NUI Galway
OÉ Gaillimh

HYDROGEN

EXPLORING OPPORTUNITIES IN THE NORTHERN IRELAND ENERGY TRANSITION

NOVEMBER 2020

This report is prepared by the National University of Ireland Galway (NUI Galway), with partners HyEnergy Consultancy and Dublin City University (DCU). It has been funded by Northern Ireland’s Department for the Economy to contribute to the evidence base for the development of a new Energy Strategy.

NUI Galway and DCU are two of Ireland's leading energy research institutions, and are both members of MaREI, the Science Foundation Ireland Centre for Energy, Climate and Marine Research. NUI Galway has expertise in the techno economics and sustainability of hydrogen technologies and supply chains, and is a partner in the GenComm, SEAFUEL and HUGE EU Interreg projects. DCU has expertise in hydrogen for mobility, power-to-X, fuel cell & electrolyser technology, energy storage and modelling, and is a partner in an EU funded project HySkills and Hydrogen Mobility Ireland.

HyEnergy is an experienced consultancy with over 50 years of expertise within the global hydrogen and renewable energy sectors. It supports stakeholders including industry, local/regional public sector organisations and national governments in transitioning to sustainable energy solutions.

NUI Galway, DCU and HyEnergy are founding organisations of Hydrogen Ireland.

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Executive Summary

As countries around Europe and the world commit to deep decarbonisation goals by 2030 and net-zero greenhouse gas emissions by 2050, the focus of policymakers is moving beyond the deployment of renewable electricity generation. Renewables coupled with electrification of transport and heating, as well as energy efficiency improvements will undoubtedly play a major role. Hard-to-abate sectors including heavy duty transport, high-temperature heat, among others will present particular challenges. Issues around electricity grid stability, seasonal storage of renewables and reduction of curtailment and constraint will also need to be addressed. Hydrogen can play a central role in integrating the electricity, transport and heating sectors, storing, and transmitting large volumes of variable renewables, while also stimulating new innovative industries and economies.

Northern Ireland is uniquely positioned in the United Kingdom (UK) and Europe to become a leader in hydrogen deployment and technology. Abundant, and in many cases untapped, onshore, and offshore renewable resources, modern gas and electricity networks, interconnection to both Ireland and Great Britain, a relatively small geographic area, availability of salt cavern storage, and an internationally recognised track record of engineering and manufacturing innovation give Northern Ireland a competitive edge. Third-level education and research institutes, exemplified by Belfast Metropolitan College and Ulster University, are leading the way in hydrogen training and safety.

The analysis described in this report presents scenarios for the deployment of hydrogen in Northern Ireland's transportation and heating sectors in 2030. Costs of delivered hydrogen and emissions savings for localised, regional, and centralised value chains for locations throughout Northern Ireland are calculated and compared. End-use applications include gas grid injection at volumes of 15% in the northwest and Greater Belfast areas, fuelling 500 trucks and 300 double-decker buses in Belfast and Derry/Londonderry, and 8 trains in Belfast. Modelling shows that larger scale regional and centralised hydrogen production results in low unsubsidised costs of £2.53-£4.99 per kg, and higher carbon dioxide (CO_2) savings.

Integrated planning for hydrogen deployment across all energy and industry sectors in Northern Ireland needs to be quickly stepped up and the necessary support put in place for technology demonstrators and hydrogen hubs. Given the stage of market development and high initial capital costs, early technology developers and adopters will need financial support to bridge the gap to commercialisation. Maintaining and strengthening cooperation on hydrogen with the rest of the UK, Ireland, and the European Union (EU) is important. Northern Ireland's ambitions on hydrogen need to be clearly articulated and a pathway to exploit its potential mapped out, if we are to realise the benefits in decarbonisation, energy security, competitiveness, economic growth, and innovation for the region.

Introduction

Hydrogen is considered to be **the** emerging energy vector which can unite many of the renewable energy technologies, whilst also offering further decarbonisation opportunities in sectors which remain hard to impact and highly fossil dependant.

Global energy systems are under tremendous pressure to transform their environmental impact and aggressively reduce carbon emissions to achieve goals agreed within the Paris Agreement.

Low carbon electricity from renewable sources offers a viable pathway to meeting the commitments required in the Paris Agreement. However, it is not as simple as installing more renewable energy capacity. Renewable power cannot always keep up with peak demand due to seasonal fluctuations and grid constraints and curtailment causes green energy to be wasted. Compounding the accessibility issue, the decarbonisation of certain sectors, such as industry, transport and heat are problematic due to their reliance on existing infrastructure as well as the cost to move to full electrification being a significant barrier.

Hydrogen is seen by many to be the key to unlocking energy transformation. Renewable energy can be used to produce hydrogen which can act as an energy store or can be used directly in a variety of applications, including those which would be difficult to decarbonise via direct electrification. Hydrogen can be the energy carrier that helps to enable the whole energy transition.

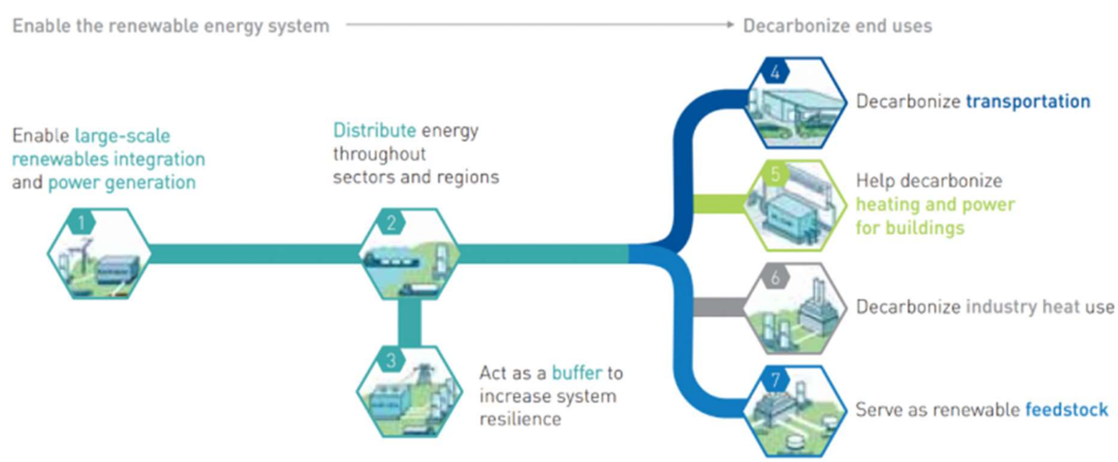

Figure 1: *Hydrogen Roadmap Overview*[35]

Energy Strategy

To understand how hydrogen can play a role in Northern Ireland (NI), we must first examine the current energy demands of the Province.

Northern Ireland's Energy Mix

Today NI is heavily reliant on imported fossil fuels to supply its energy needs. With no indigenous fossil resources, production or refining, fossil imports account for the vast majority of NI's heat and transport energy requirements. In addition, despite the high rate of growth in renewable electricity generation, imported fossil fuels, in particular coal and natural gas, comprised over half of NI's electricity feedstock in 2018[1].

Fuel	*2018 Fuel Consumption (GWh)*	*% of Total*
Coal	2,205	5%
Manufactured Fuels	319	1%
Petroleum Products	29,440	61%
Natural Gas	6,273	13%
Electricity	7,607	16%
Bioenergy and Wastes	2,080	4%
Total Final Consumption	47,923	100%

Table 1*: NI total final consumption of energy by fuel 20181 (Manufactured fuels refers to only manufactured solid fuels)*

Direct use of fossil fuels in heating and transportation made up 80% of NI's total final consumption of energy. The electricity supplied in Table 1 is generated according to the fuel mix shown below.

Fuel	*2018 electricity generated by fuel (GWh)*	*% of Total*
Coal	1,080	14.2%
Natural Gas	3,233	42.5%
Renewables	3,218	42.3%
Oil and Other	68	0.9%
Total Electricity Generated	7,607	100%

Table 2*: NI electricity generation by fuel 2018*[1]

Outside the electricity generation sector, coal, manufactured fuels, and natural gas are used for heating purposes. Consumption of petroleum products is approximately evenly split between heating and transport[1]. Bioenergy and wastes are mostly used for heating purposes. Only a very small amount of the electricity generated is used for heat and transport; this is expected to grow significantly in the coming decades.

Renewable electricity generation in NI, predominantly from wind, has grown significantly in the last decade. In 2013, 19.5% of electricity generation in NI was from renewable sources[1], compared to 42.3% in 2018. The rest of the electricity generation mix is predominantly made up of coal and natural gas-fuelled thermal generation, at 14.2% and 42.5%, respectively.

Northern Ireland’s Energy Infrastructure

Electricity

Figure 2: *Map Showing Transmission Network and Proposed Interconnector*[36]

As part of the single electricity market (SEM), NI shares an electricity grid and market with the Republic of Ireland (ROI). SONI is responsible for the operation of the transmission network in NI, while EirGrid carries out the same function in ROI, although both collaborate closely, specifically through SEM operator.

Despite sharing the SEM with the ROI, there is only one source of interconnection between North and South. The capacity of this connection is limited to 100MW from NI to ROI and 200MW from ROI to NI[2]. As a result, plans for a second 1500MW North-South interconnector have recently been approved by the NI government[3]. This will increase transfer capacity between both jurisdictions considerably, facilitating the integration of further RES. The NI electricity grid is also connected to the Great Britain (GB) grid via the 500-MW high voltage direct current (HVDC) Moyle Interconnector between Ballycronanmore, NI and Auchencrosh, Scotland[2]. This connection will only grow in importance, as both Scotland and NI increase their renewable energy source (RES) capacity. Two additional interconnectors are planned for Ireland. The Celtic Interconnector will link ROI and France. The connection is expected to be 575km long, running from Cork to northeast Brittany and capable of carrying 700MW of power. Planning on where to build the onshore facilities is underway and the connector will ’go live’ in 2026 if given the go ahead soon. The 500-MW Greenlink Interconnector will link ROI and Wales. Planning application in ROI were to get underway in Q4 2020.

Natural Gas

NI also shares a natural gas (NG) network with the ROI, much of which is owned and operated by GNI, a subsidiary of Ervia, including the connection to the ROI[4]. Mutual Energy own and operate the Scotland-NI interconnector (SNIP) and the Belfast Gas Transmission pipeline from Islandmagee to Belfast[5]. As part of the Gas to the West project, Mutual Energy and Scotia Gas Network (SGN) completed work on both a high-pressure transmission and low-pressure distribution network in 2020 to bring NG to towns in the west of NI, including Strabane, Omagh, and Enniskillen[6].

All NG imports to NI and ROI are supplied via Moffat in Scotland through the SNIP and two interconnectors (IC1 and IC2), which connect to the network north of Dublin[7].

Renewables in Northern Ireland

NI’s proportion of electricity generation from renewables was 42.3% in 2018, the majority from onshore wind. As of 2018, the total installed capacity of wind farms in NI stood at 1,393 MW, much of which is in the west and north-west, where the wind resource is greatest. In 2019, 84.5% of renewable electricity generation was from onshore wind, with the remainder coming from landfill gas, biomass, biogas, and solar photovoltaic panels (PV)[1].

The growth in renewable penetration of the electricity grid in NI is expected to continue, although the government is yet to announce its future renewable energy targets. The ROI and Scotland have committed to 70% and 100% renewable electricity systems, respectively, by 2030[2]. Given its participation in the SEM and its abundant renewable potential both on and offshore, NI is likely to set similar targets. Speaking at the NI Energy Forum in September 2020, Economy Minister Diane Dodds spoke of her belief that the goal for NI should be no less than 70% renewable electricity by 2030[8].

Assuming this goal, it would most likely be achieved by utilising onshore wind, accompanied with significant growth in solar. NI did not take part in the Crown Estate's Round 4 leasing process, which is responsible for allocating seabed area of the UK[9]. The Department for Energy (DfE) believe it is unlikely there will be any considerable offshore wind capacity operational in NI by 2030. However, large quantities of offshore wind capacity in the ROI by 2030 are forecast, with a government aim for 5 GW by the end of the decade[10], and, with announcements made by the UK government in recent weeks, it would be expected that offshore wind capacity in NI will also increase more rapidly than previously expected. Floating offshore wind platforms may also be an option in certain geographical locations given recent developments in their technology. This wind generation, predominantly located on the east and south coasts, will be indirectly available to NI should the second North-South interconnector be successfully completed in time. The result would be a closely integrated and flexible all-island electricity system, which would facilitate the growth of renewable electricity both sides of the border by 2024.

A growing issue with variable renewable electricity sources, such as wind, is the waste of energy due to 'dispatch down', of which there are two types. Curtailment is when renewable energy production exceeds the electricity system's demand, and therefore some renewable generators are disconnected to prevent overloading. Constraint is when electricity generation is turned off due to a local network issue. Despite SONI's success in increasing the level of renewable electricity generation on the grid, 17.4%, nearly 300,000 MWh, of NI's wind generation failed to reach consumers due to dispatch down in the first half of 2020[11]. This is the highest figure for any region in the SEM.

The need to tackle rising levels of dispatch down is important in ensuring the continued cost-effective growth of renewable energy in NI. A variety of solutions are needed, including increased interconnection, development of the transmission grid, and demand side management. Energy storage, including that provided by hydrogen, can also play a key role in minimising the wasted energy resulting from dispatch down.

While the renewable share of the electricity sector has grown rapidly in recent years, transport and heat remain heavily reliant on imported fossil fuels. Electrification of some heat and transport through increased deployment of heat pumps and electric vehicles is expected to take off this decade. However, harder to decarbonise sectors such as large space heating, industry, heavy goods vehicles, shipping, and aviation will need an alternative low carbon solution[12]. Low or zero carbon hydrogen has the potential to reduce/eliminate point of use emissions from such sectors.

Therefore, hydrogen enables the interlinking of the electrical and gas infrastructures, provides energy storage opportunities, and increases renewables access to hard to decarbonise markets, thereby increasing renewable penetration of the total energy market for the Province.

Energy in the UK and ROI: A Comparison

Fossil Fuels

To understand NI's energy system it is useful to compare it to those of the UK as a whole and the ROI, given its unique position within the UK, while sharing an island and electricity and NG networks with the ROI. There is no commercial oil production on or around the island of Ireland. The ROI has one indigenous source of NG, the Corrib Gas Field. As result of this, Ireland's import dependency dropped from an average of 89% between 2001 to 2015, to 69% in 2016, and further to 67% in 2018[13]. However, production volumes have fallen since, and production is due to decline over the course of this decade.

Whilst NI does not currently have any indigenous NG production, Tamboran UK has applied to the Department for the Economy for an exploration licence to investigate potential shale gas reserves in Fermanagh[14]. Should this licence be granted, and the exploration deemed a success, the shale gas would be extracted by hydraulic fracturing. However, recent exploration for shale gas in Lancashire has been halted due to seismicity induced by the hydraulic fracturing process[16]. Hydraulic fracturing has been banned in the ROI through legislation brought into law in 2017[15].

The UK has a large and mature oil and NG industry, focused primarily off the coast of Scotland in the North Sea. The UK currently meets approximately 66% and 52% of its oil and NG demands, respectively. Norway is the source of the majority of the UK's NG imports, and provides the largest share of UK's crude oil imports of any country while Russia and the Netherlands are the two largest sources of oil product imports[13]. Conventional UK oil and NG production is generally in decline, so the percentages of imported oil and NG are expected to increase unless alternative local resources are developed.

Renewables

In both the UK and the ROI, growth in renewable energy has predominantly taken place in the electricity sector, with little renewable penetration in the heat and transport sectors. This is expected to change in the next decade as technologies such as heat pumps and electric vehicles contribute to the electrification of these sectors.

When comparing NI's electricity generation mix to that of the UK and ROI (Figure 3), NI is outperforming both as of 2018, with 42.3% of electricity generation coming from renewable sources. This is in comparison to 33% for both the UK and ROI. Scotland, however, currently reaches 55% renewable generation. For all the jurisdictions, most of the renewable portion of electricity is from wind energy.

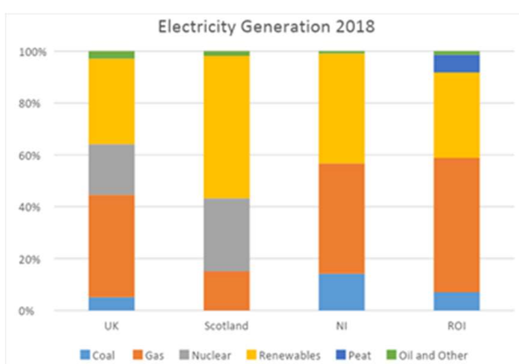

Figure 3: *Total Electricity Generation and Fuel*

As the levels of renewable energy production in Ireland and the UK grow over the next decade and beyond, interconnection of energy systems and sufficient storage will prove crucial in allowing the transfer of surplus energy between regions and market applications.

Potential for Hydrogen Production in Northern Ireland

Fossil-based, traditional hydrogen production methods can become climate neutral with the addition of carbon capture and storage technology. These so called 'blue' hydrogen solutions are not readily available in NI due its lack of fossil fuel resources. However, with high levels of renewable electricity and dispatch down, NI is a fertile ground for 'green' hydrogen production. With large amounts of renewable electricity currently going to waste in NI, a situation which is expected to worsen in the future, this energy could instead be used to create hydrogen fuel. Green hydrogen is produced when renewable electricity is used to run an electrolyser. This fuel can be used in transport – hydrogen cars, vans, buses, trucks, ships and even aircraft – as well as for both domestic and industrial heat.

When coupled with biomass or carbon capture utilisation and storage (CCUS), hydrogen can be used as a feedstock to create synthetic fuels. For example, hydrogen can be added to an anaerobic digester to increase the methane yield and thus the energy content of the biogas. Costs for these fuels are currently prohibitive. However, given the long-term potential of hydrogen for such applications, they are important to consider when making equally long-term investment plans for both CCUS and hydrogen infrastructure.

In comparison to the other regions of the UK and the ROI, there are several reasons that make NI very suitable for green hydrogen production. With relatively high levels of renewable electricity and dispatch down, NI has potential for both grid-connected and on-site hydrogen production at wind farms. Many of NI's large wind farms may be suitable for on-site electrolysis like the GenComm project at Long Mountain, while grid-connected electrolysers would have access to a highly decarbonised electricity system through the SEM. Such electrolysers could also provide ancillary services to the electricity grid in return for a fee from SONI, providing an additional source of revenue[20]. Whilst Scotland shares many similarities with NI, other regions of the UK have fewer variable renewables and better electrical connection between regions.

There are a wide variety of potential production scenarios for hydrogen in NI. As outlined, the larger wind farms in NI could produce hydrogen on-site, providing an extra market for their energy and help reduce their own dispatch down. Another possible permutation is to situate larger production sites in areas of high wind such as the Fermanagh-Omagh or Derry-Strabane regions. Such production would be connected to the electrical grid and could help to alleviate dispatch down grid issues in addition to producing hydrogen for use locally in heat and transport. A large-scale centralised production system situated near Islandmagee and Belfast is a very real prospect for NI due to its:

- Access to large amounts of electricity due to location near high voltage electricity grid and interconnection with Scotland
- Proximity to large potential demand, including:
    - The natural gas grid via the SNIP
    - Ballylumford and Kilroot power stations
    - Buses and heavy goods vehicles in Belfast and the M1 corridor
- Potential for large scale hydrogen storage at Islandmagee and potential future salt caverns at Larne
- Suitability of Belfast port for export of renewable hydrogen and its derivatives

Potential Hydrogen Enabled Applications in Northern Ireland

Industrial feedstock

NI has a strong historical manufacturing tradition. Today it has many technology-driven companies providing a high level of skills to its workforce. It lacks, however, the main hydrogen consuming industrial sectors such as chemicals, steel and refining and therefore imports all its current industrial hydrogen demand. Across the whole of the island of Ireland the trucked hydrogen demand has been estimated as being 180 tonnes/year[48]– which is small and concentrated in the power, electronics, and metal fabrication sectors. For example, currently, NI has operational fossil fuel power plants which use hydrogen for alternator cooling to improve efficiency. However, this use is minor, and demand is not expected to grow.

Although hydrogen does not have an industrial legacy in NI, the skillsets exist to enable a strong future positioning. The world-leading hydrogen safety research centre of HySAFER at Ulster University is one example. The traditional metals and manufacturing businesses, such as Harland and Woolf, will be key to development of the local supply chains for future hydrogen energy applications. The repurposing of these long-held skills could see NI rapidly establishing local supply chain manufacturing to support expected international demand growth for hydrogen storage. Here again NI is developing leading positions such as in polymer and composite manufacturing at QUB. These centres of excellence can then be expanded on as business opportunities grow.

Given the current 17.4% dispatch down of renewables and the projected increase of RES for NI in the near term, the use of hydrogen to enable energy export becomes increasingly possible. Therefore, by positioning as a green hydrogen exporter, NI can help supply excess UK and EU demand with emission free hydrogen. This could require the development of carrier molecule industries such as ammonia. The development of local ammonia production could enable domestic fertiliser manufacturing.

Hydrogen for Transport

Mobility is seen as a key hydrogen future demand in NI and the ROI. Currently, original equipment manufacturers (OEMs) have a limited range of models available including cars, vans, buses, and heavy goods vehicles. Heavier vehicle applications are most suited to hydrogen relative to battery electric alternatives. Fuel Cell Electric (FCE) trains are being sold across Europe today and marine and aviation applications are also possible in the medium/long-term.

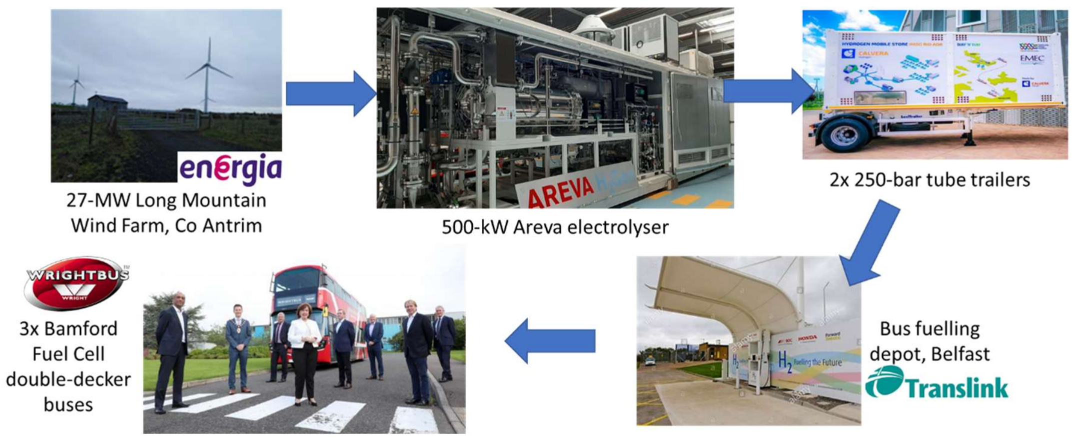

Figure 4*: The GenComm Project Roadmap*

There are already plans for several projects which will integrate curtailed energy with hydrogen in NI. The €9.4M EU funded GenComm project is closest to realisation. Within GenComm, Energia plans to produce hydrogen, via electrolysis, at its Long Mountain Wind Farm in County Antrim. The UK government, via Office for Low Emission Vehicles (OLEV), have supported Energia in this initiative with further funding of £4M which will used to construct an HRS, to be deployed at Translink's new bus facility, and a small FCE public bus fleet in Belfast. All the hydrogen required for this initial trial will be provided by the GenComm facility. The project aims to be operational in 2021[19]. On top of these original plans, recent announcements have confirmed that Translink will order an additional 20 FCE public busses.[49]

The buses in the project will be supplied by one of the key European bus OEMs, Wrightbus. Based in Ballymena, Wrightbus have been a first mover in hydrogen bus projects across Europe.

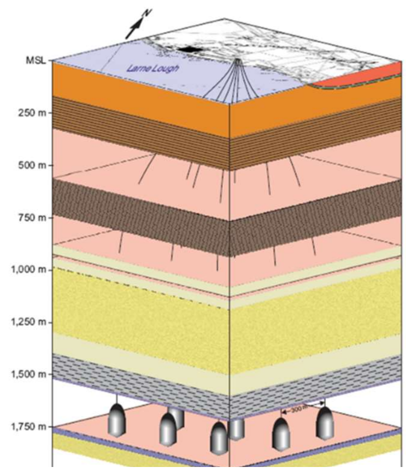

Figure 5*: Islandmagee Gas Storage Facility Northern Ireland*[37]

It has long been recognised that the deployment of fuel cell electric vehicles (FCEVs) must be coordinated with the roll out of hydrogen refuelling infrastructure. Many countries have opted to create a 'hydrogen mobility' group of interested stakeholders who work together to create possible introduction scenarios. The Irish hydrogen mobility group was founded in 2018 and has already put outlined initial roll out plans for the whole island of Ireland in a public report.

Hydrogen for the Gas Grid

NI has a widespread NG grid interconnected with the UK and ROI. Decarbonisation of NG grid infrastructure using hydrogen is developing across Europe (see Appendix B). Mixtures of hydrogen in the NG are being trialled. Percentages of up to 20% by volume can be accommodated by most modern NG grid systems such as that in NI. Eventually, pure hydrogen may be deployed once appropriate steps have been taken to mitigate its use both in the grid and in applications. NI has the same energy profile as many of these countries. It also has one of the key elements to make such a transition possible – a gas storage cavern. Salt cavern storage is a promising technology due to its large storage capacity, which can exceed even pumped hydro storage. Their use for storing NG and even hydrogen is common place. Coupling such a storage with RES is regarded as crucial to balance fluctuations in electricity generation.

Islandmagee, near Larne in County Antrim, is the location of a project of common interest (PCI) that is developing a low-cost fast cycle gas storage facility that will serve the island of Ireland and mainland UK. Seven caverns will be developed, with a combined storage capacity of up to 500 Mm^3 of gases. Project members are currently in talks with regulatory authorities in relation to discharge consent and marine construction licences needed to confirm the projects go ahead.

The project at Islandmagee and the development of storage caverns to store NG builds experience and capability in NI. This will enable decarbonisation transitions, with the NG network seeing increased hydrogen concentrations and storage capability in the Larne salt deposits.

Oxygen

When water is fed into an electrolyser to create hydrogen, it also creates oxygen as a by-product in the process. For every kilogram of hydrogen produced, 8 kg of oxygen is produced. Just like hydrogen, oxygen can be captured from this process, purified and sold for a variety of applications including manufacturing, chemicals, pharmaceuticals and waste-water treatment. Oxygen capture from electrolysers is economically challenging when compared to the more traditional methods of oxygen production, such as air separation. As a significant portion of oxygen's cost result from its transport, it is possibly economically viable if electrolysers are co-located with their potential oxygen demand or are located in remote areas.

Within NI the most logical co-location opportunity would be with Northern Ireland Water (NIW) for sludge aeration. Approximately 83% of households in NI are served by the public sewerage system, with NIW collecting, treating, and safely disposing of 320 million litres of wastewater each day. It is predicted that over half of NI's treatment plants will reach full capacity by 2027. Thus, a significant investment for wastewater and water infrastructure (including an increased oxygen demand) in the coming years. Acknowledging this, in November 2020, NI Water was awarded £5m of funding by DfE to undertake an oxygen and hydrogen demonstration that will deploy a state-of-the-art, 1-MW electrolyser.

Northern Ireland Hydrogen Demand Scenarios

The next few years are critical if NI is to develop a hydrogen ecosystem. A strategy that will map out this activity with a focus on the next ten years to 2030 is needed. Hydrogen production and market introduction must be deployed congruently, and stakeholders must work together to ensure a smooth infrastructure and policy rollout.

Hydrogen has many potential end-uses (Appendix B), ranging from an industry feedstock to transport solutions to NG grid injection, for storage or heat or reconversion to electricity. Within the context of a 10-year time frame, it has become clear that opportunities exist for green hydrogen in NI and there could be two main target markets for this green hydrogen:

1) **The transport sector with a focus on public transport (buses & trains) and heavy goods vehicles (freight)**
2) **Injection to the NG grid**

For transport and NG grid there are several social, political, and global factors that will increase the rollout of low carbon transport and increased quantities of hydrogen allowed in the NG grid. For example, the UK has recently updated its plan to ban the sale of new petrol and diesel cars bringing forward the date to 2030[30], the UK also launched a plan for a "green industrial revolution"[31] to include hydrogen in transport and the conversion of a whole town to hydrogen. In addition, external influences, and action such as vehicle emission standards, a greater ambition to manage climate change and implement Paris Agreement ambitions as well as the EU's[32] and neighbouring countries hydrogen strategies and ROIs plans to decarbonise public transport all encourage NI to develop hydrogen within its economy.

For transport, three scenarios have been projected as part of this analysis – high, medium, and low, for the forecast number of hydrogen buses, trucks, and trains in operation by 2030 in NI.

- High – represents a highly co-ordinated, public support and policy plan which delivers deployment of hydrogen production, supply, and demand. The first trains and the first large fleet of trucks arrives in the mid 20's and it is anticipated that hydrogen establishes itself as a major transport solution by 2030 with a number of HRSs beginning to link cities. Belfast is seen as a main hydrogen hub with other regional hubs that supply a fleet of c.1000 trucks, almost 500 buses operating from multiple bus termini and 18 trains on selected routes with the necessary green hydrogen.
  Planning for the truck fleet starts immediately. This scenario sees the Belfast Dublin train line as an important link with ROI to decarbonise and this becomes one of the first train fleets to fully convert to hydrogen. It projects that many new buses purchased from now onwards and replacing some of the older Ulster Bus fleet, are FCEVs due to their intercity range requirements while glider and metro have a mix of solutions including battery electric. This scenario is similar to Hydrogen Mobility Ireland's assumptions provided in their report[33].
- Medium - represents a middle of the road scenario where a measured uptake or infrastructure build out occurs, however, the same ambition of the high uptake is assumed, albeit arriving later.
- Low - represents a delayed start to a hydrogen rollout; several projects begin, but a connected NI HRS infrastructure is not in place and FCEVs remain scare. It represents an un-coordinated

approach to hydrogen rollout where a holistic methodology for production, supply and demand is not in place and limited policy support is available.

For all scenarios, the average distance travelled per journey by vehicle type is based on NI statistical data[34]. The corresponding total number of km travelled per day is used to calculate the hydrogen demand for that vehicle type. Between 310 and 341 operational days are assumed for each vehicles type.

As displayed in Figure 6, buses and trucks are projected to have a slow up-take in the first five years, due to availability of vehicles, planning time for the hydrogen production and HRSs and increasing societal acceptance. As infrastructure develops and grows, hydrogen vehicle numbers significantly increase. Passenger FCEV uptake was not used in the analysis; however, it would be expected that once HRS infrastructure is in place the number of passenger FCEVs will naturally evolve as the ability to refuel becomes easier with the wider deployment.

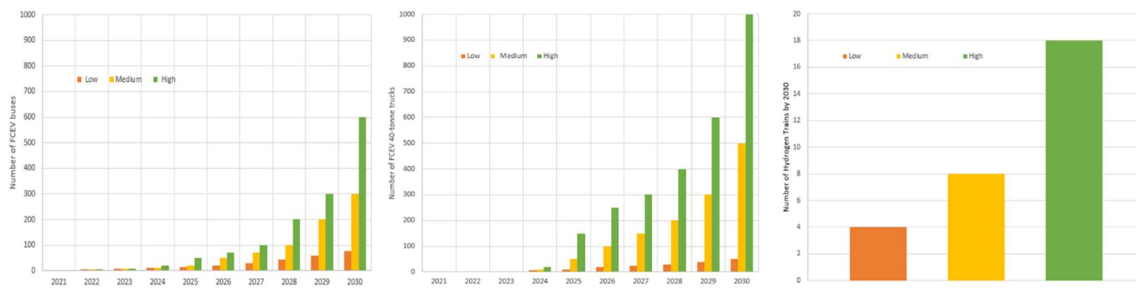

Figure 6: *Fuel Cell Electric Buses, HGVs and trains assumed by scenario to 2030.*

In relation to hydrogen injection in the NG grid, it is assumed that 5% of a region's natural gas demand could be displaced by hydrogen. This figure is equivalent to a 15% hydrogen blend by volume which is consistent with the range of 2%-20% hydrogen blending that is under examination across Europe[21].

Northern Ireland Hydrogen Supply/Demand Analysis

Methodology

Demand

As described in the previous section, two categories of hydrogen demand were identified for the 2030 timeframe: hydrogen-fuelled bus, truck, and train fleets, and injection into the natural gas grid for heating.

The medium estimates of 300 hydrogen double-decker buses and 500 hydrogen 40-tonne trucks on the road in NI were used for this analysis. Due to the high costs associated with building hydrogen refuelling infrastructure it is likely that these vehicles will be predominantly refuelled in a relatively small number of locations. For both hydrogen buses and trucks in 2030, it is assumed that 70% will refuel in Belfast and 30% in Derry/Londonderry. The medium estimate of 8 hydrogen trains is also used, all of which are assumed to refuel in Belfast. The Dublin Enterprise and Larne Line will each use 4 hydrogen trains.

The two regions considered for the gas grid injection analysis were the Greater Belfast area, and the North-west region, comprising Derry-Strabane and Causeway Coast and Glens.

Production

Three scenarios for hydrogen production from electrolysis were considered for this analysis. The first production scenario involves small-scale electrolysis at wind farms distributed throughout NI. The hydrogen is transported via tube trailer to the nearest demand, either a city bus network, or a gas grid above ground installation (AGI), which is assumed could be repurposed as an injection point. The second scenario is larger scale, regional hydrogen production from grid electricity in an area with high-RES penetration. Again, the hydrogen is transported via tube trailer to nearby demand if necessary. The third scenario is large-scale centralised production in the Belfast Area from grid electricity.

Supply-chain Scenarios

Based on the two potential hydrogen demand types identified, and the three production methods considered, the five supply chain scenarios have been modelled to identify their required sizes of electrolysers, compressors, hydrogen distribution chains, and their costs of hydrogen delivered to the gas grid or refuelling station. The cost calculations include capital and operational expenses of production and transport but exclude the costs of the hydrogen refuelling station and the gas grid injection point as these costs are highly dependent on the exact location and business model employed. Further, more detailed analysis is needed to reliably determine their costs. All scenarios are summarised in Table 3 below.

Scenario	Value Chain Type	Location	Electricity Source	Hydrogen Demand
1	Distributed	Throughout NI	Wind Farms	Various local demands
2a	Regional	Derry	Grid	90 buses, 150 trucks
2b	Regional	North-West	Grid	5% NW Natural Gas Demand
3a	Centralised	Belfast	Grid	210 buses, 350 trucks, 8 trains
3b	Centralised	Greater Belfast	Grid	5% Greater Belfast Natural Gas Demand

Table 3*: Summary of hydrogen supply-chain scenarios*

Scenario 1: Distributed Hydrogen Production at Wind Farms

For each wind farm in NI with a capacity of over 5 MW, a small-scale proton exchange membrane (PEM) electrolyser is optimised for lowest hydrogen production cost from all the available wind resource following the method of Gunawan et al, 2020[22]. The hydrogen produced at the wind farm is compressed and transported by tube trailer to the nearest available demand site. The levelised cost of hydrogen production ($LCOH_P$) and transport ($LCOH_T$) to the assumed 2030 demand is calculated.

Scenarios 2a and 2b: Regional Hydrogen Production for Transport and Heat

For Scenario 2a, a mid-sized hydrogen production plant located in an area of high RES produces hydrogen for a refuelling station in Derry/Londonderry in 2030. The station provides hydrogen for buses and trucks in the area. The hydrogen is transported by tube trailer to the station, which is located 50 km from the production plant. For Scenario 2b, the plant is located at a gas grid AGI in the Northwest. The hydrogen is injected into the transmission network which serves the Derry-Strabane and Causeway Coast and Glens regions. It is assumed that the injected hydrogen can displace up to 5% of the NG demand in the area. This is equivalent to a 15% hydrogen blend by volume.

The hydrogen production plant's alkaline electrolysers run on grid electricity, which is assumed to be 70% renewable by 2030, with an emissions factor of 100 gCO_2/kWh[23]. The plant is assumed to run year-round at full capacity, with 8% downtime for maintenance. Electricity is purchased in the Day Ahead Market (DAM) of the SEM. Low and high electricity prices of £36/MWh and £72/MWh are assumed. The average price in the DAM in 2019 was £45/MWh[24]. Though it is currently not the case, it is likely that by 2030 there will be some form of incentive to consume otherwise curtailed or constraint electricity. For this analysis, it is assumed that 10% of the electricity consumed annually by the plant is supplied by dispatch down at zero cost. Further electrolyser sources of income could include the provision of grid services. Determining reasonable estimates for this income requires more detailed time-dependent modelling, so they are not included in the present work. The plant has one day's supply of hydrogen storage on-site in compressed hydrogen tanks.

For both 2a and 2b, the plant size, in MW of electrolyser capacity, as well as the $LCOH_P$ and $LCOH_T$ in 2030 and CO_2 emissions avoided per year are calculated.

Scenarios 3a and 3b: Centralised Hydrogen Production for Transport and Heat

For Scenario 3a, a large-scale hydrogen production plant is located to the Northeast of Belfast. This location is chosen as it is near the gas and electricity transmission interconnectors with GB, it is near a likely connection point for future offshore wind farms in the north Irish Sea, it is near the Islandmagee salt cavern facility, which could be used for hydrogen storage, and it is near Belfast. The plant produces hydrogen for a refuelling station in Belfast in 2030, which supplies buses, trucks, and trains in the area. The hydrogen is transported by tube trailer to the station, which is located 30km from the production plant.

For Scenario 3b, the plant is located at/near the same place as Scenario 3a. As in Scenario 2b, the plant is assumed to be located at a gas grid AGI. It is assumed that hydrogen can displace up to 5% of the NG demand in the Greater Belfast area. This is equivalent to a 15% hydrogen blend by volume.

Alkaline electrolyser technology is chosen for the centralised scenarios. Plant operation is the same as the regional scenarios, with the purchase of grid electricity in the DAM. The plant has one day's supply of hydrogen storage on-site in compressed hydrogen tanks.

Results

A summary of the results of the scenario modelling are shown in table 4. Scenario 3b requires the largest plant size and delivers the most annual emissions savings. This scenario also has the lowest combined levelised cost of production and transport ($LCOH_P$ + $LCOH_T$). The range of values for combined LCOH are shown in figure 7. The first scenario has by far the largest variation in cost, due to the wide range of wind farms capacities and distances to end-user. Although larger wind farms may be suitable for on-site hydrogen production, many wind farms are unsuitable due to their smaller capacities and/or distance from potential hydrogen demand.

Scenario	Value Chain Type	Plant Size (MW)	$LCOH_P$ (£/kg H_2)	$LCOH_T$ (£/kg H_2)	CO_2 Emissions Avoided (t)	Annual H_2 Production (t)
1	Distributed	0.35 - 3.5	2.30 - 12.1	0.45 - 2.25	N/A	N/A
2a	Regional	9.65	2.76 - 4.59	0.4	4,741	1,424
2b	Regional	7	2.82 - 4.65	N/A	1,410	1,039
3a	Centralised	27	2.59 - 4.43	0.25	13,219	3,971
3b	Centralised	47	2.53 - 4.36	N/A	9,427	6,944

Table 4: *Results of supply-chain scenario modelling*

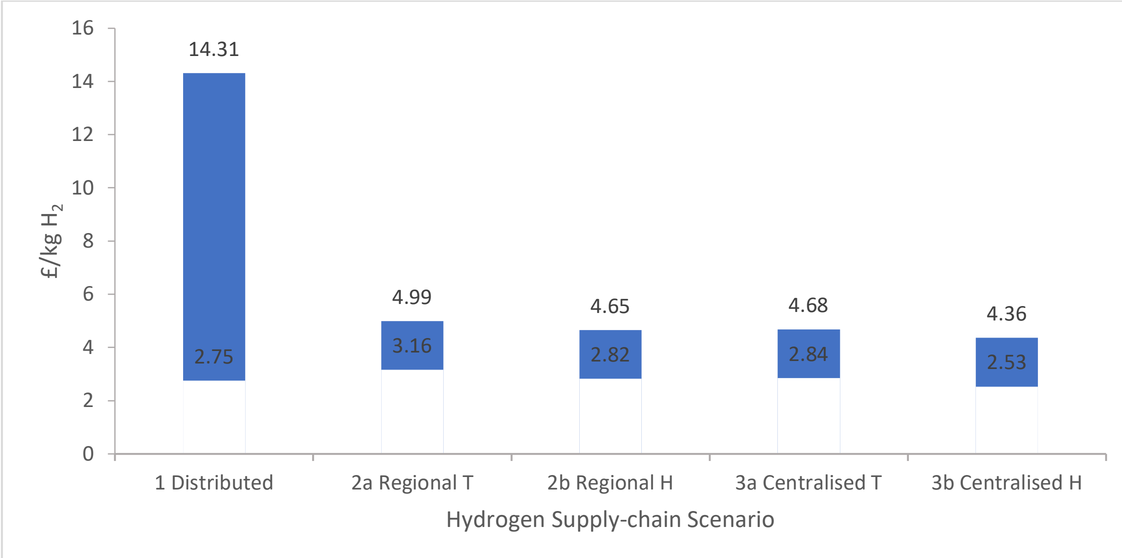

Figure 7: *Combined Levelised Cost of Hydrogen Production and Transport (T = Transport, H = Heat)*

As all the scenarios are not mutually exclusive, it is possible that all five can be realised by 2030. If this were to happen, the total annual CO_2 emissions avoided from 2a, 2b, 3a, and 3b would be 27,304 tonnes, which is equivalent to the annual greenhouse gas emissions of 5,899 cars or 3,151 homes[25]. The breakdown of these avoided emissions is shown in Figure 8.

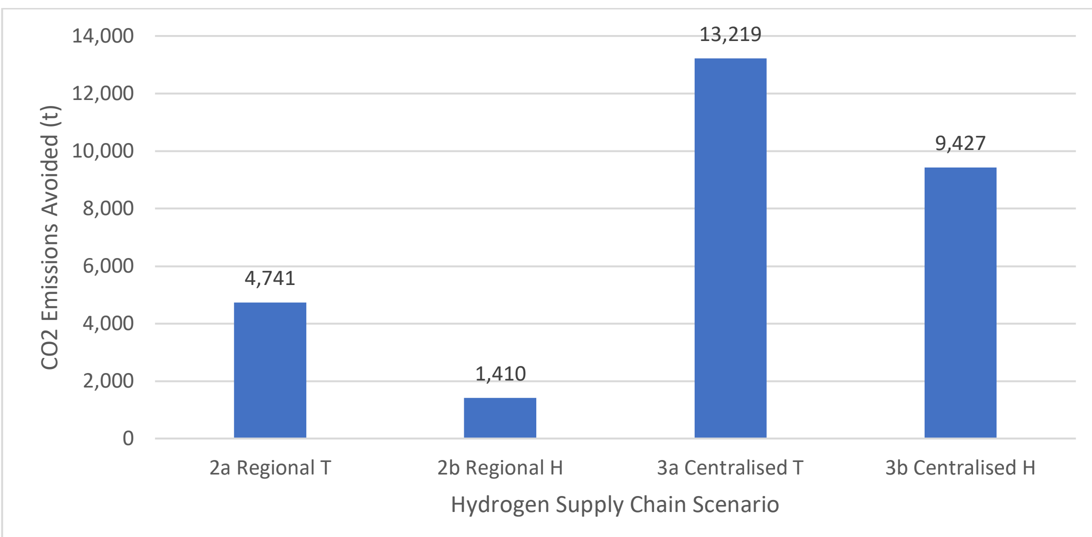

Figure 8: *Annual Emissions Avoided (t CO_2) for Scenarios 2a, 2b, 3a, 3b.*

The total annual hydrogen production of these four scenarios is 13,378 tonnes, which is 7 kg hydrogen per capita per year. For comparison, the European Union aims to produce up to 10 million tonnes of renewable hydrogen by 2030[26], which is 22.5 kg hydrogen per capita per year.

Recommendations

Northern Ireland needs a hydrogen strategy

The unique geographical and political characteristics of NI suggests that green hydrogen could have an important role to play in the region's decarbonisation plans. NI has the potential to exploit its unique position by using the abundance of naturally available resources, primarily in onshore and offshore wind and solar to advance hydrogen technologies in the region. The geographic advantage does not end there. The province's small, islanded geographic area make it ideal for deploying and testing initial hydrogen centric technology solutions.

Policy to exploit this position could be derived both from the UK or Ireland's positioning but irrespective, the release of clear policy, quickly, will be key to creating the landscape needed for deployment of hydrogen if the potential supply security that it offers to NI's energy transition and economy is to be realised. Indeed, if such policy is progressed rapidly, it will facilitate the positioning of NI as a hydrogen leading region. This can be used to attract best-in-sector UK and international companies to develop projects and for wider deployment of technology. Such activity invariably draws in further sector investment and will elevate NI's position on the global hydrogen stage. It will also enable NI to share in the funding likely to accompany the UK's release of its hydrogen strategy, which is being developed by the Hydrogen Advisory Council and BEIS and due to be released in Q1 2021.

The use of NI as a testing ground for various renewable electricity and hydrogen production technologies, will allow the Province to build on, and increase, its skilled workforce. Production capacity will increase whilst, at the same time, positioning NI as a key location in which to test the viability of locally built technology, using local expertise, land, and knowhow. When projects experience notable levels of success, expansion or replication of the technology would add value to NI's economy through outsourcing of the country's unique expertise and delivery from the supply chain which has grown to support the testing phase.

To facilitate and support the policy an inclusive NI hydrogen 'roadmapping' activity should be enabled and supported. This should be rapidly developed, locally coordinated by agnostic parties familiar with NI hydrogen and engage all relevant stakeholders.

Hydrogen fits with national climate goals

Across Europe and globally, we have seen increasing awareness of the environment as a key political topic. Hydrogen has entered the public consciousness as a key mechanism for delivering part of a sustainable energy transition. Influenced by this, and the need to drive a post Covid-19 recovery, countries have begun publishing hydrogen strategies outlining their commitment to using hydrogen as a tool in their future national energy strategies. Whilst the UK and Ireland have not yet announced their hydrogen visions, the UK's will be published in the spring, politicians and industry are engaging to define a future pathway.

The entire energy community agrees that developing a hydrogen economy is key to producing energy systems and value chains which will lead to a complete energy system reduction in carbon emissions. Countries signed up to the Paris Agreement are beginning to translate that commitment into nearer term local carbon targets and strategies for delivery. The UK, as one of the 195 signatories, has agreed to play its part towards achieving global net-zero CO_2 emissions by 2050. The UK government has already committed to a legally binding target to cut greenhouse gas emissions to 80% below 1990 levels by 2050 within the 2008 Climate Change Act, this was amended in 2019 to set a 100% reduction target, or net zero, of 1990 levels by 2050. 5 yearly carbon reduction budgets are being set, currently the 2030 target requires a 57% reduction. Transport has been singled out in the UK and ROI as a key environmental policy. Both countries have announced legislation bringing forward banning sales of diesel and petrol vehicles by 2030 – 10 years sooner than originally expected. Pressure groups are pushing for public transport vehicles to be at the forefront of this change, with UK groups wanting wholesale operational bus fleet change by 2025, which will be extremely challenging, and trains to follow soon afterwards.

Local fuel poverty solution?

Whilst the ways in which most of the UK interacts with its energy supply is established and reliable, the more isolated areas, including the more remote reaches of NI, do not have the same experience. Hydrogen offers a solution for these remote locations by providing a way to produce and harness local renewable energy sources without the need to rely on more expensive imports. This is of particular importance to rural and coastal areas of the country which frequently rely on heavily polluting, expensive fuels such as heating oil. Whilst this may not be an important consideration or target for central UK government, it could be a unique angle for NI to pioneer; especially with the potential of higher numbers of people experiencing the effects of fuel poverty made more pronounced due to Covid-19 restrictions mandating extended home working periods and more insecure income streams.

Furthermore, this may help to bring down costs for NI residents whom, from 2016-2019, experienced the highest weekly household expenditure on energy of any UK region; some 14.7% higher than the UK average for the period[27].

Northern Ireland – hydrogen exporter

The UK has also largely decided against positioning itself as a green hydrogen exporter. This is due to the potential for green hydrogen use domestically within its industrial base. It has not, however, discounted the idea of transporting hydrogen internally from region to region within the UK. At the same time, due to its naturally occurring onshore and offshore wind resources, the potential for hydrogen exports should be of strong interest to NI. Hydrogen offers a mechanism to capture otherwise wasted renewable energy, either where it is stranded (not grid connected) or through curtailment (where the grid cannot take the generated power). By 'oversizing' production capacity, NI has the potential to use the generated hydrogen not only within its own borders but also as a mechanism to grow the economy through exporting and job creation. Such aspirations will also drive inward investment in the Province. Hydrogen is unlikely to be exported in its gaseous form, therefore, additional plant will be required to enable such distribution. This can also play a role in other key Irish markets such as agriculture if the carrier molecule chosen is ammonia. By positioning NI as an exporter of hydrogen, it can also aid another of the governments' key targets 'Fostering National Technologies'.

Geological advantage

In the energy transition, countries are re assessing the infrastructure they have available and whether it is appropriate for the new sustainable world. One key aspect is hydrogen use in energy storage. Hydrogen storage costs are associated with the volumes needing to be stored. For the largest volumes, geological salt caverns provide the most cost-effective, secure storage mechanism. Currently, such caverns are predominantly used for NG storage. The Islandmagee facility available near Larne in NI can be used to facilitate the migration away from NG towards hydrogen and the eventual operational support of an all-island hydrogen grid. This facility can also be used as a hub for hydrogen for mobility applications. This dual use suggests that any future hydrogen plan should be centred on maximising the exploitation of this resource. Connection via gas grid interconnectors will act in a similar way to how they do today for NG, as the UK system has a network of NG storage caverns – which will also likely be migrated to hydrogen over time. This is the only such facility on the island of Ireland and therefore it should be an area of focus for any future hydrogen implementation plans.

Now or never

Currently the UK has focussed its CO2 mitigation measures on industrial clusters – aiming potentially at the lowest hanging fruit whilst maximising the impact per £ invested. This has led to the development of a range of green and blue hydrogen initiatives which are partly focussed on supplying feedstock hydrogen within the clusters but are also looking to spill additional product into the surrounding areas primarily for the hydrogen energy applications examined in this report. In addition, some of these clusters have wider ambitions where they perceive their excess hydrogen product could be supplied to other areas of the UK where this early-stage production and local hydrogen development has not occurred. Key targets are the south east, south west and NI. Therefore, it must be inferred that NI risks being left behind at this key development moment for future infrastructure. The province needs to build a hydrogen vision which can result in a robust request to government for support to develop a value chain with hydrogen produced and used in the region.

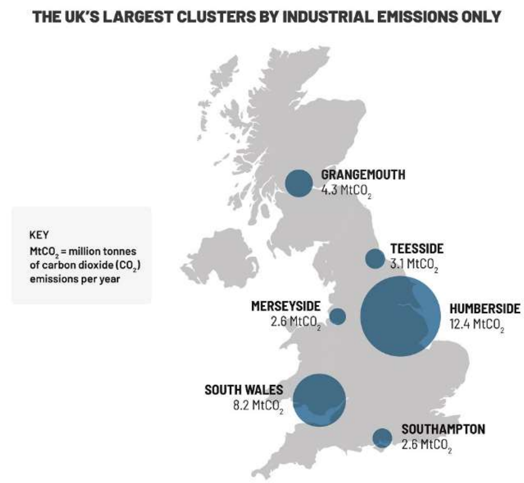

Figure 9: *Largest UK Industrial Clusters by CO_2 Emissions Only*[38]

Hydrogen Timetable in Northern Ireland

How would this scale-up towards a green hydrogen economy take place? There are likely to be three defining phases that will occur to ensure success. To foster such a timeline, policy must then adapt between periods, allowing changes in incentives to create a favourable environment for the desired economic and societal effect.

The first is market development – up until 2030 there is a requirement to simultaneously grow both hydrogen production and end use applications. At the same time policy and regulations are rapidly implemented and passed through their relevant bodies to ensure beneficial, symbiotic growth of hydrogen-influenced sectors.

From 2030-2040, constant and rapid market development will occur, with the optimisation and critiquing of suitable technologies for geographical locations and situations. Renewable energy systems will continue to increase share of the energy market. New hydrogen applications will proliferate, new supply chains will be created. Companies will innovate in and around the new hydrogen market.

Once the market has become fully established between 2040-2050, we will see the mature market development phase of these optimised technologies, reaching large scale production and mass deployment. There will be rationalisation of supply and application systems. Policy must drive the retention of local economic value and skills, to ensure that in a widely developing global market, local positions are not lost to international rationalisation.

The need for support mechanisms

Initial support, likely both capital expenditure (CAPEX) and operational expenditure (OPEX), to build on early successes will be key to driving growth within the sector as well as obtaining public buy-in. As the technologies become established, past a demonstration level, support can be decreased.

Mechanisms such as carbon tax, GOO's, feed-in tariffs, or market support constructions will be required for green hydrogen, until economies of scale can be exploited to a degree that it achieves competitiveness with alternatives. It is widely appreciated that a green/low carbon hydrogen certification mechanism is crucial for the uptake of hydrogen, and other renewable fuels. RTFCs are a good start, but the fact they only apply to fuels for some transport applications makes the platform minimal in impact, particularly given the targets to decarbonise heating with a focus on new buildings. Therefore, a wider, more inclusive RTFC-style scheme will be needed to progress the hydrogen economy in the final stages of its development into a fully-fledged competitive sector.

An all-island approach

ROI, much like NI, has a large potential of intermittent renewable electricity production. It is one of the highest in the EU both in terms of total energy production and forecasted electricity demand in 2030. According to its current hydrogen planning, Ireland will only use 2% of its technical potential in renewable energy generation – according to the European Council (EUCO) 2030 scenario predictions. Therefore, the whole of the island of Ireland finds itself in similar energy situation, where an emphasis should be placed on the use of excess renewables to produce green hydrogen. Potential avenues for all-island exploration are described below.

Codes and Standards

Much has been made in the Brexit negotiations of the divergence of codes and standards between the ROI and NI. Both sides have industrial hydrogen safety standards currently in place. Hydrogen use in energy applications is currently being mainly regulated by industry via a series of ISO standards as administrations attempt to keep pace with the rapidly changing environment. Therefore, the development of all Ireland hydrogen codes and standards provides a good platform for future cross border collaboration.

Gas-grid injection

The existing whole of Ireland NG infrastructure is operated as a single system. This could be used for transporting and distribution of a blended NG/hydrogen mix. The percentage in the mix can increase over time. UK and EU projects support the initial use of a 20% hydrogen level with few downstream modifications. In the longer term the distribution network is almost entirely made of polyethylene materials, therefore, making pipelines 'hydrogen-ready' could occur at a relatively low cost, allowing for a reasonable continuous base-load hydrogen demand.

Currently, NG accounts for about a quarter of NI's final energy demand in the built environment. Moreover, the demand for heating and transport represents 80% of NI's energy demand, where over 80% is fulfilled with fossil fuels (Table 1). Therefore, with their interconnected gas infrastructure, both NI and the ROI can work together to achieve a common decarbonisation goal.

Shared Mobility

Buses

NI has a leading position in the hydrogen transport sector thanks to the home location of the Wrightbus, who are publicly committed to rolling out hydrogen technology, and its production facility. The accelerated introduction of more buses within the local area could help embed a local value for both hydrogen production and a key transport application. This will allow the Province to gain key maintenance/operational capacities, as well as increasing base load hydrogen demand whilst, at the same time, securing and creating local jobs. The migration of significant bus fleets on both sides of the border will drive the bus production down its cost curve making it globally competitive allowing for expansion and further investment. Electrolyser operational expertise will be valued by all regions in the future and a strong service industry is envisaged for first movers. Given the UK's and ROI's desire to lead the greening of the transport sector by use of public fleets buses are deliverable from multiple OEMs, including Wrightbus, fit with future policy and be able to secure further central government funding.

Heavy Goods Vehicles

Trucking of heavy goods between NI and ROI is common practice today. Recent developments in hydrogen trucks have demonstrated their viability as replacements of conventional truck drive trains. The likes of Nikola, Daimler and Hyundai are releasing FCE trucks fuelled by hydrogen with commercially attractive ranges. Hyundai's XCIENT FC Truck is the world's first mass produced fuel cell truck, with 1,600 to deploy in Switzerland by 2025.

Analysis of the density of trucking along heavily utilised haulage routes in NI and ROI would allow key hotspots for hydrogen refuelling to be identified. At these hotspots, hydrogen infrastructure, support services and HRS's could be established. This will initially require government backing but a similar approach could be used to that in Switzerland. Purchasing of the FCE trucks by a government backed investment body, which then leases trucks to end users, could eliminate first mover risks.

Belfast – Dublin Trains

Hydrogen use for rail travel is fast becoming a key transport application for hydrogen. 500 hydrogen powered trains are projected to be in service by 2030 across Europe. The Belfast to Dublin train could see a hydrogen overhaul. This is a very visible cross border public resource which could see a direct benefit using new clean FCE technology delivering a step change in travel experience for its customers. Fuelling facilities at both ends of the track would allow additional hydrogen services to be incrementally expanded from an initial investment, providing a hydrogen base load, and creating key work force skills which are internationally transferable.

Supply Chain

With NI's historic specialist skillsets built on manufacturing, operating and the industrial service sectors, amongst others, these projects are well suited to the country's workforce. Adding the strong skill base to its unique geographic position, NI is very well positioned to be able to create a specialist hydrogen-based economy. The implementation of hydrogen projects would further develop the NI hydrogen skillset, both in terms of expertise and training, producing high-skilled, world-class jobs for the people of NI, whilst generating added value for the NI economy via a sustainable energy transition.

NI also has two recognised and very active third level institutions providing future hydrogen centric technical and safety training – Belfast Metropolitan College and Ulster University. Through research collaborations within the UK, with the Science Foundation Ireland MaREI research centre in Ireland, and through continued access to certain EU funding calls, these institutions are well positioned to lead the knowledge transition that hydrogen entails.

Upon development of an initial supply chain in NI, follow up and connecting projects would provide the next logical opportunity for sector growth, increasing both the production and demand sides of the hydrogen value chain. These projects could also provide an opportunity to export hydrogen to other regions of the UK, or further afield, given NI's wealth of renewable electricity generating resources.

Hydrogen Coordination Body

We have outlined a series of potential activities which could provide an initial kickstart to the NI hydrogen economy. There will be many others. To coordinate such a proliferation of opportunities a coordination body should be established. It would be logical, given that many projects can be seen to have cross border potential and value, that the mechanism for this enables an equivalent body to be established in the ROI. Coordination and funding can then flow through these joint institutions. Initial staff should bring international hydrogen experience to enable the Province to benefit from early market movers and ultimately leapfrog the activities undertaken around the world and position it firmly as a hydrogen sector leader.

Appendix A: Key Technologies

Introduction

To create a hydrogen-enabled, energy transition various technical solutions are needed. This section provides high level background information on some of these and to provide additional context to the report.

Proton Exchange Membrane Fuel Cells (FCs)

A FC is the main mechanism to transition hydrogen to energy. Systems convert chemical energy into electrical energy using hydrogen and oxygen and leaving water as the only by product. The hydrogen must be of a high purity for the FC to function correctly, more so than for applications in heat and industry. Regardless of their type and size they have the same basic configuration. Two electrodes and an electrolyte to connect them, but can differ in composition of electrolyte, operating temperatures, and efficiencies.

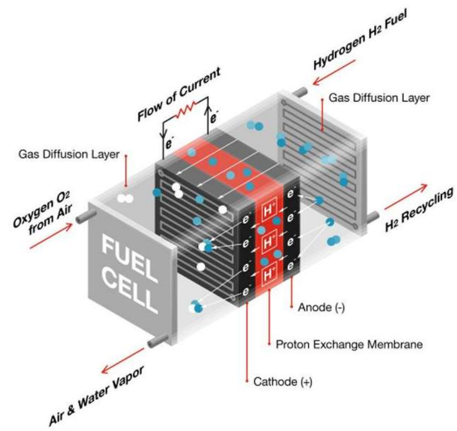

Figure 10: *A Diagram of a Hydrogen Fuel Cell*[39]

Whilst there are many types of FCs in use today, one dominates in applications such as mobility. The PEM FCs operate at the relatively low temperature of around 80oC. This makes the unit quick to start and results in less wear on the systems components. However, it uses expensive metal catalysts such as platinum, adding significant cost to the system. PEM primarily focuses on transport due to their advantageous power to weight ratio, almost all passenger and transport road vehicles will use PEM.

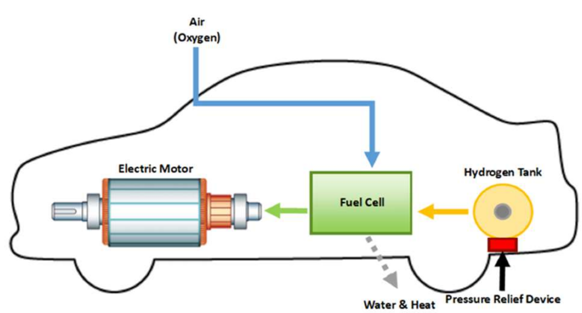

Figure 11: The Hydrogen Fuel Cell Vehicle Concept[40]

FCEVs have many benefits over traditional battery electric vehicles (BEVs) such as a refuelling time close to their fossil fuel counter parts and increased mileage when scaling up vehicles size. In addition to general road and rail vehicles, many companies are looking into what other vehicles could be powered by FCs. Factories are beginning to use FC based forklifts, ports are looking to FC powered shipping vessels and airports have begun looking into hydrogen as an alternative fuel for either jet fuel in smaller aircraft.

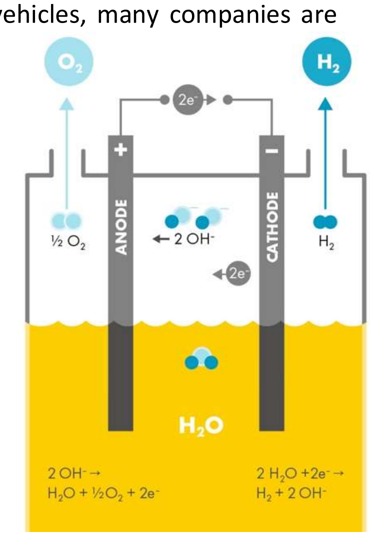

Figure 12: *A Chemical Cell Carrying Out Electrolysis*[41]

Electrolysers

Electrolysis is the key technology for future sustainable hydrogen production. Today most of the world's industrial hydrogen demand (around 70 million tonnes annually) is produced from NG and coal, by processes which emit significant amounts of carbon to atmosphere.

Electrolysis, however, when coupled with RES, creates completely sustainable, 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 the most common alkaline electrolysis (AE) and PEM. AE is the most mature technology and well suited to large-scale projects, however, many projects are opting for PEM designs as they operate more flexibly, are more responsive and thus help with managing RES power. Innovations such as membrane-free electrolysers are also under investigation.

Whilst most RES generate intermittently, hydrogen can facilitate supply/demand balancing, enabling ‘time-shifting’ via storage mechanisms, thereby disconnecting, effectively isolating, the production system from the rest of the value chain. 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 typical be wasted, can instead be fed into an electrolyser, and used to generate renewable hydrogen thereby opening access to additional markets.

Finally, 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 a further revenue stream for the system.

Many current projects are utilising electrolysers in unique settings, methodologies, and applications. HEAVENN, based in the Northern Netherlands, combines all aspects of a hydrogen value chain within a 30km radius. Using offshore wind energy coupled to large scale electrolyser units, 20, 40 and 100MW systems are being facilitated. In addition, an ambitious 9GW offshore project is being planned. The hydrogen will initially be supplied to local industry, as a process feedstock. It will also be used to facilitate mobility and community heating applications.

In the UK, the Dolphyn project is looking to generate hydrogen offshore. Electrolysers will be stationed on platforms alongside floating offshore wind turbines, generating electricity for desalination of sea water, and using this desalinated water as a feedstock for the electrolysis process. Dolphyn will start with a 2MW prototype in 2024, followed by a 10MW unit in 2027. The hydrogen will then be transported to shore via a pipeline and will be used for heat and other low carbon needs.

Another UK project called Gigastack aims to power the Philips 66 refinery using green hydrogen. Offshore wind will power a group of 5MW stacks, with the project eventually supplying 100MW in total to supply the refinery.

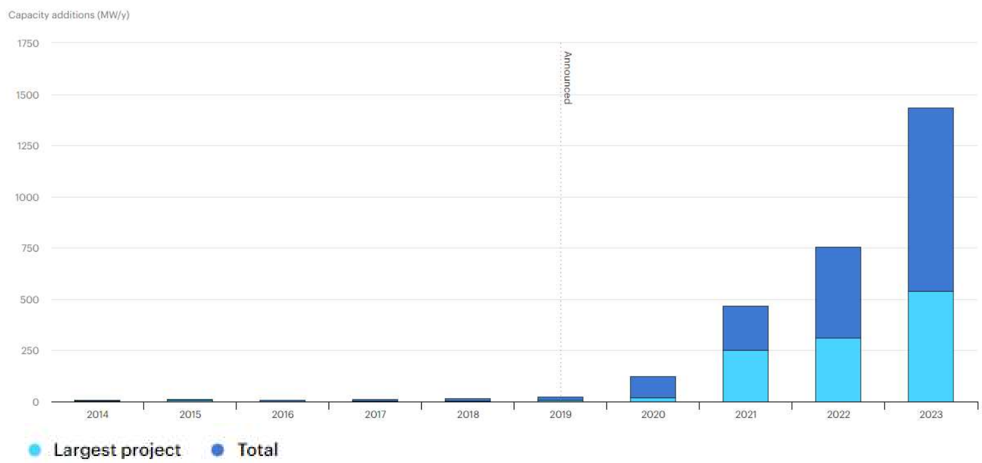

Figure 13: *Global Electrolysis Capacity Becoming Operational Annually, 2014-2023*[42].

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.

In some geographies available pure water supplies will become an issue as electrolyser use grows. The durability of electrolyser electrodes and their use with impure water for hydrogen production is being investigated in projects. As an example, in the SEAFUEL project, led by NUI Galway, researchers at that university and at the University of Liverpool are assessing the use of seawater in electrolysis systems.

Steam Methane Reforming (SMR)

SMR technology is a mature industrial process which cracks hydrocarbons, mainly NG, using catalysts and high temperatures at efficiencies of 70-85%. The process has two phases; first NG is reformed with steam at temperatures of 800-1000oC, then a subsequent water-gas shift reaction produces increased amounts of hydrogen with CO2. These are separated and traditionally the CO2 is released to atmosphere and the hydrogen used.

It is a low-cost method for large-scale hydrogen production which is commonly coupled to chemical plants and petroleum refineries for on-site hydrogen production and derives approximately 50% of the world’s hydrogen.

Large-scale SMR’s deliver the hydrogen directly to the refining process for production of high-octane gasoline and lighter hydrocarbon fuels. As crudes become more sour, additional hydrogen is required for sulphur removal; in absence of soured oils most refineries are self-sufficient in hydrogen production. SMR production plants are traditionally integrated in an industrial complex using pipeline systems to distribute large volumes to process applications.

Smaller packaged plants are also available and are targeted at medium sized customers (e.g., steel and float glass manufacturers) who traditionally receive trucked deliveries.

Hydrogen production via SMR generates the lowest cost hydrogen available today, with production costs of €1-1.50/kg H2 with increased scale bringing benefits of reduced capital and operational costs per kg of hydrogen produced. Smaller SMR plants achieve costs of €4-5/kg H2 and are expected to reach €3-4/kg H2 by 2030.

One way to combat the emission of CO2 from SMR produced hydrogen is in the use of CCUS technology. Projects are proposing to capture the CO2 and store it, and for it to be used for different applications. This is yet to be fully demonstrated in practice at scale, but the UK are looking to become world leaders in CCUS technology and there are several projects being planned that will see CCUS systems in industrial clusters around the UK.

So called ‘Blue Hydrogen’ is seen by many to be a time mitigation measure until green hydrogen from renewable sources, is economically viable. It is expected there will need to be a mixture of blue and green hydrogen to deliver carbon free hydrogen in future. If an effective, long term carbon taxation system is implemented it will increase traditional SMR production costs driving forward both blue and green hydrogen technology.

Storage

Underground Storage – Salt Caverns

Underground structures such as salt caverns, depleted oil/gas reservoirs or aquifers have been used for decades for NG and oil. Salt caverns have properties that make them ideal for storing gases including hydrogen and have been in use since the 1950s. Today there are over 30 caverns in use across the UK. The salt lining the cavern acts as an impermeable barrier that prevents both leakage of hydrogen and contaminants from reacting with the hydrogen. These properties allow the salt store to prevent unnecessary dormant loss of hydrogen and are effective at retaining high purities, often required for fuel cell applications. In addition, several adjacent caverns can often be utilised simultaneously to achieve a higher yield.

Investment costs					
Technology	**Minimum**	**Maximum**	**Units**	**Comments**	**Source**
Depleted gas field	280	424	EUR2019/ MWh_{H2} stored	CAPEX including compressors and pipes, 4% OPEX.	(BNEF, 2019)
Salt caverns	334	334	EUR2019/ MWh_{H2} stored	CAPEX for 1,160 t of working capacity (+1/3 additional for cushion gas), but highly dependent of geography. 4% OPEX, includes compressors and pumps.	(BNEF, 2019)
Rock caverns	1232	1232	EUR2019/ MWh_{H2} stored	4% OPEX.	(BNEF, 2019)
Levelized cost of storage (LCOS)					
Technology	**Minimum**	**Maximum**	**Units**	**Comments**	**Source**
Salt caverns	6	26	EUR2019/ MWh_{H2}	300-10,000 t per cavern, lower bound: monthly cycling, upper value: bi-annual cycling.	(BNEF, 2019)
	17	17	EUR2019/ MWh_{H2}		(IEA, 2019)
Rock caverns	19	104	EUR2019/ MWh_{H2}	300-2,500 t per cavern, lower bound: monthly cycling, upper bound: bi-annual cycling.	(BNEF, 2019)
Depleted gas field[22]	51	76	EUR2019/ MWh_{H2}	Cost for working gas capacity, 1 cycle/year. Including the cost of compression and pipelines needed for the facility to function.	(BNEF, 2019)

Figure 14: *Cost of Alternative Geological Hydrogen Storage Methods*

Such underground hydrogen storage offers many additional benefits such as flexibility, economies of scale, low operational and land costs. Where available this is often the lowest cost hydrogen storage option for large-scale, long-term use.

Potential sites for salt cavern storage have been mapped and mostly follow known key European salt deposits. Existing NG and hydrogen salt cavern storage systems have been developed after salt extraction for use in the chlorine industry. The development of new caverns is also possible and requires large amounts of saturated brine during their creation.

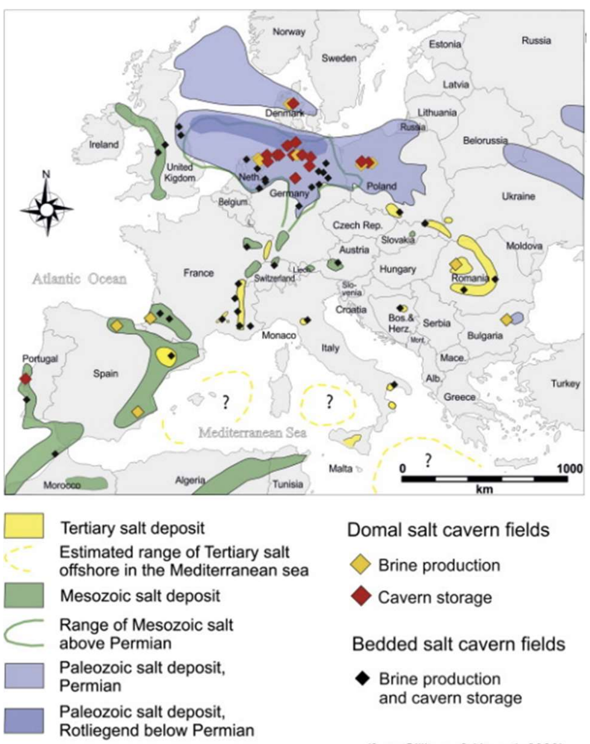

Figure 15: *Salt Structures and Cavern Storages in Europe*[43]

Salt cavern viability as a hydrogen store has been tested extensively and has shown positive results. Geomechanical analysis from *Energy Technologies Institutes in the UK* looked at the running of salt caverns in Easy Yorkshire, Cheshire, and Teesside over a 5-year period. There were no signs of tensile stress and no effect on long-term structural stability, even in worse case scenarios. Furthermore, each area was deemed to work well within the acceptable temperatures and pressures in the caverns.

Other underground structures such as aquifers and mines are also being investigated to see if they mimic the properties of salt caverns, but such work is at a relatively early stage in hydrogen terms.

Chemical Storage

Chemicals can act as a hydrogen storage method and carrier. They can release hydrogen on demand and have several advantages to their use. They seek to exploit beneficial properties of hydrogen-containing compounds to enable more advantageous energy storage than just hydrogen itself. Ammonia is an ideal chemical to use for transport and storage. It has a very high hydrogen storage density at 17.7% (wt) gravimetrically and 123kg/m^3 for liquid ammonia at 10 bar. Its synthesis, handling and transportation methods are extremely mature. Migration/expansion to a sustainable, investable sustainable hydrogen supply is therefore possible.

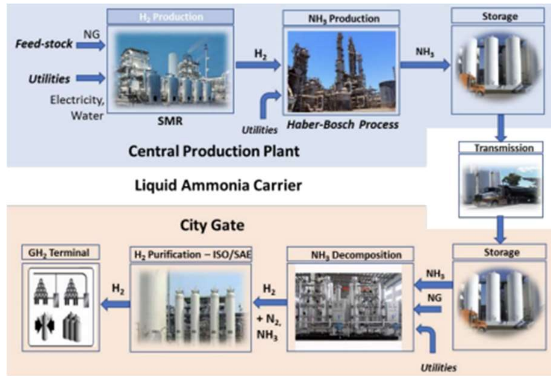

Figure 16: *Steps to Utilise Ammonia as a Hydrogen Carrier (Fossil Pathway)*

Methanol is another example of a chemical store for hydrogen. It stores hydrogen at 12.5% weight percent of hydrogen and a higher energy density than that of liquid hydrogen (LHY) with 99kg/m^3. Like ammonia it can be stored in cheaper storage tanks, as it is a liquid at room temperature. Infrastructure and supply chains exist and can be expanded/migrated to sustainable hydrogen supply for energy storage/transfer.

Hydrogen Refuelling Stations

Wide scale decarbonisation of transport is not easy to achieve. Batteries have made significant technical progress and progress is accelerating with charging infrastructure deployment. However, there remain challenges to wholesale complete adoption of EVs throughout the transport sector. FCEVs offer range and shorter refuelling times on like-for-like vehicles as well as being able to offer decarbonisation solutions for heavier vehicles/transport modes as well.

Figure 17*: Hydrogen Dispensing at a Standard Forecourt*[44]

From an infrastructure perspective, initial costs of individual refuelling stations are higher than installing electric recharging stations. However, long term hydrogen infrastructure is likely to be less costly than electric, when large scale technology change occurs.

A key public facing element of the technology chain for hydrogen mobility is the HRS which consists of compression, storage, chilling, and dispensing subsystems. Hydrogen supply is either delivered to site from an external hydrogen source typically by trailer/pipeline or is generated on-site - most commonly from a dedicated electrolyser. The HRS then makes the correct amount of hydrogen available to vehicle owners at the right pressure in a safe effective way. The HRS equipment is sized meet the required operational criteria and the predicted FCEVs demand. Hydrogen dispensers can be placed next to existing gasoline equivalents in a standard refuelling station.

A challenge for expansion of hydrogen into the transport sector has been the need to balance the deployment of HRS with that of FCEVs. Today's deployments of HRS and FCEVs are part funded by government initiatives to bridge the commercialisation gap. A joined-up approach to deployment is needed to deliver investible long term business cases – these joint approaches frequently go under a Hydrogen Mobility banner. Roadmaps charting the pathway and timeline to delivering the decarbonisation potential of hydrogen in transport on a regional/national basis have also been published. Several regions have forged ahead when it comes to FCEVs and HRSs with California, Japan and Germany having the largest deployments.

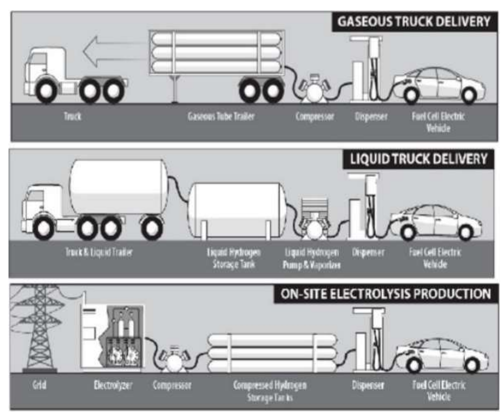

Figure 18*: Options for Supplying Hydrogen to a HRS*[45]

Appendix B: Hydrogen Applications and Activity

Introduction

Across the world the application of hydrogen in areas which affect all aspects of our daily lives is being planned. Some changes are quite easy or "short and medium-term no-regret moves" such as the change of hydrogen supply to industrial processes. Other areas foresee options on how a sustainable future can be achieved i.e., small passenger vehicles will they be BEV or FCEV?

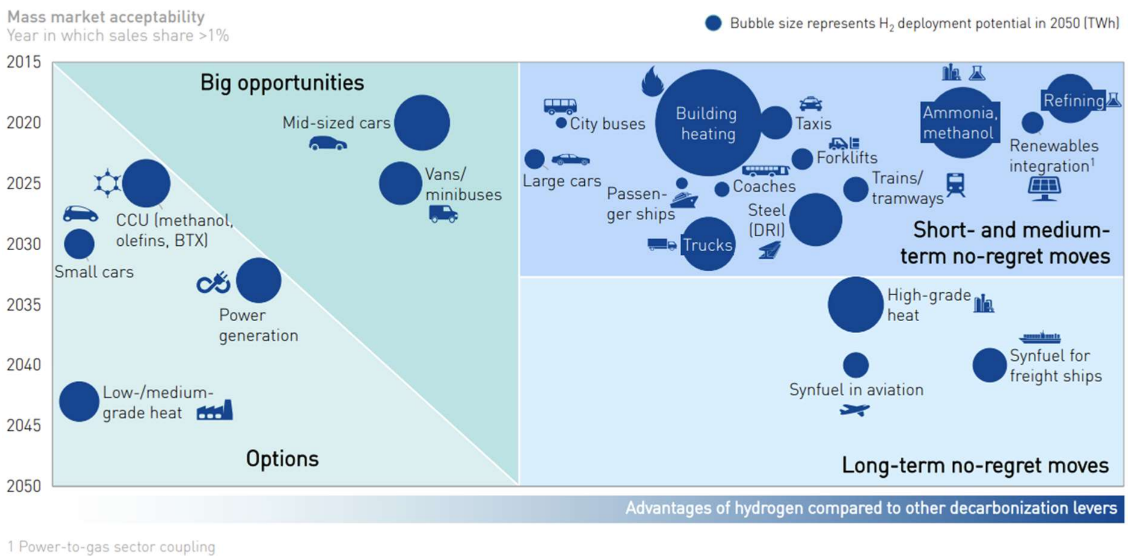

Figure 19: *Hydrogen Opportunities Timeline*[46]

In this appendix we consider some of these hydrogen applications and provide a high-level insight into some of the activity underway within the sector.

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 in the world is used for ammonia production. Typically, hydrogen is produced on-site at ammonia plants from a fossil feedstock, most commmonly via 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 possible energy carrier position, and a continuous worldwide need for this process, hydrogen demand, particularly the green variety, is likely to continue. In fact, the green ammonia market was valued at $17 million in 2019, and is projected to reach $852 million in 2030[28].

Following ammonia production, the second largest use of hydrogen in the world is by the petrochemical industry (approx. 25% of hydrogen consumed worldwide). Hydrogen is critical for refining crude oil into more useful products, such as gasoline and diesel, as well as removing impurities. Within these facilities, hydrogen is catalytically combined with various intermediate process streams, whilst also being used with catalytic cracking to convert heavier hydrocarbons into smaller, more useful compounds. It is also frequently used to produce methanol via the hydrogenation of CO_2 (A further 10% of annual hydrogen consumption).

There are a number of other industrial uses for hydrogen, including metal manufacturing (for annealing, hardening, sintering and quenching steel); the electronics industry (production of integrated and printed cricuit boards via a moisture, impurity free atmosphere) and power generation (to cool large power generation plants and minimise frictional losses). Indeed, the use of hydrogen as a heating fuel in steel production, replacing liquified petroleum gas (LPG), is being trialled in Europe. This could provide a significant future demand and environmental benefit.

With an extensive arsenal of applications supplying hydrogen to industrial users is a significant worldwide business – its importance being seen worldwide. Since 1975, hydrogen demand has more than tripled[21] and continues to rise and thus so do carbon emissions.

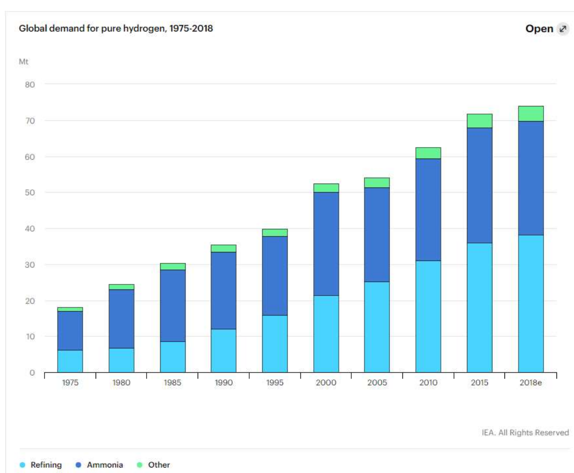

Figure 20: *The Total Global Pure Hydrogen Demand, 1975-2018*[21]

Hydrogen for the Natural Gas Grid

Although seen to be one of the most difficult sectors to decarbonise, reducing emissions from heat is one of the key drivers for hydrogen as an energy carrier. The potential hydrogen demand from this sector is projected to dwarf the amounts required for mobility.

Trial projects have already shown promise across a number of European countries. In the UK, the HyDeploy project has been trialling 20% hydrogen mixed with natural gas on Keele university's campus (30 faculty buildings and 100 domestic properties). A follow up project is already planned. Similarly, in Leeds, the H21 project has positively assessed the techno-economic viability of converting the gas grid in the North of England to 100% hydrogen. It is now focused around shaping policy surrounding the strategy and safety codes that need to be in place to enable a widespread deployment of such technology.

Elsewhere in Europe, Gasunie and Energystock have been considering where hydrogen can be utilised within the natural gas energy mix – initially, they are focusing their research on the need for storage of sufficient quantities of hydrogen within the TSO2020 project. Currently, a trial project in Hoogeveen, northern Netherlands, is looking at building new hydrogen energy homes, as well as retrofitting some existing natural gas supplied housing with hydrogen. There are further studies underway to repeat and expand on the experience gained within these initial demonstrations.

In July 2020, a number of European gas Transmissions systems operators (TSOs) came together to produce a vision document for the European gas sector[29] 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 that similar to what is used today. It can already use existing gas pipelines, and can be blended in higher percentages (if not 100% hydrogen) with minor modifications and costs in comparison 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 focusing on building up regional areas around these key hubs. The paper concluded that the cost of 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.

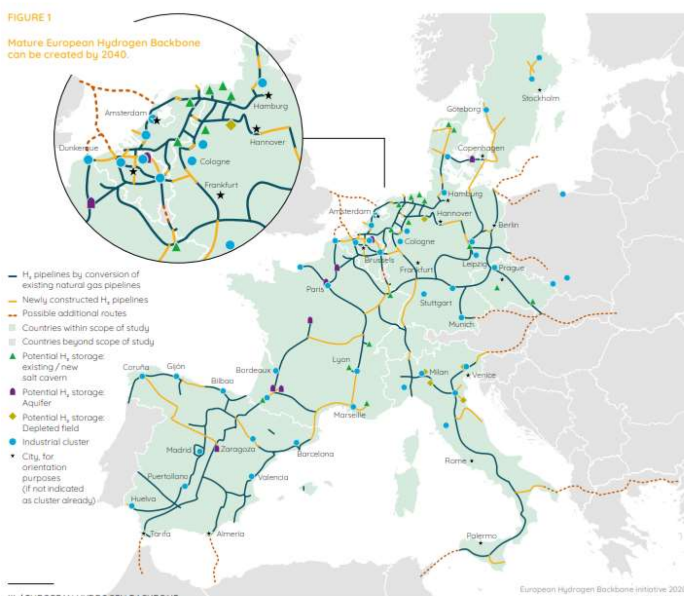

Figure 21: *European Hydrogen Backbone 2040 Vision*[29]

Import/Export

Hydrogen Europe, as part of their green deal vision, proposed the target for a total of 80GW of electrolyser capacity (more than is currently installed worldwide) amongst the EU and its neighbouring coutries. This proposes that areas of high renewable potential, whose hydrogen production potential would significantly outway their domestic demand, such as Portugal, Southern Spain and Northern Africa would produce hydrogen and export it to countries which consume more than they were capable of producing domestically.

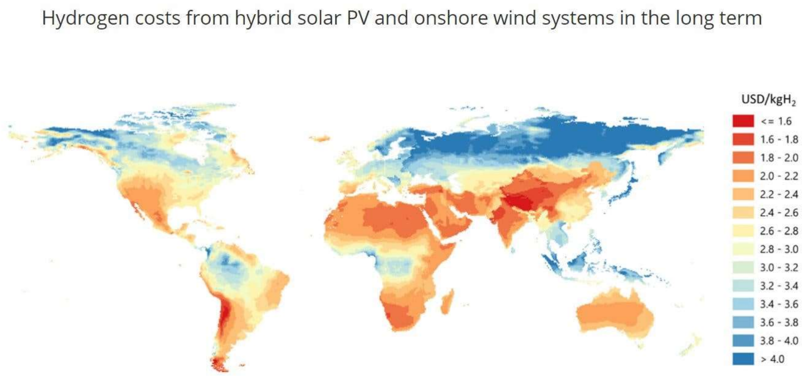

Figure 22*: Red Ares Indicate Areas of High Hydrogen Production, Due to their Prominent Renewable Resources*[21]

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

Australia are already exporting hydrogen in its liquid form to Japan. The start of the year saw the first LHY tanker was launched to operate between the two countries. Such systems are being compared to, and are competing with, chemical storage options e.g. ammonia. If LHY is eventually deemed to be the preferential method and becomes mainstream, then LHY systems and storage will become much more widespread and directly couple the regional energy transfer methods with mobility and other applications, like we see with fossil fuels today.

Figure 23*: Kawasaki's Hydrogen Transport Ship was the Very First of its Kind* [47]

Hydrogen for Transport

Passenger Vehicles

Whilst focus of FC passenger cars was at the forefront of the sector for much of the 2010s, progress has slowed in recent years. BEVs have pushed into the smaller vehicle market thanks to increased range, improved accessibility of charging and similar climate benefits. For FCEVs, focus has shifted to provide fuel efficiency options for larger vehicles has been the primary focus as of late. As HRSs are installed for busses, trucks and possibly taxis there may be a trickledown effect that allows a wider commercial roll out of passenger cars but it seems unlikely to come from projects solely targeted at passenger vehicles.

However, many OEMs believe FC passenger vehicles are the ultimate goal. There are currently 3 models that are publicly available for purchase. The Toyota Mirai, Hyundai Nexo and Honda Clarity, each has a range of over 500km. Toyota also announced the Mirai Sedan in 2019, a coupe-inspired design that boasts 30% increased driving range than the first generation Mirai and is aimed to be released in 2021. All providers believe ranges of 1000km are attainable.

The vast majority of FCEV sales have come from California, Europe and Japan. California has around 8,000 FCE cars sold or leased with 44 HRSs in operation and is seen as one of the hotspots where hydrogen powered mobility could thrive. There is currently an inverse of the supply-demand problem seen in California vs the rest of the world where hydrogen supply capacity is limiting the demand for vehicles. Japan planned to showcase a ‘hydrogen society’ during the 2020 Olympics and had much of the hydrogen infrastructure in place for the event before the Covid-19 crisis. Government purchase subsidies of c. $20,000 are in place but the vehicles are still seen as expensive even with this support. There are currently 100 HRSs, with a target of 900 by 2030.

Closer to home, in Germany, 84 HRSs are in place. However, the German car OEMs have been slow in following the lead of their infrastructure partners and the far east vehicles OEMs preferring instead to focus on BEVs. As of July 2020 the rest of the EU has a further 38 HRSs in operation.

Trucks

FC trucks have historically been ignored by OEMs and have only recently begun to appear. FC technology has been shown to be favourable for moving heavier/larger vehicles. Whilst BEVs are becoming first choice for the passenger vehicle space, they are ineffective for trucking. The batteries needed to move HGVs leaves the range/capacity of the vehicles lower than necessary which, when coupled with lengthy charging times, mean they are not ideal for commercial use. Their hydrogen counterparts have boasted ranges over 1000km for several of the models released to date and fast refuelling times similar to those experienced today.

Initial interest began with Nikola, a PR led company formed in 2016, issuing positive sustainable trucking soundbites and mirroring Tesla’s approach in the BEV market. First mover customer fuel anxiety has been eased by their intent to supply both the infrastructure and FC trucks. The company has investments from many major industry leaders such as Bosch, GM and Iveco.

However, today’s market is led by Hyundai with the worlds 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.

Buses

Unlike FCE passenger vehicles and trucks, interest and investment in FC buses has steadily increased ever since their conception. Infrastructure needs for FC buses, due to their return to base operation, are initially easier to deploy than FC trucks due to the infrastructure needs for each. Although they are not in series production yet, they have reached a high level of technical maturity. FC buses have an average range for 300 to 450km. They face increasing competition from BEV buses but have the advantages of longer range, reduced refuelling times and the ability to operate on difficult hilly routes. Its likely most cities will see a mix of technologies within their fleets going forward.

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 in 2006 to 2009 commercialisation of FC busses was seen as viable. Today further projects are being delivered. Key amoungst these are JIVE, JIVE2 and The H2Bus Consortium. Combined they expect to deploy well over 1,000 FC busses, alongside the supporting infrastructure, and the projects include municipalities and major players in the FCEV value chain including Wrightbus.

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

Trains

In Europe railway electrification has long been the clean and efficient alternative to diesel. However, such infrastructure comes at a cost which for national bodies is/was possible whereas private investors find it much harder to develop a return. In addition, low use lines are very difficult to get any form of cost benefit for.

The world's first hydrogen train 'Coradia iLint', manufactured by Alstom entered commercial service in Germany in 2018. This train has a range of 600 to 800 kilometres, a top speed of 140 km per hour, and consumes 0.25 – 0.3 kg of hydrogen per km. 14 Coradia iLint models will be delivered to Eisenbahnen und Verkehrsbetriebe Elbe-Weser in Northern Germany these will be fuelled by Linde near Bremervoerde station. Another 27 vehicles ordered by the railway operator in the Frankfurt Rhine-Maine metropolitan area. Alstom have also signed letters of intent for 60 trains with the German states of Lower Saxony, North Rhine-Westphalia, Baden-Wurttemberg, and Hessian transport association Rhine-Main-Verkehrsverbund.

The UK has commenced a hydrogen train trial under the HydroFLEX project where an existing Class 319 train set was fitted with a hydrogen fuel cell and storage. The prototype successfully made a 25-mile round trip through Warwickshire and Worcestershire and reaching speeds of up to 50 miles per hour. The project aims to be commercial by the end of 20.

Appendix C: Webinar

As part of the preparation activities for this report a webinar was held to highlight the NI's government's desire to progress a discussion on hydrogen. The webinar was recorded, and each presentation is available on the GenComm YouTube site. It consisted of the following programme:

"Hydrogen - Exploring opportunities in the Northern Ireland Energy Transition" Webinar

11th November 2020, 11:30 - 13:05 GMT

Hydrogen is increasingly seen as part of the future of a decarbonised energy mix. In this accessible webinar, a high-level overview of the hydrogen opportunities for Northern Ireland is provided within the context of European and national approaches to hydrogen development.

Agenda

11:30 GMT: **"Introduction to Webinar & to Hydrogen"**, Paul McCormack, Belfast Metropolitan College & GenComm

11:40 GMT: **"Northern Ireland Decarbonisation Policy Perspective"**, Meabh Cormacain, Department for the Economy

11:55 GMT: **"Hydrogen's Role in the EU's Plans for Energy Transition"**, Alexandru Floristean, Hydrogen Europe

12:10 GMT**: "The Vision and Progress to Date of the HEAVENN Project"**, Dr. Ing. Patrick Cnubben, New Energy Coalition, Netherlands

12:25 GMT**: "Hydrogen - Exploring opportunities in the Northern Ireland Energy Transition"**, Dr. Rory Monaghan, National University of Ireland Galway

12:45 GMT: **Q&A**

Audience Details

Representatives from all Northern Irish Departments: Economy, Finance, Infrastructure, Health & Safety Executive, the Utility Regulator, members of the NI Assembly, specifically the Green Party, and the Office of the Northern Ireland Executive in Brussels, who are responsible for energy policy and other Brussels agencies attended.

Representatives also in attendance were from big names in the Gas Industry: Phoenix, Firmus, Gas Networks and Energy Co-Ops, and all others.

Attendees from NI, ROI, and GB (Scotland, Wales, Cornwall, and England) and also from across Europe: France, Belgium, Netherlands, Denmark, Germany, Spain, Portugal and international visitors including Australia and Canada.

256 registered and audience peaked at 184 with almost 200 individuals attending over the whole webinar.

Abbreviations

Abbreviation	Meaning
AE	Alkaline Electrolysis
AFC	Alkaline Fuel Cell
AGI	Above Ground Installation
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilisation and Storage
CO2	Carbon Dioxide
DfE	Department for Energy
EU	European Union
EUCO	European Council
EV	Electric Vehicle
FC	Fuel Cell
FCE	Fuel Cell-Electric
FCHJU	Fuel Cell and Hydrogen Joint Undertaking
GB	Great Britain
GM	General Motors
GMT	Greenwich Meridian Time
GNI	Gas Networks Ireland
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt hour
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
HVDC	High Voltage Direct Current
H2	Hydrogen
ISO	International Organization for Standardization
kg	Kilograms
kg/H_2	Kilograms of Hydrogen
kg/m3	Kilograms per metre cubed
km	Kilometre
LHY	Liquid Hydrogen
LPG	Liquified petroleum gas
MT	Metric Tonne
MW	Megawatt
NG	Natural Gas
NI	Northern Ireland
NIW	Northern Ireland Water
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
OLEV	Office for Low Emission Vehicles
OPEX	Operational Expenditure
PCI	Project of Common Interest
PEM	Proton Exchange Membrane
PR	Public Relations
PV	Photovoltaic
RES	Renewable Energy Source(s)

ROI	Republic of Ireland
RTFC	Renewable Transport Fuel Certificate
SEM	Single Electricity Market
SEMO	Single Electricity Market Operator
SGN	Scotia Gas Networks
SMR	Steam Methane Reforming
SNIP	Scotland NI Interconnector
t	Tonnes
TSO	Transmission System Operator
TW	Terawatt
TWh	Terawatt hour
UK	United Kingdom
USD	United States Dollars
£/kg H2	Pounds Sterling per kilogram of hydrogen

Bibliography

1. *Donnelly, S. Energy in Northern Ireland 2020. (2020).*

2. *Group, E. & Capacity, A. G. All-Island Generation Capacity Statement. (2020).*

3. *Mallon grants planning permission for North South Electricity Interconnector | Department for Infrastructure. https://www.infrastructure-ni.gov.uk/news/mallon-grants-planning-permission-north-south-electricity-interconnector.*

4. *Ervia Ireland. A look at the Irish Gas Market. 1–12 (2017).*

5. *Gas | Mutual Energy. http://www.mutual-energy.com/gas-business/.*

6. *SGN. Press Release Thursday 16th January 2020 Arrival of natural gas in west celebrated at official launch event [Ends]. (2020).*

7. *Gas Networks Ireland. Ireland 's Gas Network. (2014).*

8. *Minister highlights plan for ambitious new renewable electricity target | Department for the Economy. https://www.economy-ni.gov.uk/news/minister-highlights-plan-ambitious-new-renewable-electricity-target.*

9. *Cornwall Insight & Ionic Consulting. Future of Renewables in Northern Ireland. (2020).*

10. *Government of Ireland. Programme for Government. (2020).*

11. *EirGrid Group. All Island Quarterly Wind Dispatch Down Report 2020. 1–8 (2020).*

12. *Energy Transition Commission. Mission Possible - report summary. (2018).*

13. *Sustainable Energy Authority of Ireland. ENERGY SECURITY IN IRELAND 2020 Report. https://www.seai.ie/publications/Energy-Security-in-Ireland-2020-.pdf (2020).*

14. *Fracking: Fermanagh council investigating 'significant error' in consultation - BBC News. https://www.bbc.com/news/uk-northern-ireland-54295913.*

15. *Oireachtas Éireann. Petroleum and Other Minerals Development (Prohibition of Onshore Hydraulic Fracturing) Act 2017. (2017).*

16. *Government ends support for fracking - GOV.UK. https://www.gov.uk/government/news/government-ends-support-for-fracking.*

17. *Electricity | Energy Statistics In Ireland | SEAI. https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/electricity/.*

18. *Sub-national total final energy consumption data - GOV.UK. https://www.gov.uk/government/collections/total-final-energy-consumption-at-sub-*

national-level.

19. *Hydrogen, the fuel of the future, is becoming a reality in Ireland | Interreg NWE. https://www.nweurope.eu/projects/project-search/gencomm-generating-energy-secure-communities/news/hydrogen-the-fuel-of-the-future-is-becoming-a-reality-in-ireland/.*

20. *Matute, G., Yusta, J. M. & Correas, L. C. Techno-economic modelling of water electrolysers in the range of several MW to provide grid services while generating hydrogen for different applications: A case study in Spain applied to mobility with FCEVs. Int. J. Hydrogen Energy **44**, 17431–17442 (2019).*

21. *IEA. The Future of Hydrogen. (2019).*

22. *Gunawan, T. A. et al. At What Cost Can Renewable Hydrogen Offset Fossil Fuel Use in Ireland ' s Gas Network ? Energies 1–24 (2020).*

23. *Turner, M., Zhang, Y. & Rix, O. 70 By 30. (2018).*

24. *Market Data. https://www.semopx.com/market-data/.*

25. US EPA, O. Greenhouse Gas Equivalencies Calculator.

26. *European Commission. The hydrogen strategy for a climate-neutral Europe. (2020).*

27. *Donnelly, S. Energy in Northern Ireland 2020. 103 (2020).*

28. *Research and Markets. Global Green Ammonia Market (2019 to 2030). https://www.globenewswire.com/news-release/2020/07/23/2066360/0/en/Global-Green-Ammonia-Market-2019-to-2030-Featuring-Siemens-Man-Energy-Solutions-NEL-Hydrogen-Among-Others.html (2020).*

29. *Buseman M., Peters D., van der Leun K., Wang A. European Hydrogen Backbone. 4 (2020).*

30. *Intelligent Transport. UK to ban sales of petrol and diesel cars by 2030 in zero emissions bid. https://www.intelligenttransport.com/transport-news/111719/uk-to-ban-sales-of-petrol-and-diesel-cars-by-2030-in-zero-emissions-bid/ (2020).*

31. *The New York Times. Boris Johnson Lays Out U.K. Plan for a 'Green Industrial Revolution'.* https://www.nytimes.com/2020/11/18/world/europe/johnson-britain-energy-electric-cars-carbon.html (2020).

32. *European Commission. EU Hydrogen Strategy. https://ec.europa.eu/commission/presscorner/detail/en/FS_20_1296 (2020).*

33. *Hydrogen Mobility Ireland. Resources. https://h2mi.ie/publications/ (2020).*

34. *Northern Ireland Statistics and Research Agency. Northern Ireland Transport Statistics 2019-2020. https://www.infrastructure-ni.gov.uk/system/files/publications/infrastructure/ni-transport-statistics-2019-2020.pdf (2020)*

35. *Fuel Cell and Hydrogen Joint Undertaking. Hydrogen Roadmap Europe. 19 (2019).*

36. *EirGrid. North-South 400kV Interconnection Development. 7 (2017).*

37. *Islandmagee Energy. Project Overview. https://www.islandmageeenergy.com/project-overview/#how-gas-works (2020).*

38. *Zero Carbon Humber. Capture for Growth – A Roadmap for the World's First Zero Carbon Industrial Cluster. 14 (2019).*

39. *Cummins. Five key questions about the next frontier: Hydrogen fuel cells. https://www.cummins.com/news/2019/10/08/five-key-questions-about-next-frontier-hydrogen-fuel-cells?utm_source=facebook&utm_medium=social&utm_campaign=electric-hydrogen (2019).*

40. *Rivkin C., Schmidt J., Schmidt K. FIREHOUSE. Hydrogen Fuel Cell Vehicles – What First Responders Need to Know. https://www.firehouse.com/rescue/article/12385113/hydrogen-fuel-cell-vehicles-what-first-responders-need-to-know-firehouse (2017).*

41. *Shell Germany. Shell Hydrogen Study – Energy of the Future?. 14 (2017).*

42. *International Energy Agency. Hydrogen. (2020).*

43. *Bünger U., Crotogino F., Donadei S., Landinger H. Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies. (2010).*

44. *Envirotec. Grant awarded for facility to convert waste plastic to hydrogen. https://envirotecmagazine.com/2020/01/17/grant-awarded-for-facility-to-convert-waste-plastic-to-hydrogen/ (2020).*

45. *Californian Hydrogen Fuel Cell Partnership. Resources.* https://cafcp.org/resources (2020).

46. *Fuel Cell and Hydrogen Joint Undertaking. Hydrogen Roadmap Europe. 62 (2019).*

47. *Blain, L. Kawasaki launches the world's first liquid hydrogen transport ship. New Atlas: https://newatlas.com/marine/kawasaki-worlds-first-liquid-hydrogen-transport-ship/ (2019).*

48. *Energia internal market report prepared by DCU and HyEnergy (2018)*

49. *Translink Announcement https://www.translink.co.uk/corporate/media/pressnews/hydrogen (2020)*