Co-designing opportunities towards the development of Irish offshore wind

Project acronym: EirWind
Collaborative project
Start date: 01st August 2018
Duration: 02 years

Work Package 5: Markets, infrastructures, storage and economic benefits

Deliverable D5.1 Identification of New and Future Markets for Offshore Wind and Hydrogen Energy

Delivery date: 01st November 2018
Dissemination level: Public

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This project has received funding from the industry partners, Science Foundation Ireland (SFI) under Grant No 12/RC/2302, and University College Cork, Ireland

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Attribution - Please cite the report as follows:

V. N. Dinh, P. Leahy, V. Cummins, E. McKeogh (2018). *Identification of new and future markets for offshore wind and hydrogen energy*. EirWind Project Deliverable D5.1 Report, MaREI Centre, MaREI Centre, ERI, University College Cork, Ireland. DOI: http://doi.org/10.5281/zenodo.3944474

Document control:

Version	Date	Prepared by	Reviewed by	Approved by
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Executive Summary:

This report highlights the importance of hydrogen energy in Ireland. For the benefits of potential stakeholders, particularly EirWind industry partners, methods of hydrogen production, storage and transportation, including the present and the predicted costs, and a description of fuel cells are briefly reviewed and discussed. The discussion includes a concept of offshore platforms for hydrogen production from windfarms. The markets for hydrogen are first demonstrated by its supply and consumer chains and schematic and sectorial applications. A number of relevant reference case studies of hydrogen markets are reviewed including (i) present and future viability of renewable hydrogen produced from wind farms in Germany and Texas, USA, (ii) the green hydrogen economy in the Northern Netherlands, (iii) the H21 Leeds City Gate project studying technical and economic feasibility of converting the existing natural gas network in Leeds to 100% hydrogen, and (iv) a list of typical hydrogen-based vehicles and infrastructures in operation or under construction throughout the world. The opportunities for new and future hydrogen markets in Ireland are finally discussed with respect to reduction of wind energy LCOE and dispatch-down and to transport, industry, residential and other sectors. Actions to accomplish the market push and pull effects that need to be taken as a first priority by both market stakeholders and regulatory bodies, are proposed. Hydrogen needs to be included in scenarios of Ireland's future energy and government policy. In order to push the market-push, government policy intervention is required to overcome major barriers to a hydrogen economy. That include policy and incentives for utilities to transition to hydrogen. After generating such initial push, a retrospective market pull across the hydrogen supply chain as certainty of a hydrogen economy should be established through regulatory business plans.

List of Abbreviations

AEC – Alkaline Electrolyser Cell

CAES – Compressed Air Energy Storage

CHP – Combined Heat and Power

ESS – Energy storage systems

EU – European Union

GWh – Gigawatt hour

GH2 – Gaseous Hydrogen

HHV – Higher Heating Value (of Hydrogen)

LCOE – Levelised Cost of Energy

LH2 – Liquid Hydrogen

LOHC – Liquid Organic Hydrogen Carriers

MOF – Metal Organic Frameworks

MW - Megawatts

MWh – Megawatt-hour

OSWF - Offshore Wind Farm

PEMEC – Proton Exchange/Polymer Electrolyte Electrolyser Cell

PHES – Pumped Hydro Energy Storage

SMR – Steam Methane Reforming

SNSP – System non-synchronous penetration

SOEC – Solid Oxide Electrolyser Cell

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1 Introduction

Ireland's target under the EU Renewable Energy Directive (2009/28/EC) is to produce 16% of all its' final energy consumption from renewable energy sources by 2020. The target has been subdivided in to three: 40% renewable electricity, 12% renewable heat, and 10% renewable transport [1]. To meet the 40% energy target, Ireland is heavily dependent on renewable electricity from wind. Ireland has an excellent offshore wind potential, and this can provide significant support to meet the set targets.

The installed wind capacity in Ireland is continuously increasing (from 145 MW at the end of 2002 to 2,600 MW as of 2017) and is expected to rise to 4,300MW in 2020 [2]. The 25 MW Arklow Bank wind farm is currently the only operational offshore wind farm (OSWF) in Ireland. Several other offshore wind farms, like the Dublin Array, Oriel Wind Farm and Sceird Rocks, are proposed sites. The Arklow Bank Phase 2 and Codling Wind Park are awaiting construction [3] [4]. Consequently, as the level of wind penetration in the system increases, curtailment can also be expected to go up [4].

Since wind energy is an intermittent source, it poses a challenge as to how to accommodate the energy on to the grid. Of the 7,620 GWh energy generated from the wind in Northern Ireland and the Republic of Ireland in 2016, 2.9% (227GWh) was curtailed. In the Republic of Ireland alone 2.8% (177GWh) of wind generated electricity was curtailed [5]. The challenge is to meet the 40% renewable electricity target by further development of wind energy whilst maintaining the grid stability. Energy storage systems (ESS) provide a suitable alternative to curtailment of wind energy that has no demand. They also provide the chance to operate as ancillary services to improve the grid stability. Currently, a variety of methods may be employed for energy storage in power systems. Pumped-Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES) and Battery storage are the most popular and commercially used among these technologies [6] [7]. Hydrogen energy storage is currently the widely researched area and proves a promising alternative to the existing technologies.

National energy security is a central issue in Ireland, where around a half of the country's electricity is generated from natural gas [8, p. 73] but 40-50% of gas supplies are currently imported from the UK [9]. The remaining productive lives of the Corrib and Kinsale Head gas fields, – the two major domestic natural gas fields, are just 15 years [10] and 3 years [11], respectively. Gas also contributes significantly to the heating and cooling sector and to the transport sector in Ireland, where the energy consumptions in those two sectors are 38% and 37% of the country's total, respectively [12, p. 8].

It is worth noting that exploitation of the vast wind resource in Ireland is further constrained by a relatively weak electricity grid in some locations and limited interconnections. That consequently constrains the electrification in transport, heat and industry sectors. The idea to facilitate a large penetration of wind energy in the country, overcoming some such barriers to its deployment and lessen its value by integrating with hydrogen systems has been therefore discussed for some 15 years [13] [14]. Cost-reductions, low surplus wind electricity average value, and high hydrogen market prices may render the technology cost-effective, allowing for the installation of electrolysis units of sufficient capacity to attain the desired levelling effect and thus facilitating a larger wind penetration [13]. The use of wind-generated hydrogen in the transport and heat sectors will have a substantial contribution to the abatement of CO_2 and other emissions. A study to propose a pilot project for demonstrating and testing the hydrogen systems integrated with onshore wind farms in Ireland is recently reported [15]. The future of hydrogen is anticipated to take off through its use as a transportation fuel [16, 17] and through extensively used industrial applications [18], [19]. Renewable or "green" hydrogen can play a vital role in decarbonizing the future energy sector [19].

Recently, Isabelle Kocher, CEO of ENGIE, highlighted that renewable hydrogen would be the real missing link for a totally carbon-free world [20]. Two major problems that stand in the way of a 100% renewable world are [20]:

- Intermittent production of renewable energies which is a familiar problem. The production of renewable energies is variable, discontinuous and cannot be scheduled. It depends first and foremost on uncontrollable weather conditions, such as sunlight or the wind. In addition, we do not yet know how to store this electricity in large quantities for long periods of time. Electric batteries can cover short-term needs, but how can we cover seasonal variations and use the solar energy produced in the summer, to cover needs in the winter?
- Decarbonisation of all energy uses: transport, heating and industrial processes. For example, transport fuel is 95% dependent on oil and the sector is responsible for 23% of CO_2 emissions worldwide. Focusing all our efforts on electric vehicles would require huge investment. Consider that the size of the electricity grid of Beijing would have to be doubled simply to convert 10% of the fleet to electricity.

Isabelle's reply was in one word: "*hydrogen, the missing link for a completely decarbonised world*" [20].

Currently 98% of hydrogen production is from fossil fuels, - the majority using the Steam Methane Reforming (SMR) method of natural gas [21]. Hydrogen production from renewables has been widely researched, some of the examples are [22] [23] [24]. Because of the promising role of hydrogen in addressing the: (i) intermittency of wind and renewable energy resources, (ii) high dependence of electricity generation on imported natural gas, (iii) grid issues , and (iv) decarbonisation goals in Ireland and globally, as discussed above, this deliverable therefore focuses on identifying market opportunities for hydrogen in Ireland.

2 Hydrogen Production

2.1 Summary and comparison of methods

Hydrogen is the most abundant substance in the universe and it is the most abundant substance on the Earth's crust. Hydrogen is not readily available in its elemental form as it is usually found combined with other materials in its natural state. Hydrogen can be produced using various methods; from use of conventional energy sources like natural gas or coal, from nuclear energy, from renewable energy sources like biomass, wind, and solar as shown in **Figure 2-1**. These fuel sources can be used to produce hydrogen through electrical, thermal and photo chemical processes [25] [26]. The most common and commercially available method for production of hydrogen is Steam Methane Reforming and Electrolysis of water [19].

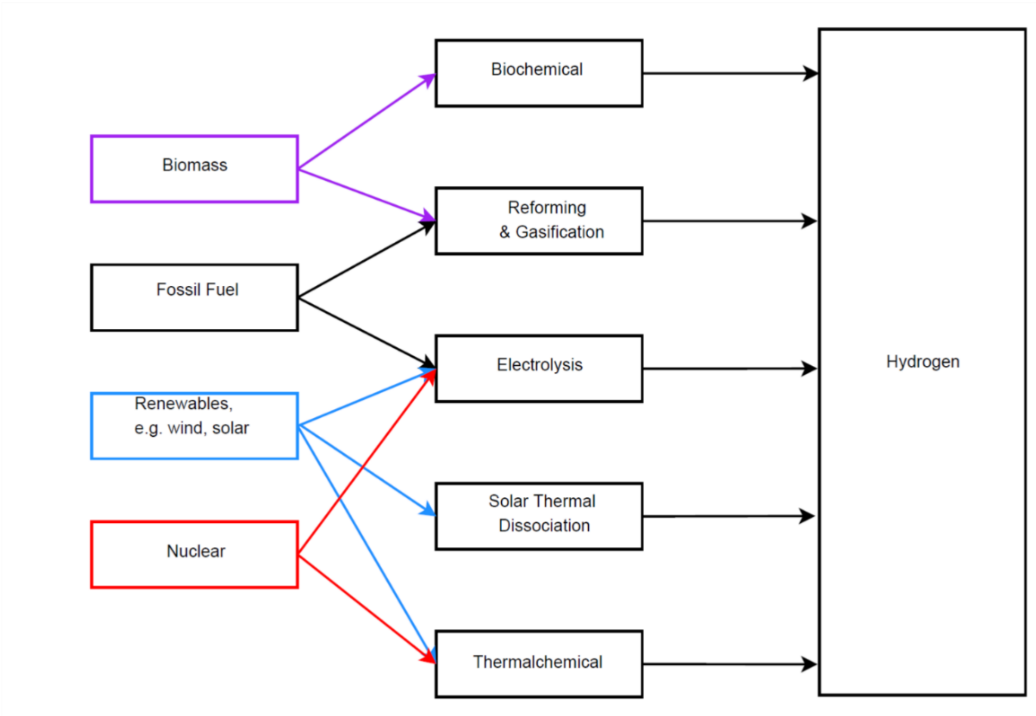


Figure 2-1: Different methods of Hydrogen Production [19], [22].

A comparison of key benefits and problems of hydrogen production methods is given in **Table 2-1**:

Table 2-1: Comparison of Hydrogen production methods [23].

	Natural Gas Stream Reforming	**Coal and Biomass Gasification**	**Thermo-chemical**	**Water Electrolysis**
Key Benefits	Most viable approach in the near term	Low-cost synthetic fuel in addition to H_2	Clean and sustainable	No pollution with water electrolysis
	Lowest cost, Existing infrastructure	Abundant and affordable Reactor costs		High efficiency of conversion.
Critical Challenges	Capital, operation and maintenance costs	Resource constraints and limitation; Carbon emissions	Effective and durable materials of construction	Integration with renewable energy sources, Efficiency, capital costs

2.2 Hydrogen from Water Electrolysis

Currently the most basic industrial process to produce purest form of hydrogen is water electrolysis, and its significance is expected to increase in the future. Water electrolysis is the process of splitting of water molecules to give hydrogen and oxygen by circulating electricity directly through it. The electrolysis process consists of two electrodes immersed in an electrolyte. The electrodes must be resistant to corrosion, must exhibit good conductance, and the electrolytes must be neutral to any reactions. The electrolyser will also have a diaphragm to prevent the recombination of hydrogen and oxygen; these diaphragms are chemically and physically stable as well. The process of electrolysis is a combination of electrochemistry and thermodynamics.

The process of conversion of water into hydrogen requires both thermal as well as electrical energy [27]. Two important factors for electrolysis are its current densities and efficiencies. Efficiencies of water electrolysis may vary from 70 to 90%. Catalysts are used to increase the rates of the reaction. The purity of water used for electrolysis is most important since the resulting product may vary based on this. Hydrogen produced using electrolysis from the electricity made from renewable energy sources has low global warming potential as well [28]. The production of hydrogen from wind-based electrolysers is the most effective way of ensuring minimum pollution. The most important advantage of electrolysis of water is the production of extremely pure hydrogen, with the only by-product being oxygen. The major drawback is the investment cost and low overall efficiency [29].

Table 2-2: Main characteristics of Alkaline, PEMEC and SOEC Electrolysers [30].

	Alkaline	**PEMEC**	**SOEC**
Electrolyte	Aq. Potassium Hydroxide (20 - 40 wt% KOH	Polymer membrane (e.g. Nafion)	Yttria stabilised zirconia (YSZ)
Cathode	Ni, Ni-Mo Alloys	Pt, Pt-Pd	Ni/YSZ
Anode	Ni,Ni-Co alloys	RuO_2, IrO_2	LSM/YSZ
Current Density (A cm^{-2})	0.2-0.4	0.6-2.0	0.3-2.0
Cell Voltage (V)	1.8-2.4	1.8-2.2	0.7-1.5
Voltage Efficiency (%$_{HHV}$)	62-82	67-82	<110
Cell Area (m^2)	<4	<0.3	<0.01
Operating Temperature (°C)	60-80	50-80	650-1000
Operating Pressure (Bar)	<30	<200	<25
Production Rate (m$^3_{H2}$ h^{-1})	<760	<40	<40
Lower Dynamic Range (%)	10-40	0-10	>30
System Response	Seconds	Milliseconds	Seconds
Cold-start Time (minutes)	<60	<20	<60
Stack lifetime (h)	60,000-90,000	20,000-60,000	<10,000
Maturity	Mature	Commercial	Demonstration
Capital Cost (€/kW$_{el}$)	1000-1200	1869-2320	>2000

Alkaline electrolysers have an operational capability of 20 to 100% of their design capacity but require continuous operation for better performance. PEM Electrolysers are more favourable in the varying-load environment of wind farms owing to their faster cold-start, higher flexibility, and better coupling with dynamic and intermittent systems [31]. PEM electrolysers may be preferred over Alkaline ones due to the low permeability of the membrane and poses lower risk of mixing hydrogen and creating a flammable condition. The SOEC and PEM electrolysers are compared with each other [32], where both cell technologies are comparable in performance and that SOEC might even be cheaper in terms of overall investment costs. Three electrolyser cell technologies are compared [30] as summarised in **Table 2-2** which shows that alkaline electrolysers are presently the cheapest and mature technology. PEM Electrolysers are currently commercialised [30] [33]. SOEC cells are still in development phase and are the most expensive of the three types. The costs of each of these technologies are expected to drop significantly by 2030. PEM Electrolyser technology is expected to be the dominant technology from 2020 onwards, and the capital expenditure for PEM is expected to drop by 20-27% [30].

Figure 2-2 shows the more up-to-date and predicted costs of electrolyser technologies for Power-to-Gas (PtG) applications with data from multiple sources for Alkaline Elecrolysis (AEL) and Polymer Electrolyte Membrane (PEM) electrolysis [34]. These projections for the system prices of electrolysers are based on hand-collected data covering the years 2003 – 2016 from manufacturers, operators of PtG plants, articles in peer-reviewed journals, and technical reports, and using univariate regression for a constant elasticity functional form.

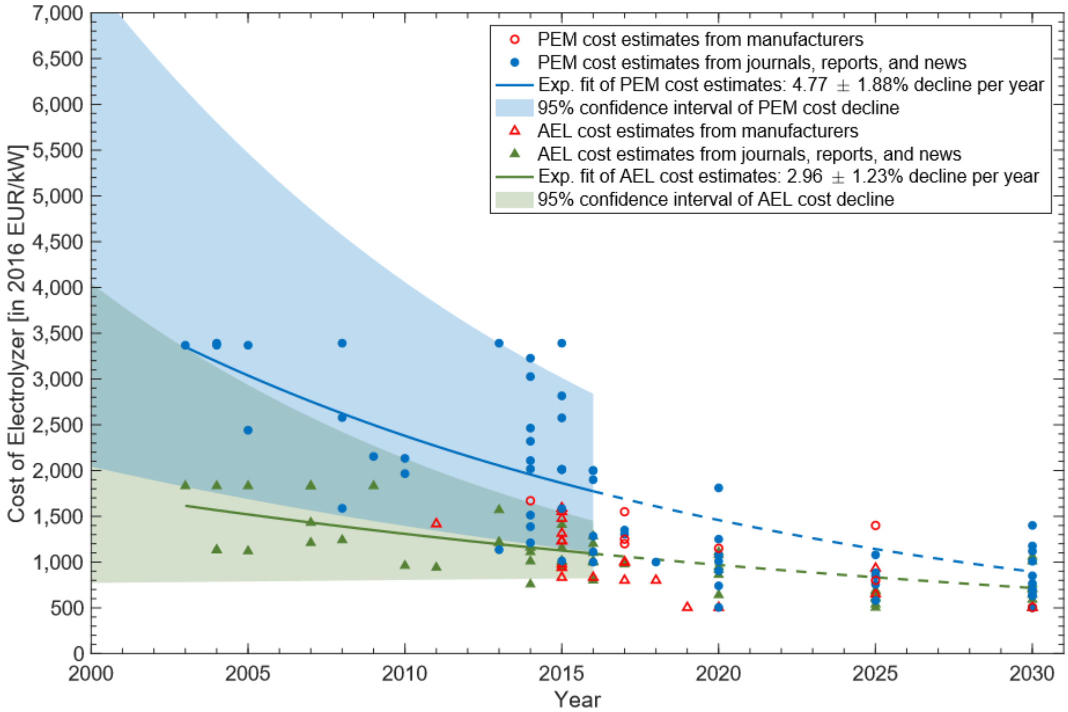
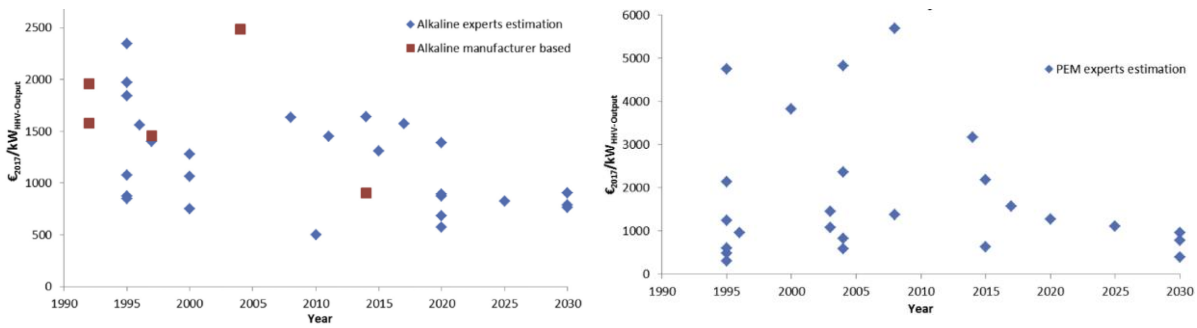


Figure 2-2: Cost of electrolyser technologies for Power-to-Gas application [34].

Data gathered from AEL and PEM experts and manufacturers in the past 30 years have been adjusted for inflation and transferred into €$_{2017}$ and projected for future investment costs until 2030 as shown in **Figure 2-3** [35]. The average annual inflation rate data from 1990 to 2017 purchased from Statista and Eurostat were 2.5% in the U.S., 1.45% in the Europe, and 025% in Japan. The estimations for the future investment costs of AEL and PEM electrolysis plants in year 2030 are narrowed towards values of 787 - 906 €$_{2017}$/kW$_{HHV\text{-}Output}$ and 397 - 955 €$_{2017}$/kW$_{HHV\text{-}Output}$, respectively [35] that are in good agreement with **Figure 2-2**. The costs of PEM electrolysers in 2030 are expected to drop to similar or lower levels as those of alkaline electrolysers [35].



(a). Alkaline electrolysis plant cost (b) PEM electrolysis plant cost

Figure 2-3: Development of expected Alkaline electrolysis plant cost (a) and PEM electrolysis plant cost (b) according to experts and manufacturers in the past 30 years [35].

2.3 A Concept of Offshore Platforms for Hydrogen Production from Windfarms

A concept for hydrogen production at an offshore platform connected to wind farms has been proposed in a recently published paper [36] [37] as shown in **Figure 2-4**. In the future and at a larger scale, the produced hydrogen is expected to be partly transformed back to electricity via a fuel cell that turns the intermittent wind-based electricity into base load energy [38].

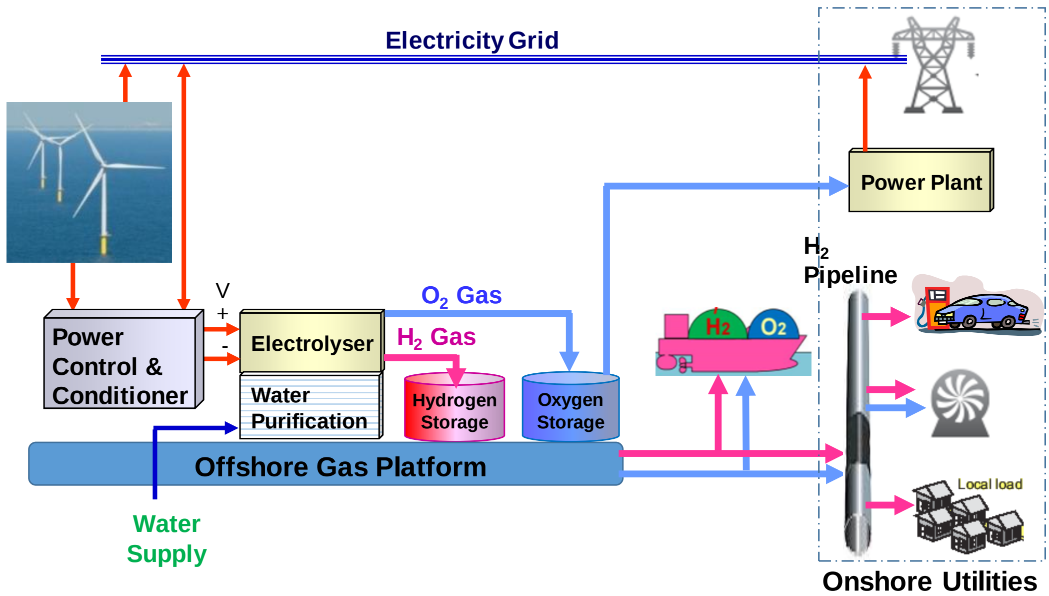


Figure 2-4: Production concept of electricity and hydrogen from offshore wind [36].

The synergy with or replacement of offshore oil and gas platforms is another potential and cost-effective solution for offshore wind farms to ensure future energy fuel, by utilising a part of existing infrastructure, operation and maintenance services [39]. For short term scenarios such as for the North Sea [38], a pilot can be set-up to connect a wind farm to an existing platform that otherwise would be decommissioned. In medium term scenarios a large offshore wind farm could be connected to a platform and synthetic natural gas (SNG) generated at the platform will be added to the natural gas grid where the CO_2 and SNG could be stored at the depleted gas field capacities [38]. In long-term scenarios, hydrogen can be produced at the platform as shown in **Figure 2-4** at a larger scale and partly transformed back to electricity via a fuel cell that turns the intermittent wind-based electricity into base load energy [38].

3 Hydrogen Storage and Transportation

3.1 Methods and Challenges

Hydrogen is a light element. It is colourless, odourless and can dissolve into the atmosphere. In order to improve upon the status of hydrogen energy applications, it is important to develop cheap, effective and safe methods to transport and store hydrogen [7] [19]. Hydrogen has the highest energy per mass of any fuel; however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density [40]. Hydrogen can be stored physically as either a gas or a liquid as in **Figure 3-1**. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure) [40]. Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption) [40].

Challenges of hydrogen storage:

- High density hydrogen storage is a challenge for portable applications and remains a significant challenge for transportation applications while duel-cell-powered vehicles require enough hydrogen to provide a driving range of more than 450 km with the ability to quickly and easily refuel the vehicle [40]. Presently available storage options typically require large-volume systems that store hydrogen in gaseous form.
- Low energy density with present storage methods: liquid hydrogen has a density of 8 MJ/L whereas gasoline has a density of 32 MJ/L. Onboard hydrogen storage capacities of 5–13 kg hydrogen will be required to meet the full driving range for light-duty vehicle platforms.

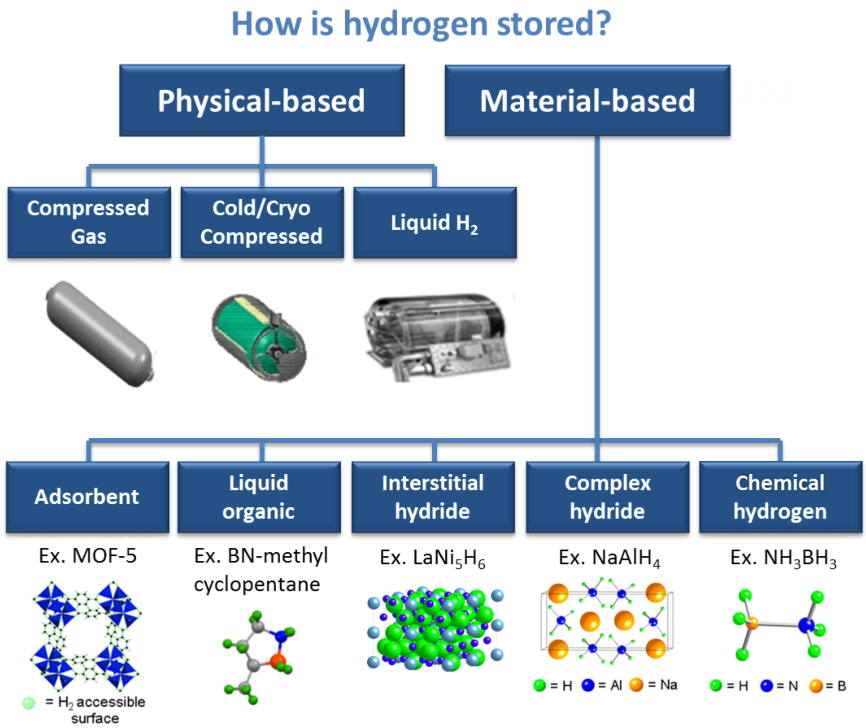


Figure 3-1: Production concept of electricity and hydrogen from offshore wind [29].

Figure 3-2 displays the volumetric and gravimetric density ranges of different technologies for hydrogen storage for transportation [41] where compressed and liquid hydrogen are the current state of the art. All alternative hydrogen carriers like MOFs, metal hydrides, chemical hydrides or LOHCs were initially investigated for on-board hydrogen storage in a fuel cell vehicle. LOHCs are thereby promising candidates since the loaded as well as unloaded carriers exist naturally in a liquid state [41].

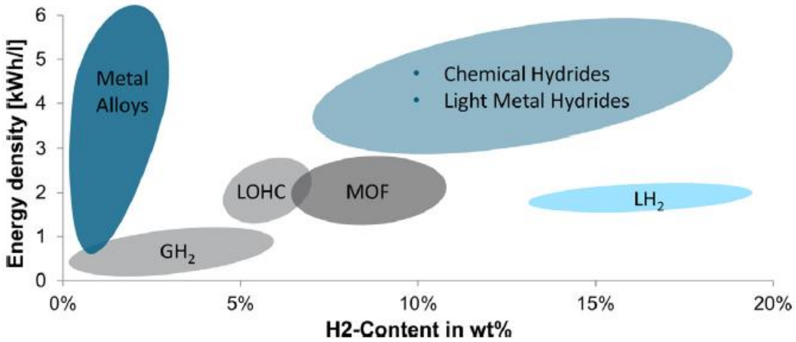


Figure 3-2: Comparison of different hydrogen storage technologies; LOHC – Liquid Organic Hydrogen Carriers; MOF – Metal Organic Frameworks; GH2 – Gaseous Hydrogen; LH2 – Liquid Hydrogen [41].

3.2 Fuel Cells

A fuel cell is an electrochemical device that uses the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity [42]. If hydrogen is the fuel, electricity, water, and heat are the only products. Fuel cells work like batteries, but they **do not run down or need recharging**. They produce electricity and heat as long as fuel is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte, as depicted in **Figure 3-3**. A fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. In a hydrogen fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat [42].

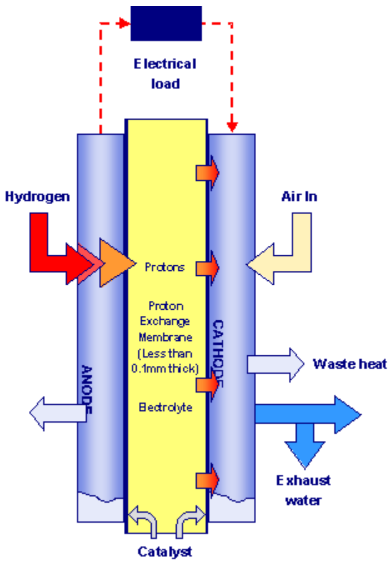


Figure 3-3: Cross section through a typical PEM fuel cell [43].

Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer [42]. Fuel cells can be used in a wide range of applications, including transportation, material handling, stationary, portable, and emergency backup power applications. They have several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles [42].

Fuel cells are part of a portfolio of technologies that can enable energy security, resiliency and economic growth through a number of applications across sectors. As research and development (R&D) continues to help drive down cost and improve performance, States and the private sector have been deploying fuel cells in stationary, transportation, and portable power applications, helping to achieve economies of scale in this emerging industry. Despite the primary challenge of cost, fuel cells offer a number of following benefits [44]:

- High quality, reliable power, enables resiliency
- Fuel flexible – can use diverse domestic fuels (conventional, renewables or waste products such as waste water or landfill gas) and enables energy security
- Scalable to fit any power need and diverse applications across stationary, transportation and portable power sectors
- Offers combined heat and power options and can co-produce fuel
- Efficient – 50%+ electric efficiency, 90%+ electric and thermal efficiency (combined heat and power)
- Quiet, durable, rugged, and exceptionally low/zero emissions

Motive:

- Fuel Cell Vehicles (FCVs) – replicates today's driving experience: range of 300+ miles per hydrogen fuelling, refuel at a pump in 3-5 minutes.
- Material Handling Equipment – fuel cell provides constant power, and can refuel in minutes.

Stationary:

- Flexible siting – indoors or outdoors and Lightweight – enables rooftop siting.
- Modular/scalable to meet any need, ranging from a few watts to multi-megawatt systems.
- Able to provide primary, supplemental, or backup power.
- Can be grid-tied, or can operate independently from the grid.
- Compatible with solar, wind, batteries and other renewable/conventional technologies
- Can be connected to existing natural gas infrastructure, or use hydrogen fuel generated by renewables.
- Operates in water balance/uses very little water in operation.

Portable:

- Refuel on the go by swapping a cartridge
- Low-thermal, low-sound profile

4 Markets for Hydrogen

4.1 Hydrogen Energy Supply Chain and Consumer Chains

Figure 4-1 depicts the key components of a hydrogen energy chain from the primary energy source to the market applications. Some of the key technologies that could be involved at each stage of hydrogen energy chains are highlighted in **Table 4-1** below:

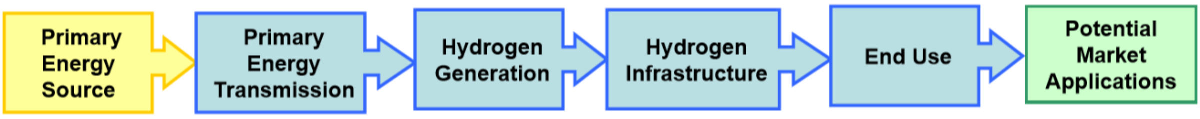


Figure 4-1: Components of a hydrogen energy chain [43].

Table 4-1: Key technologies involved at each stage of hydrogen energy chains [43].

Primary energy source	Primary energy transmission	Hydrogen generation	Hydrogen storage	Hydrogen distribution	End-use	Potential market application
Natural gas, coal, oil fired power plant	Electricity transmission	Electrolyser	Compressed gas Liquefaction and liquid storage Solid state storage	Delivery by truck (gas & solid state) Hydrogen pipeline (gas) Tanker truck (Liq.) Barge (Liq.)	Fuel cell Combustion engine Hydrogen turbine Boiler Catalytic converter	Transport Stationary power Portable power Heating demands Cooking / niche applications
Nuclear power						
Renewable electricity						
Natural gas, biogas	Gas grid, pipeline	Steam reformation				
coal	Delivery truck	Gasification				
Biomass	Delivery truck	Gasification				

CO_2 impact of the energy chain:

In order to understand the carbon dioxide impact of delivering a particular energy service, for example hydrogen transport, it is necessary to consider the complete energy chain, as CO_2 could be produced at each stage. If the primary energy source is renewable, the overall CO_2 impact is likely to be low, but it is not necessarily zero. For example, once the hydrogen has been generated, it is compressed and then transported by truck to the end-use location. In this case CO_2 could be attributed to the electricity consumption of the compressor and to the road transport of the compressed gas.

Hydrogen and oxygen are used in a broad range of industries as summarised in **Table 4-2** and **Figure 4-2**:

Table 4-2: The broad range of industrial application of hydrogen and oxygen [45].

Market	Oxygen	Hydrogen
Metals	Enhance combustion temperatures in Metals industrial process	Mixed with inert gases for reducing atmosphere
Chemicals, pharmaceuticals & petroleum	Feedstock; combustion enhancer; catalysis enhancer	Feedstock; purification
Glass and ceramics	Combustion enhancer	To prevent oxidation
Pulp and paper	Bleaching agent (replacing chlorine); Combustion enhancer	
Health care	Respiratory aid	
Environmental	Enhance biological waste treatments; chlorine replacement	
Aquaculture	Increase oxygen content of water & therefore increase yields of fish	
Breathing apparatus	Diving	
Fitting and turning	Combined with fuel gas for welding, gas. Fitting & turning cutting etc	Aluminium welding; underwater cutting & welding
Rockets	Fuel	Fuel
Food and beverages		Unsaturated fatty acid hydrogenator
Semiconductor manufacture		Carrier gas for active trace elements
Electricity generation	Oxy-Fuel Combustion, Gasification	Generator coolant; protective atmosphere for nuclear fuel rod fabrication

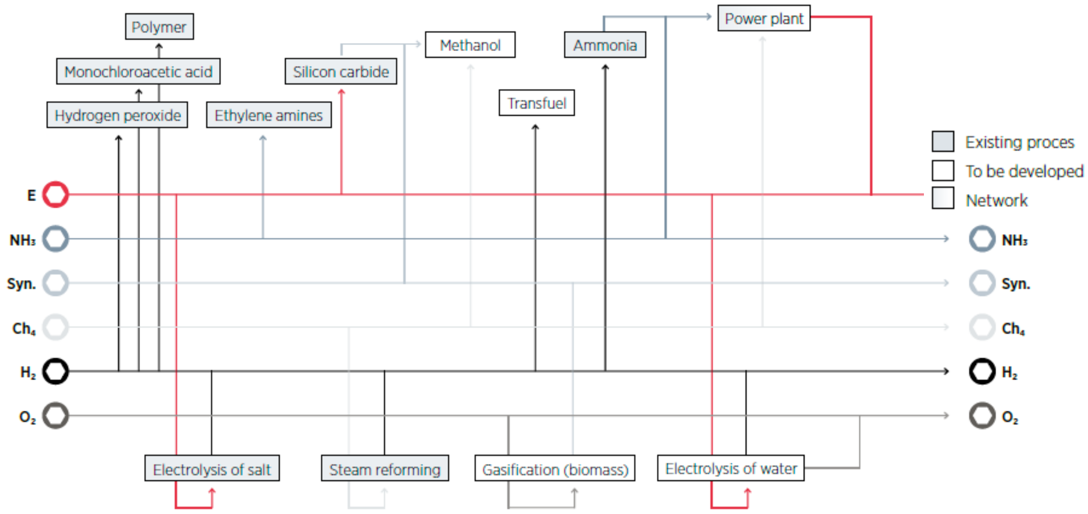


Figure 4-2: Schematic overview of the use and production of industrial gasses and electricity network [46].

4.2 Reference Case Studies of Hydrogen Markets

4.2.1 Case Study 1: Present and future viability of renewable hydrogen produced from wind farms in Germany and Texas, USA

Economic analysis models have been developed in which the available capacity can be optimized in real time so as to take advantage of fluctuations in electricity prices and intermittent renewable power generation [34]. The models are calibrated to the current environment in both Germany and Texas and applied to wind parks in Germany and Texas with main input variables listed in **Table 4-3**. Renewable hydrogen is found to be economically viable if it is sold at prices of at least 3.23 €/kg in Germany and 3.53 $/kg in Texas. In the current environment, these prices are compatible with small- and medium-scale hydrogen supply but not with large-scale industrial sales as shown in **Figure 4-3.**

Table 4-3: Main input variables for economic analysis of renewable hydrogen in Germany and Texas [34].

	German	Texas
PtG system price, SPh	2,287 €/kW	2,009 $/kW
Conversion rate of PtG	0.019 kg/kWh	0.019 kg/kWh
Wind system price	1,367 €/kW	1,596 $/kW
Wind capacity factor	30.27 %	34.61 %
Electricity price	3.18 €¢/kWh	2.55 $¢/kWh
Subsidy: PP or PTC	6.16 €¢/kWh	2.30 $¢/kWh
Cost of capital interest rate (WACC)	4.00	6.00 %

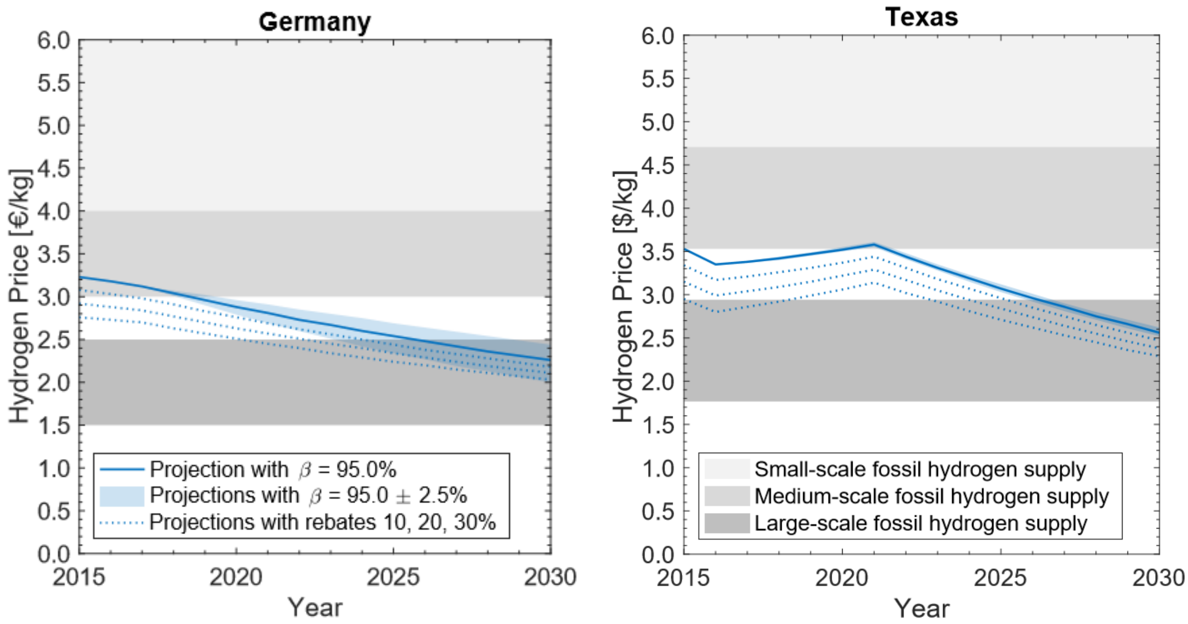


Figure 4-3: Prospects for renewable hydrogen production, β = adjustment rate [34].

However, if the acquisition prices for electrolysers and wind turbines continue on their respective recent learning curves, it is expected that in about a decade, renewable hydrogen will also become competitive with the lower prices paid for large-scale industrial hydrogen. These results also underline how this convergence process could be accelerated through policy support mechanisms such as rebates or investment tax credits [34].

4.2.2 Case Study 2: The Green Hydrogen Economy in the Northern Netherlands

A vision document for a green hydrogen economy in the Northern Netherlands [46] has resulted from a collaborative process among industry, governments and organizations, initiated and led by members of the Northern Netherlands Innovation Board. The concept and electrolysis exemplary cost are respectively illustrated in **Figure 4-4** and **Figure 4-5**. Many companies, institutions and governmental organizations were consulted.

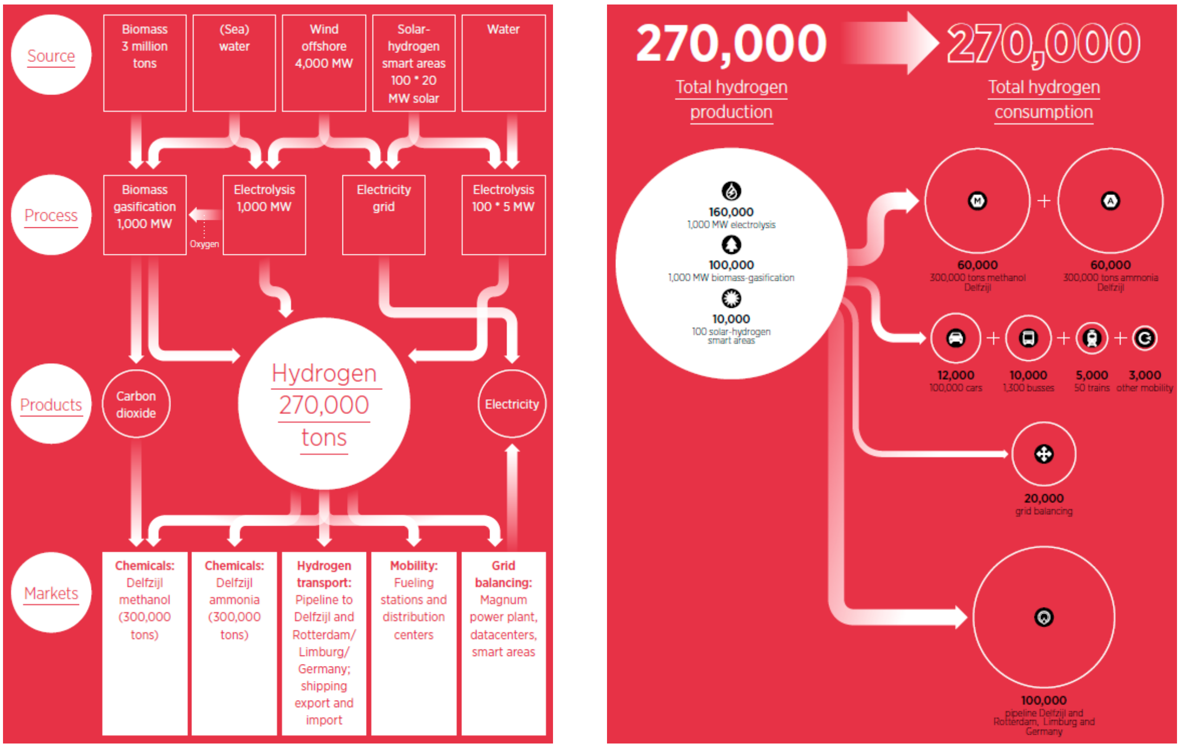


Figure 4-4: Concept of green hydrogen economy in the Northern Netherlands [46].

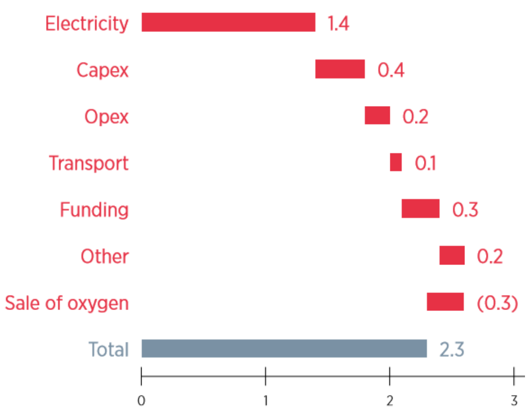


Figure 4-5: Electrolysis Exemplary cost breakdown of hydrogen (electricity: 25 EUR/MWh, EUR per kg) [46].

The key findings and identified business opportunities and markets included the following:

- Large-scale green hydrogen production could create competitive hydrogen prices (2-3 €/kg)
- Increasing renewable energy production, rapid development towards clean mobility.
- **Future production:** Far offshore wind farm hydrogen production - Offshore wind farms produce electricity that can be brought onshore via an electrical cable, which is expensive. The farther offshore the wind farm is, the more expensive the cable. In the North Sea, an alternative solution for these wind farms would be converting the electricity into hydrogen at an existing oil/gas platform and, after mixing it with gas via an existing gas pipeline, transporting it. Once onshore, the hydrogen can be separated from the natural gas and cleaned for transportation via pipeline, ship or truck to the markets. Several natural gas networks will allow mixing with hydrogen (the present limit of concentrations is 10%) [47].
- **Markets:** 300,000 tons of green methanol and 300,000 tons of green ammonia. Ammonia is produced from H_2 and nitrogen (N_2) captured from the air. Methanol is primarily used to produce other chemicals, such as formaldehyde for plastics and paints, DME, olefins (ethylene, propylene) and acetic acid, among others. In the past, natural gas was used to produce methanol. Ammonia is primarily used to produce fertilizers, but it is also used in a variety of other pharmaceutical and chemical products and in fuel cells [48].
- **Markets:** 100 hydrogen fuelling stations in the Northern Netherlands: Refuelling vehicles in the Northern Netherlands will require the installation of hydrogen fuelling stations (HRS). These fuelling stations will be able to fuel passenger cars, light and heavy duty commercial vehicles with pressurized hydrogen at 700 bar and, in some cases, buses at 350 bar. Buses will continue to be primarily fuelled at the bus depot, so there should be dedicated hydrogen fuelling stations at the depots. Hydrogen dispensers will be integrated into existing or recently built fuelling stations featuring other fuels, electric charging, shops and carwashes, among others. Therefore, in principle, hydrogen can be integrated into existing sites and business models. The minimum hydrogen supply is about 200 kg per day (40 to 60 cars), but should grow to about 1,000 kg per day (200 to 300 cars). Hydrogen fuelling stations will need to be SAE 2601 and PGS-35 compliant.

Table 4-4: Hydrogen fuelling stations (HRS) investment costs [46].

Type	Capex (x M€)	Number of HRS	Investment (x M€)
HRS; hydrogen supplied by truck	1.5-2	90	135-180
HRS; local hydrogen production by electrolysis	3-5	10	30-50
Total investment			165-230

4.2.3 Case Study 3: H21 Leeds City Gate

The H21 Leeds City Gate project is a study with the aim of determining the feasibility, from both a technical and economic viewpoint, of converting the existing natural gas network in Leeds, one of the largest cities in the UK, to 100% hydrogen [49]. The project has been designed to minimise disruption for existing customers, and to deliver heat at the same cost as current natural gas to customers.

The project consists of several sections:

(1) Calculation of the energy demands for the area of conversion:

Table 4-5: Calculated energy demands.

Average yearly	Max peak yearly	Max peak hour	Peak day average	Total average yearly	Total peak year
678 MW	732 MW	3,180 MW	2,067 MW	5.9 TWh	6.4 TWh

The demand in **Table 4-5** is serviced by the following production and storage facilities:

- Hydrogen production capacity of 1,025 MW_{HHV} (305,000 Sm^3/h) provided by four Steam Methane Reformers (SMRs), fitted with 90% carbon dioxide capture.
- This CO_2 is then compressed to 140 bar and assumed to be exported 'over the fence' to permanent sequestration deep under the North Sea.
- Additional intraday storage, which together with the SMRs and inter-seasonal storage, will supply a maximum 1 in 20 peak hour demand of 3,180 MW_{HHV}. This will be in the form of salt cavern storage, some which may be repurposed from already existing caverns.
- Inter-seasonal storage of 702,720 MWh_{HHV} (40 days of maximum average daily demand (coldest year), 209 million Sm^3 hydrogen), in the form of salt cavern storage on the coast.
- A Hydrogen Transmission System (HTS) will connect the SMRs and salt caverns to the proposed area of conversion (Leeds) and will be capable of transporting at least the peak supply requirement of 3,180 MW.

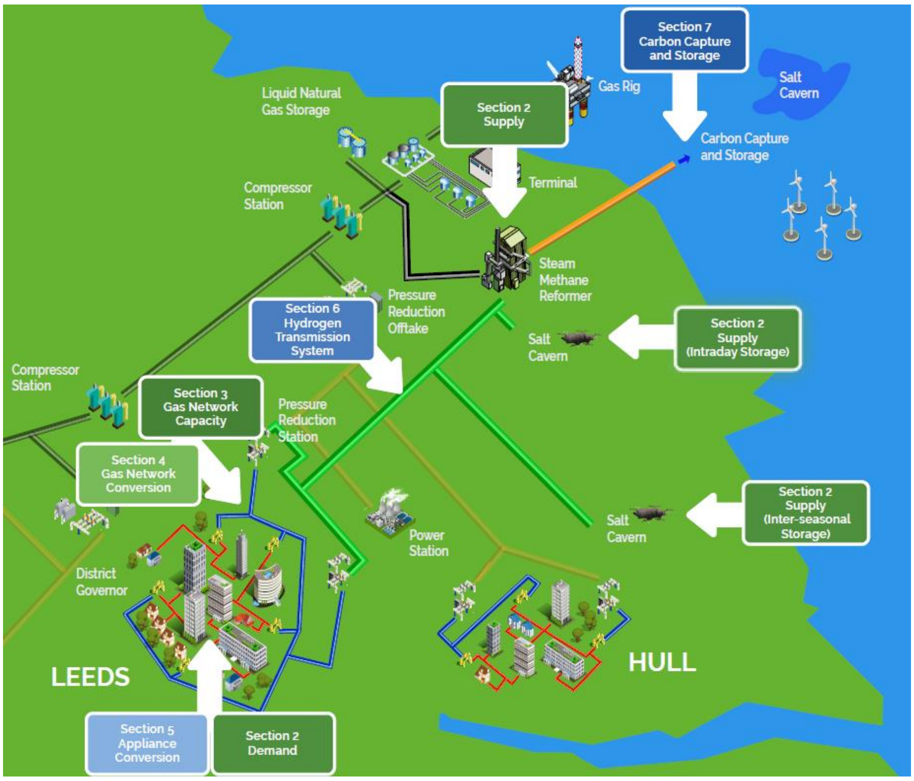


Figure 4-6: H21 Leeds City Gate System Schematic [49].

(2) Gas Network Capacity: Modelling the Medium Pressure and Low Pressure (LP) gas distribution networks within the area of conversion for hydrogen conversion using the network analysis software and data currently used by Northern Gas Networks. It concludes that the gas networks have sufficient capacity to convert to 100% hydrogen with relatively minor upgrades

(3) Gas Network Conversion: The existing gas network is segmented and converted from natural gas to hydrogen incrementally through the summer months over a three-year period. This approach would mean minimal disruption for customers during the conversion.

(4) Appliances Conversion: Hydrogen appliances and equipment for domestic, commercial and industrial sectors are developed. There are already a few models on the market, although sales are extremely low, due to an absence of piped hydrogen. A firm long-term plan and significant stimulus would be needed and potentially be in the form of a national heat policy.

(5) Hydrogen Transmission System: High-pressure hydrogen transmission pipelines carry hydrogen from the SMR site to the conversion area and hydrogen storage sites.

Total costs associated with the Project are summarised in **Table 4-6** below:

Table 4-6: H21 Leeds City Gate Financial model [49].

Tasks	**Cost incurred (£ Million)**	**Ongoing costs each year (£ Million)**
Network Capacity and Conversion Preparatory Work	10	
Hydrogen Infrastructure/Conversion Costs:		
Steam Methane Reformer (SMR) Costs	395	
Intraday Salt Caverns	77	
Inter-Seasonal Salt Caverns	289	
Appliance Conversion (Domestic, Commercial and Industrial users within area of conversion)	1,053	
Hydrogen Transmission System	230	
Ongoing OPEX Costs:		
Carbon Capture and Storage		60
SMR/Salt Cavern/HTS Management		31
SMR Efficiency loss (30%)		48
Total	**2,054**	**139**

The project has shown that:

- The gas network has the correct capacity for such a conversion.
- It can be converted incrementally with minimal disruption to customers
- Minimal new energy infrastructure will be required compared to alternatives
- The availability of low-cost bulk hydrogen in a gas network could revolutionise the potential for hydrogen vehicles and, via fuel cells, support a decentralised model of combined heat and power and localised power generation.

4.2.4 Hydrogen-based vehicles and infrastructures in operations/ on building in the world

Figure 4-7: The ix35 Fuel Cell became the world's first mass-produced hydrogen-powered vehicle in **2013**. Since its launch, it has set new records for the longest fuel cell vehicle road trip across Europe, covering **2,500km**, and set a new speed record of **170 km/h** on **public roads** in Europe [50].

Figure 4-8: ENGIE has inaugurated the largest hydrogen (H2) utility fleet and the first alternative multi-fuel station in France [51].

Figure 4-9: Coradia iLint hydrogen train receives approval for commercial operation in German railway networks [52]. It has a 1,000-kilometre range and can reach speeds of up to **140 kmh**.

Figure 4-10: Japanese group Kawasaki, in partnership with Australia and Shell, is building a transport vessel for liquid hydrogen that will be ready by 2020 [53].

5 Opportunities for New and Future Energy Markets in Ireland

5.1 Reduction of Wind Energy LCOE and Dispatch-Down

Along with capacity factor, dispatch-down of wind energy plays a very important role in determining the actual generation of electrical energy from a wind farm. Wind dispatch-down is a term used to define the amount of wind generated electrical energy that is not introduced into the electrical grid for use by end user. Wind dispatch-down can be further defined by classifying the reasons of curtailment or constraints [54].

Wind *Curtailment* refers to "the dispatch-down of wind for system-wide reasons". There are different types of system security limits that necessitate curtailment namely - System stability requirements (synchronous inertia, dynamic and transient stability, Operating reserve requirements (including negative reserve), Voltage control requirements, System Non-Synchronous Penetration (SNSP) limit. In order to securely operate the system these limits result in minimum generation requirements on the conventional (synchronous) generation portfolio [55].

Wind *Constraint* refers to the dispatch-down of wind for network reasons is referred to as a constraint. Constraint of wind can occur for two main reasons - more wind generation than the localized carrying capacity of the network and during outages for maintenance, upgrade works or faults [55].

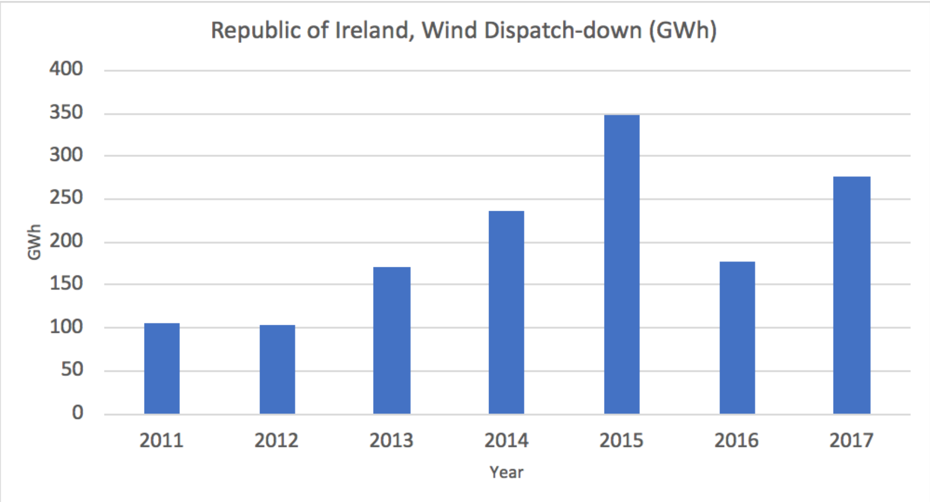


Figure 5-1: Yearly wind energy dispatch-down in Ireland, 2011 – 2017 [54].

Wind dispatch-down also has a seasonal, yearly and monthly variation with percentage of dispatch down varying between maximum and minimum amounts. The losses due to dispatch-down are significant and will effect profitability of projects especially in the highly competitive world where each project is separated from next by only a single digit profit percentage. Amount of dispatch-down is also dependent on wind farm capacity present during the year. **Figure 5-1** and **Figure 5-2** [54] summarises yearly variation of wind dispatch-down and year 2017 monthly variations respectively. Henceforth wind curtailment will be used to signify wind dispatch-down and constraints.

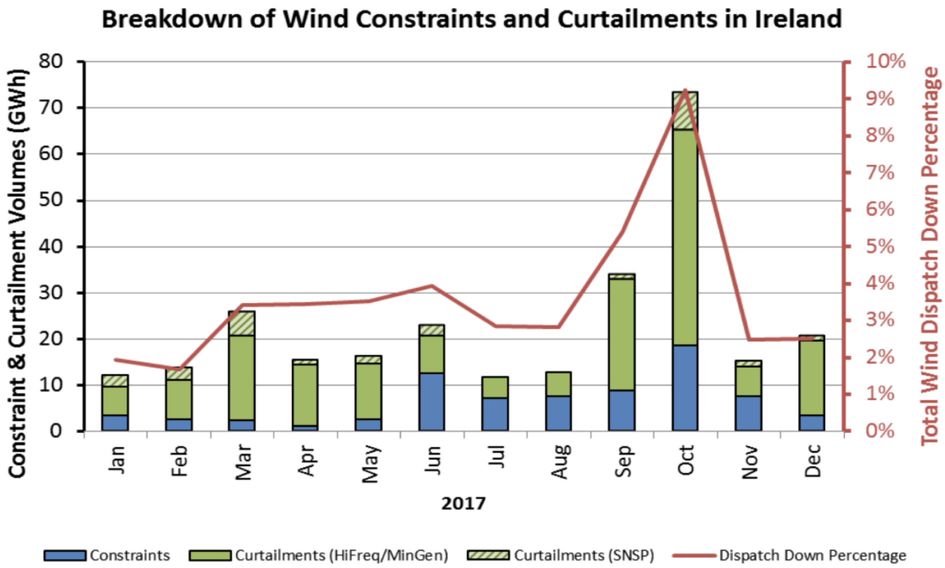


Figure 5-2: Monthly wind energy dispatch-down in Ireland in 2017 [54].

In a recent research project on offshore wind power in Ireland [54], where hydrogen production is considered, a large number of scenarios have been generated by the combinations of:

- Offshore wind installation sizes in 2030 of 4500 MW, 2300 MW and 800 MW.
- High, medium and low curtailment scenarios of 9.75, 7.80, and 5.85%, respectively
- Several electrolyser plant sizes, Feed in Electricity prices, Electrolyser efficiencies
- Several OPEX and CAPEX values of offshore wind, and electrolysers those are available.

In the baseline scenario, the electrolyser CAPEX is 850€/KW and OPEX is 1.5% of CAPEX. The electrolyser efficiency 74%, and the hydrogen selling price is 6€/Kg [54]. The reduction of hydrogen selling price in the future will be counter-balanced with the reduction of offshore wind costs, electrolyser CAPEX and OPEX. The LCOE values of offshore wind farms with P2H systems are found to be **€20/MWh lower** than that without P2H [54].

5.2 Sectorial Markets

The sectorial energy consumption in **Table A-1** of the Appendix shows that there are high-potential markets in the following sectors:

- **Transport:** It is the largest and most feasible market that consumes 5076 – 4685 ktoe annually. This represents nearly 40% energy in Ireland and can be hydrogenated by fuel cell vehicles. That can support decarbonisation while the electrification is being constrained by the electricity grid.
- **Industry:** There are increasing figures in gas consumption (462 ktoe in 2005 to 1064 ktoe in 2017), and electricity consumption (660 ktoe in 2005 to 895 ktoe in 2017) those could have potential for hydrogen-based applications.
- **Residential**: The consumption in oil, gas and electricity in 2017 are 920, 638 and 705 ktoe, respectively. With the on-going and fast development of technology, hydrogen-injected gas, and fuel cell heating could be the future applications.

Ervia, previously known as Bord Gáis (meaning "Gas Board of Ireland") - a multi-utility state-owned company distributing pipeline natural gas and water services in Ireland, in a recent report, stated that Ireland has a major asset in its safe and reliable gas network [9]. It is also one of the most modern networks in Europe and is suited to transporting other gases like hydrogen. Ervia is aware of the advantages of hydrogen and that it is the potential to significantly decarbonise Ireland's heating needs by 2050 through regional conversion using the existing distribution networks [9]. Ervia is currently progressing a study on the potential for hydrogen in Ireland.

5.3 Carbon Abatement

In a recent research project on offshore wind power in Ireland [54] described in Section 5.1, where some 7000 scenarios have been generated. Each scenario run will provide a different hydrogen gas generation in kilograms. It is assumed that for each kilogram of hydrogen gas produced, an average fuel cell equipped car can travel 100 km [39] [54] [56]. As per European norms, an average road going personal vehicle can emit a maximum of 95 g/km of CO_2 [57].

In the calculation of CO_2 abatement, CO_2 intensity of manufacturing of hydrogen propulsion system, manufacturing and commissioning of off shore platform, and transportation and storage of Hydrogen gas generated is not considered [54]. These assumptions were considered to facilitate a qualitative discussion on the utility of P2H systems in carbon dioxide abatement [54]. The assumptions also embody the relatively minuscule lifecycle carbon intensity (g/kWhe) of offshore wind farms of around 16g CO_2/kWhe [58] [54] in comparison to other electricity producing technologies for example, hydroelectric 15–40g CO_2/kWhe, photovoltaics 50 - 100gCO_2/kWhe. Even for electrolyser plants and wind farm setups, the lifecycle carbon intensity of the electrolyser forms only a small percentage of the overall plant total [59] [54].

The generated scenarios have been run, and in each scenario run, CO_2 abatement potential was calculated [54]. The values expressed in **Million Tones (MT)** of CO_2 had a median of 0.15 MT CO_2 and a mode of 0.060 MT CO_2. **Figure 5-3** shows that 0.45 MT CO_2 can be abated in the best scenario.

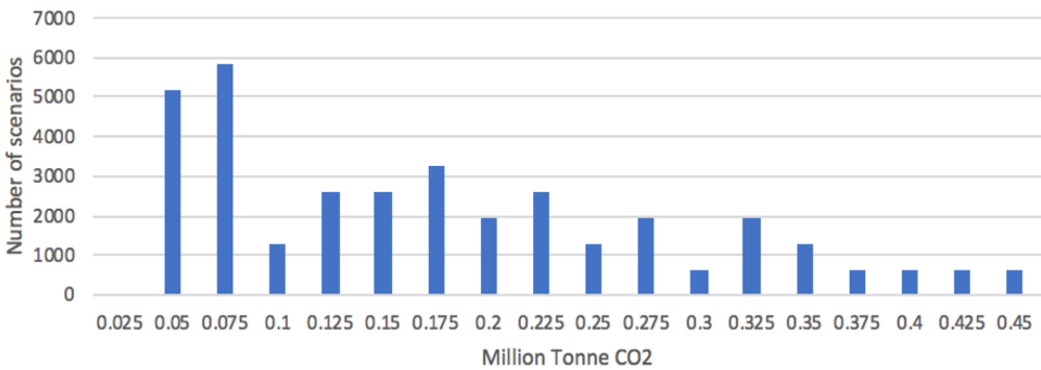


Figure 5-3: Distribution of CO2 abatement [54].

5.4 Hydrogen Production – Recommendation for Irish Market 'Push and Pull'

With reference from the H21 Leeds Citi Gate study [49, p. 349] discussed in Section 4.2.3, in order to start the decarbonisation of heat or other utilities including transport through hydrogen conversion the only viable way is to produce the large amounts of hydrogen required. However, as the rollout of the hydrogen economy grows there will be other options that could become available. It is recommended that the following market-push and -pull action plan is taken:

Market-push:

- A significant barrier to a hydrogen economy is mass hydrogen availability at point of use [49]. In order to address this issue, government policy intervention is required.
- Government policy and incentives for utilities to transition to hydrogen are simultaneously required. That would effectively 'push' the energy market towards a hydrogen conversion.
- Once this initial push has been generated, it could then be managed and funded through regulatory business plans. There could be a retrospective market pull across the hydrogen supply chain as certainty of a hydrogen economy would have been established.

Market-pull:

- Once a definite move towards a hydrogen economy is established, it would inevitably create a retrospective market pull both nationally and globally.
- This market pull is likely to affect all ends of the hydrogen supply chain including hydrogen production and hydrogen utilisation technologies those would include anything and everything that can be fuelled via hydrogen.

EirGrid, the transmission system operator for Ireland, is aware that hydrogen could act as a long term store of "electricity", that other uses for hydrogen exist including heat and transport energy, and that trials for this technology are taking place in other countries [60, p. 58]. Recognising the 'market push effect', it is important to include hydrogen in the scenarios of Ireland's future energy and government policy.

6 Conclusion

The following points have been drawn from this report:

- Hydrogen is a highly promising solution in Ireland for addressing (i) intermittency of wind and renewable energy resources, (ii) high dependence of electricity generation on imported natural gas, (iii) weak electricity grids and the challenges in their expansion, and (iv) decarbonisation of the entire energy sector.
- There are existing applications such as Hyundai's ix35 Fuel Cell, ENGIE's alternative multi-fuel station, and the German Coradia iLint hydrogen train. These and the viability of scale hydrogen systems in The Northern Netherlands, and in Leeds City are potential models for Ireland.
- There are potential large markets for hydrogen in transport and other sectors in Ireland.
- Actions to accomplish the market push and pull effects need to be taken as the first priority by both market stakeholders and regulatory bodies. Hydrogen needs to be included in the scenarios of Ireland's future energy and government policy as the 'market push effect'. A revised version of this report needs to be published and disseminated to relevant organisations.

Appendix A: Sectorial energy consumption in Ireland

Table A-1: Sectorial energy consumption in Ireland (2005 – 2017, Units: ktoe, NRW = Non Renewable Waste, R = Renewable, E = Electricity) [54].

FUEL	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Transport													
Coal	0	0	0	0	0	0	0	0	0	0	0	0	0
Peat	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil	5076	5428	5689	5384	4782	4501	4321	4084	4242	4402	4651	4825	4685
Gas	0	0	0	0	0	0	0	0	0	0	0	0	0
R	1	3	22	56	77	93	98	85	102	116	128	118	148
E	5	5	4	5	4	4	4	4	4	3	4	4	5
Heat	0	0	0	0	0	0	0	0	0	0	0	0	0
NRW	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry													
Coal	212	183	186	165	112	113	98	97	82	107	106	110	102
Peat	0	0	1	1	1	0	0	1	1	1	1	1	0
Oil	1,136	1,024	1,007	998	765	757	576	514	545	478	464	484	302
Gas	462	527	518	514	430	446	574	626	621	685	767	762	1064
R	163	164	153	139	140	152	142	135	141	171	179	173	176
E	660	773	729	686	740	783	816	788	799	808	847	872	895
Heat	0	0	0	0	0	0	0	0	0	0	0	0	0
NRW	0	0	0	0	13	9	14	27	39	42	44	42	37
Residential													
Coal	246	219	208	230	267	254	230	242	273	219	206	179	195
Peat	273	284	271	280	272	254	241	215	218	200	201	197	195
Oil	1145	1116	1101	1197	1173	1263	1035	910	917	857	956	1005	920
Gas	607	632	593	669	625	710	569	600	606	536	555	563	638
R	23	27	38	41	50	54	53	61	64	65	76	83	82
E	646	695	693	733	699	735	712	698	684	663	678	677	705
Heat	0	0	0	0	0	0	0	0	0	0	0	0	0

NRW	0	0	0	0	0	0	0	0	0	0	0	0	0
Commercial/ Public Service													
Coal	27	27	27	27	0	0	0	0	0	0	0	0	0
Peat	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil	511	461	452	500	411	394	387	360	304	251	243	247	253
Gas	299	308	350	384	412	440	366	401	407	401	399	461	421
R	4	8	13	20	23	21	26	31	38	44	36	51	59
E	728	699	749	822	683	616	559	540	547	554	580	598	726
Heat	0	0	0	0	0	0	0	0	0	0	0	0	0
NRW	0	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture													
Oil	281	269	256	277	235	222	213	203	176	157	152	159	N/A
E	55	53	48	48	48	48	48	48	48	48	48	48	51
Fisheries													
Oil	47	42	39	33	31	25	20	23	25	24	21	19	**N/A**

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