

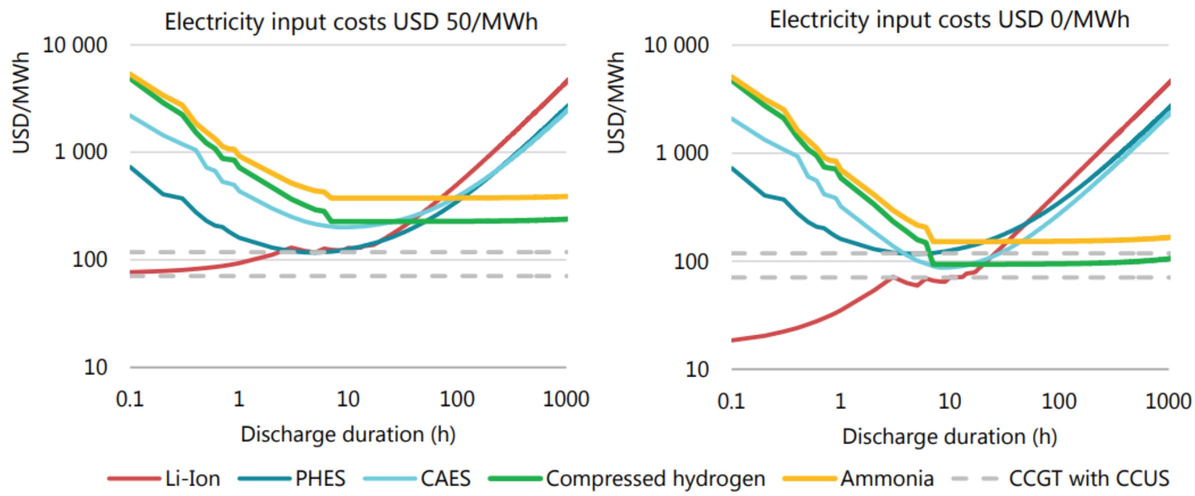
The GNI Connection Policy V5.0 also states that the client must pay 30% of the total connection cost (following their economic approval), where the remaining 70% is collected from the network tariff over a 10-year assessment period[124].

6.2 Pairing Electrolyser with Battery Energy Storage System

Although there is no known commercial pairing of electrolysers with Li-ion batteries, it is worth pointing out that the two share technological commonalities and have significant synergies. The BESS will help improve the system's dynamics, providing the quick response needed for DS3 frequency system services.

[124] Connections Policy Document, Gas Networks Ireland, October 2018, https://www.gasnetworks.ie/business/renewable-gas/renewable-gas-information/Gas-Networks-Ireland-Connections-Policy-Document-Revision-5.0.pdf

Furthermore, batteries are typically the lowest cost storage option for short discharge times. At the same time, electrolysers and hydrogen are now believed to be the cheapest for long-duration storage, as shown in Figure *15* below. Combining both technologies at a single site provides cost-effective storage for a wide range of timescales.



Notes: PHES = pumped-hydro energy storage; CAES = compressed air energy storage; Li-Ion = lithium-ion battery. Compressed hydrogen storage refers to compressed gaseous storage in salt caverns, ammonia storage to storage in tanks.
Source: IEA 2019. All rights reserved.

Figure 15: Storage costs for different technologies over different discharge times[125].

HG2S can provide frequency control services which are essential for maintaining the grid in the case of an imbalance between electricity consumption and production. A decrease in the grid frequency corresponds to a deficit in power production, while an increase in grid frequency corresponds to a surplus in power production. HG2S as a demand side unit will rapidly decrease or increase its load in response to a changing grid frequency and balance demand with generation.

6.3 Conjoined Injection Point for Biomethane

Another revenue source for could be utilising the gas connection for the injection of gases other than hydrogen (e.g., biomethane) onto the gas network. The process of injecting Biomethane into the natural gas networks can be seen in Figure 13.

[125] The Future of Hydrogen, IEA, June 2019, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

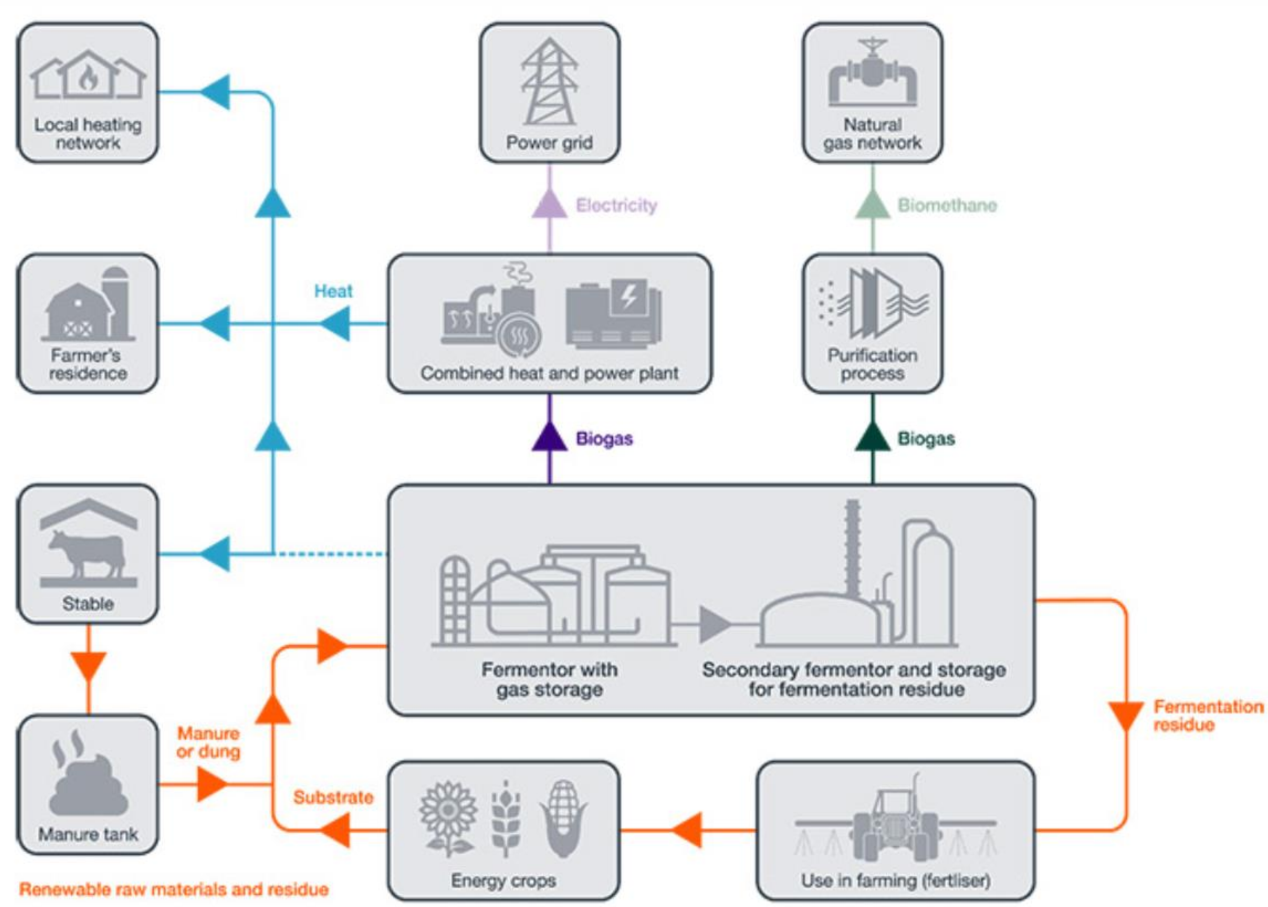


Figure 16: Overview of the Biomethane production process[126].

Biomethane is a carbon-neutral renewable gas made from farm and food waste through a process known as anaerobic digestion. Biomethane can seamlessly replace natural gas on the network today and is fully compatible with existing appliances, technologies, and vehicles[127]. Ireland, a large beef and dairy exporter, has substantial GHG emissions related to agriculture, with GHG emissions representing over 35% of national emissions.

If the project location was chosen to be an area with significant agricultural practice, the gas injection point could also inject blends of biomethane and hydrogen. This biomethane could be produced using on-site anaerobic digestors (with farm waste supplied by local farmers). The facility could also work as a biomethane aggregation centre, whereby biomethane is

[126] What is Biogas and why is it important, Howden, https://www.howden.com/en-gb/articles/renewables/what-is-biogas
[127] The future of renewable gas (biomethane) in Ireland, Gas Networks Ireland, https://www.gasnetworks.ie/corporate/company/our-commitment/environment/renewable-gas/

transported and deposited by local farmers who have anaerobic digestors. In the latter option, the facility would charge a fee for this service on a per-usage basis.

The advantages of this regarding project revenue will be wholly based on the local agricultural practices and the uptake by the local farmers. Therefore, figures for revenue are location-based and would need to be accurately modelled. Due to the nature of this revenue, indications for the injection of biomethane in conjunction with hydrogen are not touched upon in this feasibility study.

6.4 Technology Readiness Level of Project

Before beginning any large-scale grid project, a baseline assessment of technological readiness is necessary to provide a comprehensive view of the facility's capabilities. This section will provide an overview of the technological readiness of the components of the project and the current state of project development. The technology readiness of the primary, individual project components is at a technology readiness level (TRL) 9. However, the technical readiness of the existing gas network to transport the hydrogen is yet to be determined but is otherwise still maturing in Ireland and across the world through research and pilot projects described in Section 3.

No.	Technical Use and/or Combination	Innovative Operational Advantage
1	Hydrogen mixed with natural gas in existing gas network	Mixing hydrogen with natural gas avoids significant amounts of GHG emissions. A new use is created for the existing infrastructure, minimizing the additional impact on the land.
2	A fast-switching mechanism with sub-second response for the efficient provision of system services	Typically, the electrolyser does not have fast-switching capability, and a BESS is required. However, the electrolyser must be operable at low loads and capable of being turned off when necessary.

Table 2:Innovative and operational advantages of each of the technical combinations

6.5 Revenue Contracts

The project will target several potential sources of revenue during the operational phase. Revenues will be generated from the provision of hydrogen and electricity. The revenue from electricity will come from established markets for DS3 System Services, and Capacity Market.

DS3 System Services will account for most of the Electricity related revenue and will be provided by the project being available to reduce its electricity demand. This will be achieved by rapidly transferring the electrolyser load from the grid (primary electricity source) to the battery. Alternatively, the electrolyser could be turned off during this period and the energy stored in the battery could be exported to provide double system services provisions (assuming the BESS and electrolyser are scaled similarly). The project will deliver a range of DS3 System Services products, determined by the speed and duration of response, including FFR, POR, SOR, TOR2, SSRP, and DRR.

Capacity Market revenue will require the project to manage its demand to avoid peak electricity demand periods on the grid. During peak demand, the electricity will be supplied to the electrolyser from the battery rather than the electricity grid. This will alleviate a load from the electricity grid and will assist in avoiding the need for emission-intensive peaking generators.

The market for **Hydrogen** is in its infancy in Ireland and is expected to evolve in the coming years as part of the decarbonisation efforts. The revenue from Hydrogen is expected to come from two sources: the injection of Hydrogen into the national gas grid and the provision of Hydrogen as a transport fuel.

Hydrogen as a Transport fuel in the mid-future is expected to account for most of the revenue from hydrogen, as hydrogen is seen as a valuable fuel source for transportation, particularly for heavy goods vehicles. The project would aim to secure a supply contract with a public city bus company in Dublin, where there are ongoing trials for hydrogen-fuelled public transport.

Gas Network Injection revenue will be generated by supplying Hydrogen as a gas into the existing gas network. Hydrogen, based on its energy content and renewable nature when produced using wind/solar energy, is a premium product compared to the natural gas contained in the existing gas network. As the market develops, it is expected that renewable subsidies/incentives will be offered to green hydrogen suppliers.

This project will deliver a practical solution that will bridge the electrical and gas networks to effectively use the electricity and assist the power grid with system services while also producing green hydrogen that will be injected into the gas pipeline. This type of power to gas layout is a fundamental element of the EU's Strategy on Energy System Integration[128]. The following table summarises the problems and the solutions.

The project will provide:

Problem	Solution
Wind curtailment	Increased electricity consumption when the grid is experiencing low demand.
Frequency deviation	Demand-side unit for frequency system services: FFR, POR, SOR, TOR1, and TOR2.
Voltage deviation	Demand-side unit for voltage system services: SSRP and DRR
Carbon intensive natural gas for heat generation	Inject green hydrogen into the natural gas network to decarbonise heating.
Transport pollution	Decarbonizing transport by providing green hydrogen to the wholesale transport market.

Table 3:Project benefits of the Irish energy system

+HG2S is an innovative example of how the electricity and gas networks on the island of Ireland can be coupled to facilitate the growing renewable generation capacity and simultaneously help to decarbonise a modern and flexible gas grid. This project aims to show how this system can be replicated on a larger scale around the country and also around Europe.

6.6 Scalability, Employment in Ireland, and Foreign Investment

At present, the hydrogen market in Ireland is undeveloped; therefore, it was essential to assess potential scaling for hydrogen demand and its market barriers. The majority of hydrogen in Ireland is produced and consumed on-site at the Whitegate oil refinery in Cork. Other niche markets for hydrogen in Ireland include its usage as a power plant coolant and in the electronics manufacturing industry, but hydrogen consumption in these markets is not significant in comparison to other markets.

[128] EU strategy on energy system integration, European Commission, https://ec.europa.eu/energy/topics/energy-system-integration/eu-strategy-energy-system-integration_en

Hydrogen's impact as a clean energy vector has led to opportunities to decarbonise sectors which are not as trivial to decarbonise. These include heavy duty transport and industrial heat. Modes of transport such as heavy goods vehicles (HGVs), buses, and trains, as well as modern gas pipeline networks, are key sectors that can avail of hydrogen's potential towards a green economy.

Across the world, the application of hydrogen in areas which affect all aspects of our daily lives is being planned. Some changes are straightforward or "short and medium-term low risk moves", such as the change of hydrogen supply to industrial processes. Other areas depend on parameters which determine if the application of hydrogen is more efficient and sustainable than others, i.e., will small passenger vehicles be BEV or FCEV? Given policy ambitions in Ireland and the EU, there is a clear directive to establish infrastructure that fully optimizes the country's sources of green energy. For example, GNI's "Hydrogen and Ireland's National Gas Network" and the European Commission's Hydrogen Roadmap show clear ambitions to implement a hydrogen market both in Ireland and across the EU respectively, with the intent to achieve a decarbonised economy. The technologies proposed in the project have been utilized and technologically approved already in both pilot and commercial-scale projects and have demonstrated a high level of performance and potential for scalability. Flow batteries capacity is proportional to the quantity of the electrolyte, easily allowing the battery to be scaled up. There is also potential for the addition of larger electrolysers or many smaller ones. This hydrogen production could then be either added to the gas network in a higher blend if the necessary adjustments have been made to the gas network or stored for use in other markets. Possible funding could come from the EU Innovation Fund[129] due its large budget for projects like this. Projects like this could generate employability in Ireland for construction, operation, and maintenance. Beyond this, hydrogen projects show great potential for having multiple project sites across Ireland to increase hydrogen productivity. An innovative project like this could even provide the necessary experience to replicate this project across Ireland and even across the world as other countries push toward lowering carbon emissions in the future.

[129] EU Innovation Fund, European Commission, https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en

7 Conclusion

Although there are several challenges in its implementation, the injection of hydrogen into the existing gas infrastructure would be the backbone of an Irish green hydrogen economy. It would encourage the generation and sale of hydrogen, enabling the coupling of the gas and energy sectors, all while decarbonising both grids.

The curtailment of wind energy is a huge issue which discourages new development and increases electricity prices for the consumer. Using this otherwise wasted energy to generate green hydrogen encourages further development of renewables by providing a stable source of income during low demand periods. It will also help to alleviate grid congestion by transferring energy out of constrained regions using the pre-existing natural gas grid. An increase in the percentage of hydrogen in the natural gas grid would also abate emissions in a variety of difficult to decarbonise sectors such as industrial heating and gas turbine power generation.

If green hydrogen was adopted in the Irish market and generation exceeded demand, there is the opportunity to export excess hydrogen gas to markets such as the United Kingdom and the EU. Creation of a market would also allow for the development of hydrogen-fuelled transport in both the public and private sectors, which are currently limited by the lack of hydrogen fuel availability.

Another potential use of hydrogen is for short-duration energy storage. However, this is currently not a good option due to the low roundtrip efficiencies when compared to alternative solutions like battery energy storage systems. A hydrogen market must be developed in Ireland before such projects in can be made financially viable.

Overall, injecting green hydrogen into existing gas network infrastructure and developing a green hydrogen economy will substantially benefit GNI, the end-use consumer, and renewable energy developers in Ireland. It will support Ireland in becoming energy independent whilst also helping to ensure the security of supply of both gas and electricity. This will help Ireland to reach its GHG emission reduction targets while creating a reliable and sustainable power grid.

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