Hydrogen Supply Programme

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H2H Feasibility Report

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Executive Summary

This report provides a summary of the feasibility assessment carried out on the viability of low carbon hydrogen production by electrolysis using nuclear generated electricity at the Heysham nuclear power station.

The Hydrogen to Heysham (H2H) project seeks to demonstrate a path to bulk low carbon hydrogen supply, supporting the UK Government's commitment to net zero carbon emissions by 2050. The Phase 1 feasibility study involved EDF Energy working in collaboration with Hynamics, Lancaster University, EIFER and Atkins to implement a solution for low carbon bulk hydrogen supply for industry, power, transport and gas injection. EDF Group sees hydrogen as an integral part of its 2030 strategy, and the H2H project presents a novel approach in the production of low carbon hydrogen by connecting an electrolyser system directly to the Heysham nuclear power plant to produce hydrogen from low carbon baseload electricity.

In the feasibility study, a concept design was carried out for a 2MW electrolyser system (1 x 1MW Alkaline and 1 x 1MW PEM) capable of producing up to 800kg of hydrogen per day. The project presents a unique opportunity to study the similarities and differences in operational parameters of Alkaline and PEM electrolysers. The H2H project also assess the use of the by-product oxygen from the H2H project, for on-site use at the Heysham power stations or any further applications. In addition to the local environmental benefits of the use of low carbon hydrogen, the H2H project could also attract investment into the Lancashire area. By creating a small nucleus of first adopters in the Lancashire region, the project aims to achieve a critical mass that could open up other local and regional hydrogen supply markets.

The feasibility study and integrated concept design work undertaken confirmed the technical feasibility of the production of hydrogen coupled with nuclear generation and that it meets the relevant nuclear safety and industrial regulatory requirements (including health and safety and air quality). The innovative approach of this system enables production of low carbon hydrogen with flexible supply for various applications.

Over a 20-year lifetime of the H2H project, assuming a wholesale electricity price of £63/MWh, the levelised cost of hydrogen (LCOH) calculated was £6.73 – £8.60/kg. This range captures the uncertainty in construction cost estimates. Having a significant demand of oxygen at the Heysham nuclear power stations means that the sale of the by-product oxygen from the H2H plant can be used to offset the LCOH. In terms of carbon emissions, the H2H project will have a carbon footprint of 24 gCO_2/kWh H2, compared to 509 gCO_2/kWh H2 for an equivalent grid-connected project.

Finally, the system could be scaled up at other nuclear power stations to meet the future demand for low carbon hydrogen and supports a flexible electricity system and the UK ambition for net zero. The replication of the H2H solution at other EDF nuclear power stations across the UK to produce ~220,000 kg of hydrogen per day by 2035 would require a total electrolyser capacity of about 550MW.

1 Introduction

EDF Energy has an existing network of eight operational nuclear power stations across the UK, with one in construction (Hinkley Point C) and another in development (Sizewell C). As the largest producer of low-carbon electricity in the UK, EDF Energy provides 23% of the country's electricity and is closely involved in the local development of the regions in which it operates. EDF Group sees hydrogen as an integral part of its CAP 2030 strategy[1], with the goal of offering electrolytic hydrogen production solutions to industries and the transportation sector. With the launch of its hydrogen subsidiary Hynamics[2] in 2019, EDF has indicated its ambition to become a key industrial stakeholder in this field. As such, EDF proposes the Hydrogen to Heysham (H2H) project, an innovative approach in the production of hydrogen using low carbon nuclear generated electricity to produce low carbon hydrogen by water electrolysis at the Heysham nuclear power station, with the possibility of replication and scaling up at other nuclear sites across the UK.

Given the fact that, the majority of hydrogen production at present is based on Steam Methane Reforming (SMR) of natural gas or partial oil oxidation, resulting in carbon emissions (even with carbon capture and storage)[3], the H2H approach offers a reliable, sustainable, low carbon solution to this problem. The H2H project presents a path to bulk hydrogen supply that is free of the use of fossil fuels, supporting the UK Government's commitment to net zero carbon emissions by 2050. Using low carbon baseload electricity from nuclear means that low carbon hydrogen can be produced in bulk due to a relatively high electrolyser utilisation factor, supporting the business case. The H2H project will also assess the use of the by-product oxygen from the electrolysis process, for on-site use at the Heysham Nuclear Power Stations or any further applications.

The H2H feasibility study was undertaken by a consortium of EDF Energy and Lancaster University, with support from Hynamics, Atkins and the European Institute for Energy Research (EIFER). The feasibility study included:

- An assessment of the market size for low carbon hydrogen;
- Options appraisal and engineering design at Heysham Nuclear Power Stations;
- Process risk assessment; and
- Development plan for the solution.

The outcome of the feasibility study confirmed that the H2H project is technically feasible. This report discusses and presents the results of the feasibility assessment carried out by the consortium. Section 2 describes the project and the hydrogen market assessment. The concept design of the hydrogen supply solution is presented in Section 3 and the main outcomes of the feasibility study are featured in Section 4. Sections 5 highlights the local hydrogen market in the Lancashire region, and section 6 outlines a development plan for the replication and scaling up of the hydrogen supply solution.

[1] https://www.edf.fr/en/the-edf-group/who-we-are/strategy-cap-2030
[2] https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/edf-launches-hynamics-a-subsidiary-to-produce-and-market-low-carbon-hydrogen
[3] CCC (2018) Hydrogen in a low-carbon economy. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf

2 Project Rationale

A strong consortium of partners with a wide range of skills and expertise in hydrogen, energy innovation projects, project management and business development were put together for this project. This included:

- From the EDF Group:
  - EDF Energy R&D UK Centre
  - EDF Energy Nuclear Generation
  - Hynamics
  - European Institute for Energy Research (EIFER)
- Atkins
- Lancaster University

2.1 Global, European & UK Hydrogen Market Overview

2.1.1 Market Background

The current global hydrogen industry is in a transition process, from where the carbon intensity of production has historically not been a consideration, to where carbon intensity is one of the two key focus points, with the second being the economics of production. The carbon intensity focus is such that the stakeholders in the hydrogen market have created and somewhat adopted an informal hierarchy (Table 1). There is no single point of origin of this and no academic paper to reference and as such no legally agreed-upon definitions on what is and what is not covered by this.

Colour	Production Route	Notes
Green	Hydrogen which is produced from renewable energy	In California this includes hydrogen from biomass; and Nuclear is not included in this, or any colours in the current hierarchy.[4]
Blue	Hydrogen production from Fossil Fuels with subsequent carbon capture and storage of the CO_2 emissions associated with production (CCS)	Primarily this is purported to be from natural gas with carbon capture and storage (CCS); First such project likely to go live in 2020; Coal and oil are very rarely included; and Measurement of CO_2 captured is not accurate.
Grey	Hydrogen Production from Fossil Fuels with no carbon abatement	Sometimes referred to as grey or black hydrogen; Waste / by-product hydrogen also included in this; and Mainly SMR: 1kg of H2 produced unleashes 10kg of CO_2.

Table 1 Hydrogen Hierarchy

[4] As there is no legally agreed definition of what each colour covers it could be argued that nuclear is neither excluded or included. Most reports state that green hydrogen is hydrogen produced using water electrolysis of renewable energy. In other words, there are no explicit descriptions of this exclusion.

The current hydrogen market operates as a hypothetical molecule "pool", where hydrogen is produced and stored at a virtual depot, for delivery to the end user. As a consumer of hydrogen, there is no differentiator between the type of hydrogen purchased, e.g.: blue, green or grey hydrogen. Any low carbon hydrogen which is not consumed at the point of production is not traceable through the system and is 'lost' in the pool.

The current market is likely to improve if changes are implemented to the current paperwork and agreements are created. This would allow hydrogen molecules to be traced through the production process; and therefore, could result in an increase in consumers requesting hydrogen by the carbon intensity of the production process. This would allow carbon accounting of the supply chain and potentially trading of excess carbon permits. The first step in providing the platform for this market to be created is the creation and adoption of agreed-upon definitions of what type of hydrogen is what.

At present, green hydrogen is seen by most as renewable sourced produced hydrogen. This is different from saying a zero-carbon or low carbon production process of hydrogen.

Evidence from previous conference presentations suggests that most people in the industry understand blue hydrogen as Steam Methane Reforming (SMR) with CCS, which comes with a carbon reduction of approximately 60% under that which is achieved without any level of capture and sequestration. This number is derived from partial capture of CO_2 emissions, focusing on the CO_2 produced in the chemical reactions and not that produced from combustion of hydrocarbon fuel. Capture of the former can be achieved at lower capital investment (CAPEX) and operating cost (OPEX) than the latter.

A 90% reduction is technically achievable, which would be deemed 'low carbon'. In other words, with enhanced capture from the flue gases at the SMR plant, it is possible to remove, and sequester, 90% of all carbon from the hydrogen production process. In the UK and other European countries, where governments which are looking at deep decarbonisation targets, accepting a 60% reduction with the tag "low carbon" is unlikely to gain political traction, and / or financial incentive. A minimum carbon capture rate of 90% for blue hydrogen production will be required.

Government buy-in to low carbon hydrogen is essential with some form of financial incentive to enhance end users to switch from fossil fuel to the use of low carbon hydrogen, resulting in a need for certification of the carbon intensity of the hydrogen production method.

Producing hydrogen from electrolysis of water has significant carbon benefits over other forms of production (Figure 1), as seen from the global warming potential from production, manufacturing and decommissioning of various conversion technologies (Wulf & Kaltschmitt, 2018).

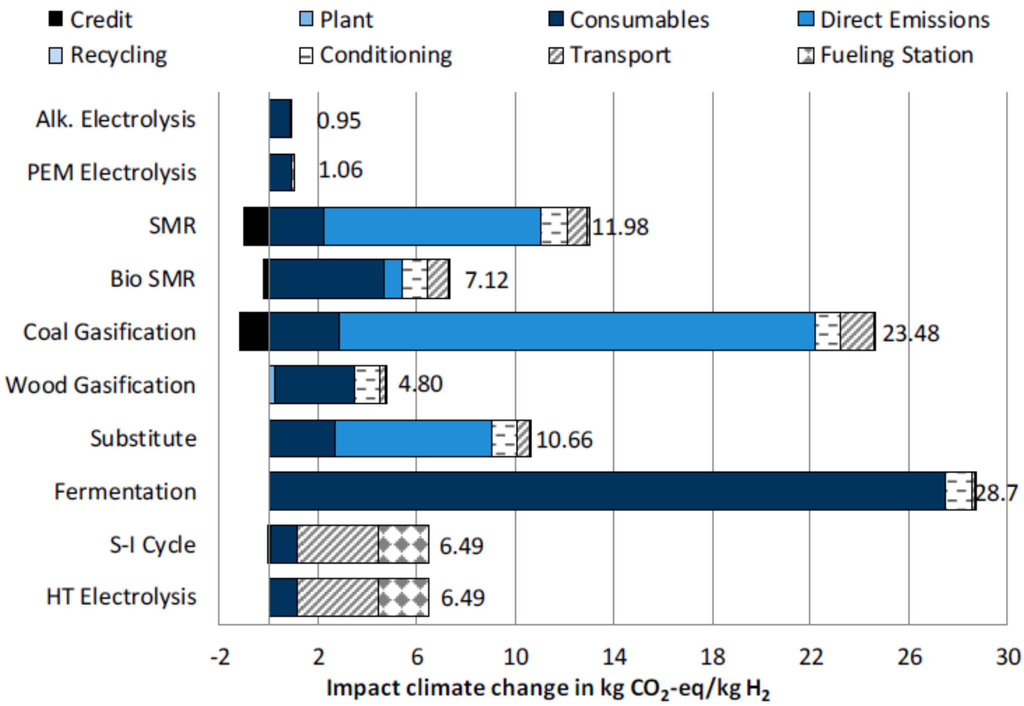

Figure 1 Impact of Hydrogen Supply on Climate change

2.1.2 Global Consumption Breakdown

For reference, at present, hydrogen in vehicles use is less than 2% of the global market. Whilst some of the markets, including polymers, glass, and fats, are fairly stable markets, with limited growth potential, forecasting shows that overall hydrogen use, in refining and vehicles, will experience significant overall growth in the coming two decades. It is forecasted that this is the start of an increased use in the iron and steel production process, although this overall rate of increase will be shallower than for refining and vehicles.

As the merchant hydrogen market is not an openly traded commodity, has no futures price and has open book price, the price, as opposed to production cost, is somewhat flexible, with several market and non-market factors being taken into account when the prices are created. This is slowly starting to change, primarily due to the emergence of the electrolytic hydrogen market, with a different set of stakeholders, dynamics and drivers. It should be noted that the water electrolysis market currently represents less than 1% of global demand and, whilst companies such as Siemens and ThyssenKrupp are marketing designs of 20 MW+ electrolysers, these are still only schematics.

Waste hydrogen / by product hydrogen is hydrogen produced from a process which it is not used in the process or captured as a value-add product. The best known of these is in chlor-alkali plants, where hydrogen is created as a by-product of the manufacturing of chemicals such as chlorine. The electrolysis process to make sodium chlorate is analogous to chlor-alkali and by-product hydrogen gas is also produced.

By 2030, the European hydrogen demand market is projected to reach 116 billion Nm^3 per annum, covering usage in industry, transport and buildings. This is from demand (production & waste) in 2018 of 75 billion

Nm³. (Advisian, 2019) For reference, if all of this demand was to be met by electrolysers this would require an installed base of 13 GWs of electrolysers in 2018 and increase to 20 GWs by 2030.

Within this period and throughout the forecast period, demand from industry, including refineries, ammonia production, methanol production, etc., represents the majority of market demand. Towards the end of the forecast period and predicated on interest in the UK into using the gas grid as a hydrogen carrier, there is an increase in the use of hydrogen in buildings. This is linked hand in hand with hydrogen for heat. Transport demand covers all uses of hydrogen in transport within territorial waters, so includes usage from river vessels, as well as short-range ferries, say from Oban and the Isle of Mull. It does not cover longer-range marine vessels. The forecast does not cover the "Power-to-X" market. Power to X represents a vector, not end-use. So, for example, Power to Transport demand is captured in the transport number and Power to Heat in the buildings number.

2.1.3 UK Emerging Markets for Compressed Hydrogen

Due to the long-term supply agreements in place, most companies producing hydrogen, independent of colour, are seeing the new market entrants as potential business growth engines. On one hand for the electrolyser industry, which is still very much in its infancy, this relatively low demand works well. New orders are followed by capital investment to allow increased manufacturing, which in return allows an expansion of business development efforts, which secures more orders. For the larger traditional suppliers, these new markets are currently seen more as marketing efforts but, without exception, all the current industrial gas companies are clear that they are looking to control supply and demand in these new sectors. Figure 2 illustrates these new markets for hydrogen.

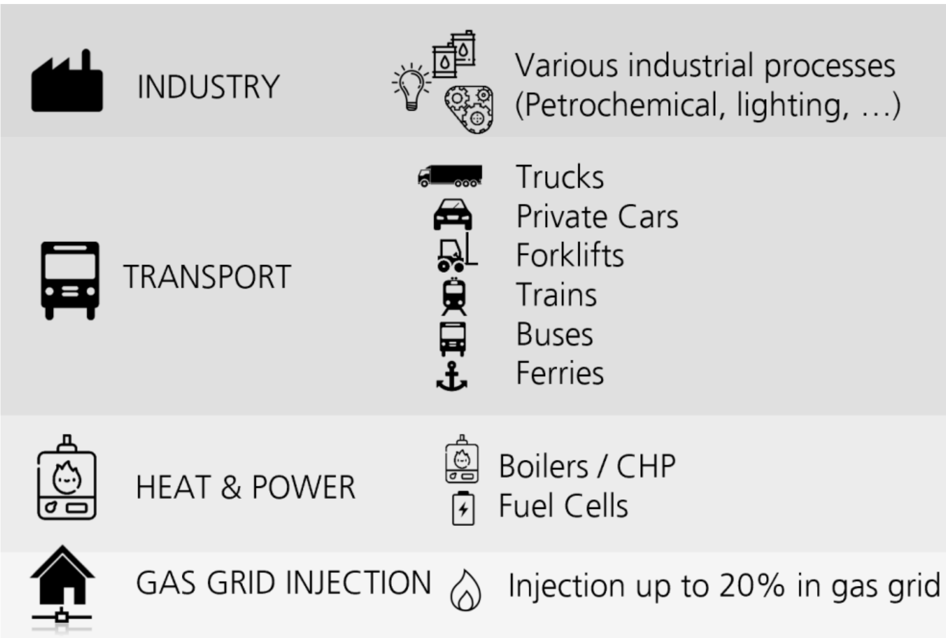

Figure 2 Emerging markets for low carbon hydrogen

2.1.4 Hydrogen Pricing

There is no open book price for hydrogen; the price is not created by an open equation which can be reported. It is hidden inside confidential long term supply deals. Outside of vehicle refuelling, any public price will include delivery, and these costs are also controlled by the hydrogen production companies.

The publicly available data is from HRS's and industrial gas price lists, which both include a mark-up, profit, and in the case of industrial gas price lists, the costs of the storage cylinders. The breakdown between cylinder cost and hydrogen cost is not provided by the sellers.

In a UK refuelling station, pump price hydrogen currently varies from £9.99 per kg to £12 per kg of hydrogen, which equates to between £0.83 per Nm^3 to £1 per Nm^3.This is a mix of onsite generation through electrolysis and hydrogen being brought to the site.

BOC Hydrogen Genie, which contains 424 g of hydrogen, costs £56.65 (BOC, 2019), but includes the price of the cylinder and a delivery cost per cylinder of £59.95, which also needs to be taken into account. The derivation of how these costs are created is not known and other prices are negotiated in confidential agreements, which are not disclosed to the market.

2.2 Innovation

Current state-of-the-art electrolytic hydrogen supply solutions can source electricity from either renewable energy sources (low carbon emissions), or the grid (relatively high carbon emissions). In the H2H project, coupling hydrogen electrolysis to low carbon nuclear electricity generation, introduces a number of innovative approaches to the hydrogen production and supply market. These include:

1. Direct connection of electrolysers to low carbon baseload electricity;
2. Operation of both Alkaline and PEM electrolysers at the same site;
3. Valorisation of the by-product oxygen; and
4. Carbon emissions savings.

2.2.1 Direct connection of electrolysers to low carbon baseload electricity

The H2H project will follow an innovative approach, by directly connecting an electrolyser system to Heysham 2 Nuclear Power Station (HYB) through a private wire, producing hydrogen using low carbon baseload, pre grid electricity. The majority of hydrogen production, at present, is produced by steam methane reforming of natural gas or partial oil oxidation, resulting in carbon emissions. This uses fossil fuels and requires CCS to be low carbon but cannot get to zero carbon due to the current incomplete capture of CO_2 in the production process. Other hydrogen production methods avoid these carbon emissions through the use of renewable energy sources, such as wind and solar, in combination with electrolysers to produce low-carbon hydrogen. The use of a baseload generation technology like nuclear power in the H2H project ensures a stable and consistent supply of low carbon electricity to the electrolysers.

The H2H project will use electricity from HYB's reactors, which are a low carbon and baseload generation technology. The feasibility study determined that by allowing for 3% losses in load factor for planned unavailability and 4% for unplanned availability, the H2H Project can achieve a utilisation factor of 93% per year, when it is at full production.

2.2.2 Operation of both Alkaline and PEM electrolysers at the same site

A key innovative feature of the H2H project (as will be described in Section 3) is that hydrogen will be generated from the two main electrolyser technologies currently available on the market, Alkaline and PEM electrolysers. Research to date suggests there is currently no other hydrogen production plant in the UK that utilises both technologies at the same time on an existing site, producing hydrogen in a complementary and collaborative manner to serve various end users. In the integrated concept design for H2H, the two electrolysers have their hydrogen outlet streams interconnected to provide some redundancy to the installation.

This increases the reliability of the hydrogen supply and presents a unique opportunity to study the similarities and differences in operational parameters of Alkaline and PEM electrolysers at the same site. There will be an opportunity to run and test a number of specific scenarios on the operation of the electrolysers under different constraints. Alkaline is the most mature and cheapest electrolyser technology, however, it has a relatively slower response time (~10 minutes) and lower flexibility. With faster response times (~1 second – 5 mins) and a wider operating range (0 – 160% of its nominal load capacity), a PEM electrolyser is more adapted to a fluctuating demand.

The electrolysers will benefit from a stable electricity supply, offering particularly good operating conditions for Alkaline electrolysers, due to the need to maintain ~20% of its nominal load capacity. The hydrogen end users of the H2H project are likely to have different and fluctuating needs and demands, in particular as it is intended to feed an HRS. In this context, the PEM electrolyser may offer a significant advantage in terms of operational flexibility.

2.2.3 Valorisation of the by-product oxygen

For most low carbon hydrogen production projects using electrolysers, the by-product oxygen of the electrolysis process is vented. The H2H project will not only produce low carbon hydrogen but also proposes to leverage the by-product oxygen as a source of low carbon high purity oxygen. Oxygen is already used safely at both Heysham 1 (HYA) and Heysham 2 (HYB) for the reformation of CO_2 in the nuclear reactors.

HYA and HYB combined consumed a significant amount of oxygen over the past year. The H2H project will capture the oxygen and leverage the revenue from the sale of the oxygen onsite to offset the levelised cost of hydrogen (LCOH). The H2H demonstrator will validate the findings of the feasibility study that the oxygen produced can be used in industrial applications to reduce the cost of hydrogen production.

2.2.4 Carbon Emissions Savings

The majority of hydrogen consumed globally is sourced and produced from hydrocarbons, through the steam methane reforming which has a carbon footprint of 300 gCO_2/kWh H2[5]. Even through the carbon capture process, steam methane reforming has a carbon footprint of 45 – 120 gCO_2/kWh H2[6]. There are no direct CO_2 emissions produced from hydrogen production using electrolysis; however, there may be indirect emissions from the input electricity. At current UK electricity grid intensities, a grid connected electrolyser could see emissions of about 255 gCO_2/kWhe[7]. In the H2H project, both electrolysers will be directly powered

[5] UK Houses of Parliament POST and UK Houses of Parliament (2017) 'Decarbonising the Gas Network', Postnote, (565), pp. 1–6.
[6] CCC (2018) Hydrogen in a low-carbon economy. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf.
[7] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019

by nuclear power (HYB), which typically has a life cycle emission of 12 gCO_2/kWhe[8]. The innovative nuclear-electrolyser hydrogen solution that is being proposed, has more carbon saving potential than current grid connected electrolyser systems. The H2H project will have a carbon footprint of 24 gCO_2/kWh H2 compared to 509 gCO_2/kWh H2 for an equivalent grid-connected project.

Hinkley Point C (HPC) is forecasted to have a life cycle emission of 5 gCO_2/kWhe[9]. Hence the replication and scaling up of the H2H project at HPC, could have more carbon savings potential than some renewables-electrolyser projects.

[8] IPCC 5th assessment report, median values from Annex III, Table A.III.2 (https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf)
[9] Based on Hinkley Point C DCO planning application

3 Hydrogen Supply Solution

The design process for the H2H project involved a review of potential site location options and the appropriate technology options for the hydrogen production equipment. This was followed by a basis of design and the shortlisting of potential technology suppliers. A conceptual integrated design was completed based on system design decisions, which included safety, innovation, environment, performance, interfaces, security, cost and delivery. This section of the report presents the details of the concept engineering design of the H2H project.

3.1 Initial System Design

3.1.1 Hydrogen production system

The design and layout of the hydrogen production system evolved through an iterative design process. A review of technology options for the hydrogen production systems, coupled with the integrated system design criteria led to Alkaline and PEM electrolyser technologies being chosen for the H2H project. An Alkaline electrolyser provides the advantages of being the most mature and affordable of electrolyser technology currently available, whilst the PEM electrolyser offers a faster response time, flexible operation and is better suited to fluctuating demand.

High temperature electrolysis was also considered as part of the review of technology options. The solid oxide electrolyser cell (SOEC) is one such emerging technology which uses heat from other sources to increase the efficiency of hydrogen production significantly. The disadvantages of this technology in the context of the H2H project and low carbon hydrogen supply, is the electrolysers available are small (at hundred kWs) and prototype scale. In addition to that, heat management and pressurised operation is still viewed as complex. Until the technology in industrial applications becomes more mature, the latter factor (and associated process risk implications) was viewed as a barrier for operation at the H2H site.

The resulting concept design was of a 2MW electrolyser system (1 x 1MW Alkaline and 1 x 1MW PEM) capable of producing up to 800kg of hydrogen per day, with the capacity to capture a portion of the by-product oxygen for onsite use. The system was designed to produce low carbon hydrogen supply for multiple local applications, including in the short term, onsite use as rotor coolant for both HYA and HYB, mobility, industry, electrical power and heat, and in the longer term; gas grid injection and industrial processes. Figure 3 illustrates the basic components and features of the H2H plant.

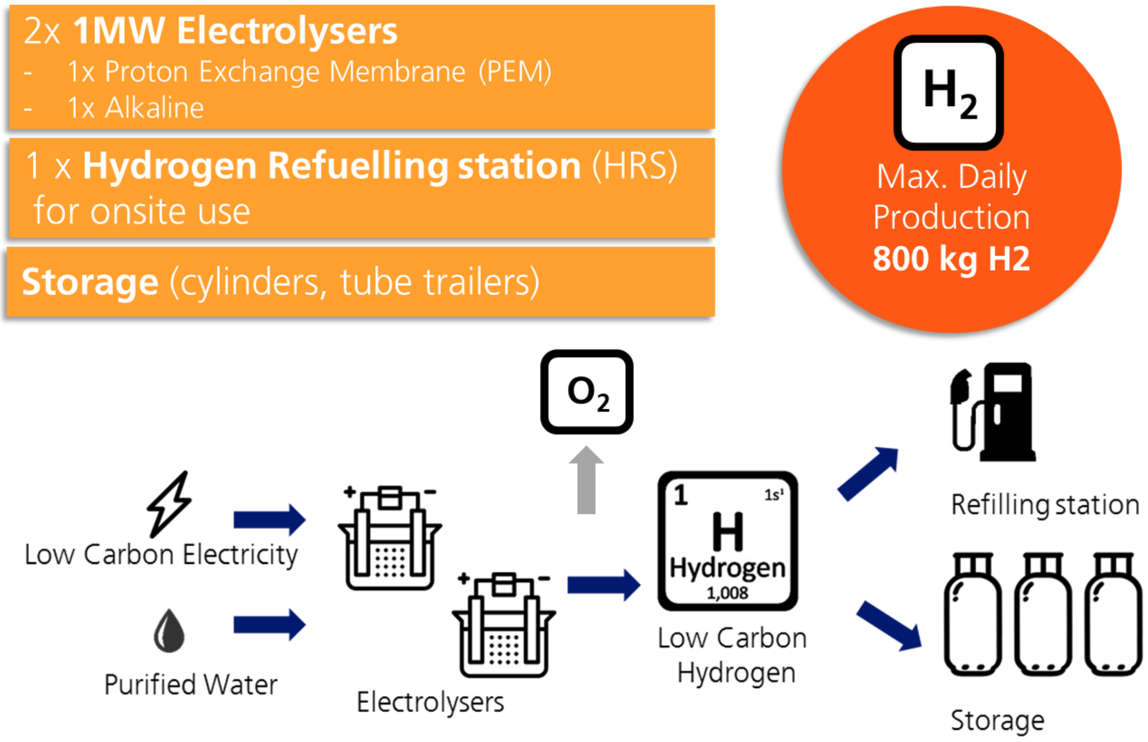

Figure 3 H2H basic components and features

3.1.2 Site Location

The site was carefully selected and is sufficiently distant from local communities and the existing HYA and HYB Nuclear Power Stations. The technical requirements considered for the site selection of the H2H site were as follows:

- Proximity to the electricity supply;
- Proximity to a consistent water supply;
- Suitable distance from the nuclear license site to reduce impact on Nuclear Safety Case;
- Suitable ground conditions for foundations and / or slab; and
- Minimum interference with environmental designations.

3.2 Risk and Regulatory requirements

As part of the feasibility assessment, a Hazard Identification (HAZID) was undertaken to consider safety and operational issues associated with the H2H project concept design. The primary objective of the HAZID study was to systematically identify significant safety, environment and health hazards resulting from the new project, operation or activity. The HAZID identified recommendations for development in detailed design and potential areas to improve the inherent safety.

3.3 Engineering Design

A summary of the technical details of the hydrogen production and distribution facility, 2MW electrolyser system (1 x 1MW Alkaline and 1 x 1MW PEM) is discussed in this section. The H2H design consists of two hydrogen production stations. Hydrogen station 1 will install the PEM electrolyser technology and Hydrogen station 2 will install the Alkaline electrolyser technology. Each of the electrolysers has a pump, cooler and chiller package to maintain its operating temperature. The electrolyser container produces hydrogen at pressure which is captured for use in the HRS. Oxygen from the PEM electrolyser is vented at a safe location to the atmosphere. Hydrogen from the PEM electrolyser is routed to a dedicated hydrogen storage drum / compressor suction drum and fed to the HRS.

Station 2 Alkaline electrolyser produces hydrogen and oxygen at pressure and both product streams are individually recovered. Oxygen is fed to a scrubber where the oxygen is washed with demineralised water to remove all impurities. The oxygen from the scrubber is then dried in a desiccant dryer. The purified and dried oxygen is routed to a compressor suction drum prior to compression and subsequent storage. Hydrogen from the Alkaline electrolyser is routed to a hydrogen storage drum / compressor suction drum and fed to the dedicated hydrogen compressor which pressurises the hydrogen to 200 barg prior to storage. Hydrogen at 200 barg is stored for rotor coolant use in Heysham power station and for offsite industrial use.

The hydrogen production and distribution facility packages include:

- Two hydrogen production stations each including an electrolyser, auxiliaries including water demineralisation, a transformer, rectifier, pump, chiller and cooler;
- Hydrogen station 1 has a PEM electrolyser;
- Hydrogen station 2 has an Alkaline electrolyser;
- A Hydrogen Refuelling Station (HRS);
- Hydrogen storage;
- A hydrogen dispenser;
- A hydrogen compressor; and
- Purification, compression and storage of oxygen from the Alkaline electrolyser.

The two electrolyser hydrogen outlet streams are interconnected to provide the ability to operate the Alkaline electrolyser lined up to the HRS if the PEM electrolyser is shutdown or the PEM electrolyser to the hydrogen compressor if the Alkaline electrolyser is shutdown. Figure 4 below show several images that capture the integrated concept design of the H2H installation at Heysham.

Figure 4 3D visualisations of the H2H installation set up

4 Results

This section of the report presents the outcomes of the feasibility study. The following sections discuss the technical feasibility of the H2H design, the estimates of the hydrogen production costs, performance parameters of the H2H solution and its potential impact in Lancashire.

4.1 Technical Feasibility

The concept engineering design process confirmed that the H2H design was technically feasible. The components of the hydrogen production system are commercial-off-the-self (COTS) equipment, that have been used in similar systems. The infrastructure requirements (towns water supply, power supply and plot area) were met by the selected site for the H2H plant.

The risks identified during the H2H design process were captured and mitigation plans were put in place. The hazard identification process determined recommendations for development in detailed engineering design stage. A construction strategy was also laid out that capture the key activities such as site preparation, excavation, drainage, enabling works and installation of equipment. By adhering to the engineering codes and the recommendations identified during the integrated concept design, the study determined that the nuclear safety case of the Heysham nuclear power stations would not be impacted by the H2H project.

4.2 Hydrogen Production Costs

This section of the report outlines the lifetime costs of the H2H project and the larger scaled up replication of the H2H solution at other EDF nuclear power stations. The use of a baseload generation technology like nuclear power ensures a stable and consistent supply of low carbon electricity to the electrolysers. The feasibility study determined that by allowing for 3% losses in load factor for planned unavailability and 4% for unplanned availability, the H2H project can achieve a load factor of 93% per year when it is at full production.

Over a 20-year lifetime of the H2H project, assuming a wholesale electricity price of £63/MWh (inclusive of averaged wholesale market price and Climate Change Levy), the levelised cost of hydrogen (LCOH) calculated was £6.73 – £8.60/kg. This range captures the uncertainty in construction cost estimates. Having a significant demand of oxygen at the Heysham nuclear power stations means that the sale of the by-product oxygen from the H2H plant can be used to offset the LCOH. The replication of the H2H solution at other EDF nuclear power stations across the UK to produce ~220,000 kg of hydrogen per day by 2035 will require a total electrolyser capacity of about 550MW.

At present the capital cost of electrolysers is one of the main factors impacting the competitiveness of electrolytic hydrogen. A study of expert view estimates that future increases in research and development funding for electrolysers could reduce capital costs by 0 – 24%, while production scale-up could have a further impact of 17 – 30% reduction[10]. In the period of time leading up to 2030, the capital cost reductions of PEM electrolysers will result in a significant reduction in difference with Alkaline. For SOECs, it is predicted that even though capital costs would have dropped, compared to Alkaline and PEM it will remain relatively high.

[10] Schmidt, O. *et al.* (2017) 'Future cost and performance of water electrolysis: An expert elicitation study', *International Journal of Hydrogen Energy*, 42(52), pp. 30470–30492. doi: 10.1016/j.ijhydene.2017.10.045.

The lower CAPEX estimates for 2035 from Element Energy's Hydrogen Supply Chain Evidence Base for Alkaline and PEM (£302.5/kW and £352/kW respectively)[11] are assumed in these calculations. The lessons learnt from the H2H project, along with the economies of scale as the electrolyser system installations across EDF Energy's nuclear sites is scaled up, will also result in cost savings in detailed engineering design and construction.

As with the H2H project, the large scale hydrogen supply solution will also leverage the by-product oxygen of the electrolysis project. The revenue generated from oxygen sale is then used to offset the hydrogen production cost.

A load factor of 93% for the electrolyser system will be demonstrated in the H2H project, and accounting for operational learnings, a load factor of 95% has been assumed for the large scale hydrogen solution due to the reduction of unplanned unavailability to 2%. By 2030, improvements in electrolyser efficiencies will translated into lower power consumption (49.3 kWh/kg and 48.9 kWh/kg for PEM and Alkaline respectively)[11]. Apart from electricity costs, the other OPEX are cost of water, equipment replacement costs, operation and maintenance (O&M) costs and carbon costs.

Table 2 shows a range of estimated LCOH values for the 2MW H2H project compared to the large scale hydrogen supply solution in 2035 at various electricity prices.

Electricity Price (£/MWh)	2MW (£/kg)	550MW (£/kg)
53	6.08 – 7.78	1.89 – 3.83
63	6.73 – 8.60	2.58 – 4.53
73	8.02 – 9.42	3.27 – 5.22
83	8.84 – 10.24	3.96 – 5.91
93	9.66 – 11.06	4.65 – 6.60
126	10.48 – 11.88	6.93 – 8.88

Table 2 Estimated levelised cost of hydrogen (LCOH) at various electricity prices

Electricity cost is the biggest contributor to the lifetime costs accounting for over half of the total costs. The sale of oxygen contributes to a £1 - 2/kg reduction in the LCOH. The results show that the LCOH in 2035 for the large scale hydrogen supply solution, is comparable to the hydrogen cost in 2040 for steam methane reforming with CCS (£1.34 – 2.25/kg).

[11] Element Energy (2018) 'Hydrogen supply chain evidence base'

4.3 Performance Parameters

4.3.1 Safety and security

For the proposed solution of connecting an electrolyser to a nuclear power station, safety and security is the most paramount performance parameter. In the engineering design of the H2H demonstrator, an Inherently Safer Design approach was adopted for the various aspects of the design; the process design, electrical, control & instrumentation (EC&I) design and the civil, structural & architectural (CS&A) design. In the EC&I design, the electrical design follows British and European standards, where required. A Welfare facility has been positioned at a suitable distance away from the hydrogen processing equipment, storage and substations in order to protect both operators and communication equipment, should an incident occur. The facility shall include well-lit paths to reduce slips, trips and falls risk; and is covered by security CCTV cameras that can be used to remotely monitor operator actions.

For security and operational efficiency reasons, the H2H project and other replicated projects will be sited outside the nuclear license area. The thorough regulatory review and process risk assessment carried out as part of the feasibility study has ensured that the design of the H2H project and other replicated projects will have been through a more detailed safety assessment compared to current state of the art hydrogen production plants.

Control of Major Accident Hazard (COMAH) regulations and the Dangerous Substances and Explosive Atmosphere Regulations (DSEAR) were reviewed. The feasibility study concluded that COMAH will not apply to the H2H project as the total hydrogen storage (1055kg) is below the 5000kg of hydrogen inventory which is the lower limit before the regulations of a lower tier COMAH site are mandatory. DSEAR is applicable to the H2H project and to address it, in the concept design the separation distances recommended by BCGA CP33 were applied to the general arrangement.

In addition to this, a hazard identification exercise was conducted as part of the concept design to highlight high level safety, environmental and health concerns. In accordance with the expectation by the Health and Safety Executive (HSE) to demonstrate that risks have been reduced by applying the principles of Inherently Safer Design at concept phase, this will be the approach adopted along with the lessons learnt from the H2H demonstrator, when considering larger replicated projects of the hydrogen solution at other EDF Energy nuclear power sites as laid out in the development plan.

4.3.2 Hydrogen production flexibility

Supplying various end users with hydrogen means production flexibility becomes an important factor. Leveraging the unique properties of both Alkaline and PEM electrolyser technologies in the H2H project, the impact of variable end user demand can be minimised. In the H2H project, the two electrolyser hydrogen outlet streams are interconnected to provide the ability to operate the Alkaline electrolyser lined up to the HRS if the PEM electrolyser is shutdown or the PEM electrolyser to the hydrogen compressor of the Alkaline electrolyser if it is shutdown. This in addition to the storage equipment ensures that there is always at least 4 weeks' worth of hydrogen supply for the nuclear power plant.

This model of interconnecting two electrolyser technologies could also be rolled out across EDF Energy's other nuclear sites as outlined in the development plan. The stability of the baseload electrical supply which offers good operating conditions for the Alkaline electrolyser, is complemented by the PEM electrolyser which, due it its wide operation range can scale up production up to 160% of its nominal load capacity in the event of an increase in demand.

The electrolyser connected to EDF Energy's nuclear stations could also be grid connected to provide grid services and load shifting. This marries the stability of constant hydrogen production with the variability and flexibility of grid services. There are synergies between hydrogen production for industry, mobility gas grid injection and grid services. In fact, gas grid injection could not only help de-risk the business case but also provide production flexibility.

4.3.3 Carbon emissions savings

Currently, a very small fraction of hydrogen demand is met by electrolytic hydrogen. The bulk of hydrogen consumed globally is sourced from hydrocarbons by the steam methane reforming which has a carbon footprint at 300 gCO_2/kWh[12]. Even with carbon capture, steam methane reforming has carbon emissions up to 120 gCO_2/kWh[13]. The carbon emissions of hydrogen produced by electrolysis are those associated with electricity source. At present UK electricity grid intensities, a grid connected electrolyser could see emissions of about 255 gCO_2/kWh[14]. Considering that in the H2H project the electrolysers are directly powered by nuclear power which typical has life cycle emissions of 12 gCO_2/kWh[15], the proposed nuclear-electrolyser hydrogen solution has more carbon emissions saving potential than current grid connected electrolyser systems. The H2H project will have a carbon footprint of 24 gCO_2/kWh H2 compared to 509 gCO_2/kWh H2 for an equivalent grid-connected project.

At maximum production capacity the H2H project can produce approximately 800 kg of hydrogen per day. Table 3 below compares the carbon emissions from the production of 800kg of hydrogen in the H2H Project with other production routes.

	Carbon Emissions (gCO_2/kWh)	Carbon Emissions ($kgCO_2$/kg H2)
Steam Methane Reforming	300	12
Steam Methane Reforming + CCS	120	5
H2H Project	24	1
UK grid + Electrolyser	509	20

Table 3 Carbon emissions from the production of 800kg of hydrogen by various supply solutions

12 UK Houses of Parliament POST and UK Houses of Parliament (2017) 'Decarbonising the Gas Network', Postnote, (565), pp. 1–6.
13 CCC (2018) Hydrogen in a low-carbon economy. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf.
14 https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019
15 IPCC 5th assessment report, median values from Annex III, Table A.III.2 (https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf)

4.3.4 Hydrogen storage and delivery

Station 1 of the H2H site will have 2 high pressure storage units of 275kg at 450bar and 130kg at 350bar within the HRS. Hydrogen storage for Station 2 entails 3 bundles of 239kg storage and 2 tube trailers of 350kg at 200bar for mobile industrial storage, which will be the interface of the hydrogen logistics system to be implemented to supply end users off-site.

The immediate logistical needs of the potential hydrogen end users can be served directly from the current hydrogen production site and there is no immediate need for developing a multi-echelon distribution network. Optimal routes for hydrogen delivery have been identified based on end user characteristics such as consumption per day, volume able to be stored on their site, distance from production and possible difficulties encountered in urban area for truck delivery.

One approach to the transport of hydrogen to end users will be to employ a logistics company with certification in the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) and expertise in the distribution of compressed gases. The cost of hydrogen distribution is estimated to be about £1/kg[16], and this value entails logistics operation only and not equipment investment. The potential for hydrogen liquefaction over the next decade is to be considered for large scale replicated hydrogen production plants within the EDF Energy network. This will enable hydrogen to be transported across UK.

4.3.5 Hydrogen quality

The hydrogen quality is differentiated by degree of purity. Hydrogen is available up to a purity grade of 7.0; this corresponds to a purity of 99.99999 %. Impurities and accompanying substances in hydrogen are dependent on the manufacturing process. In comparison to hydrocarbon-based production paths, hydrogen produced from electrolysers can be relatively easily configured to meet automotive grade hydrogen 99.999% purity levels, with the contaminants being water, nitrogen, and oxygen at the parts per million level. Steam methane reformation and gasification require multiple stages of post-production purification to achieve such purity levels, and this often results in an increase in capital and operating costs. The H2H installation has hydrogen purification units as part of both electrolyser systems which yield fuel cell grade hydrogen purities of 99.999% that comply with ISO 14687-2:2014 and SAE J2719.

4.3.6 Reliability and redundancy

The reliability of our proposed hydrogen solution is key to the acceptance by the market. The H2H project ensures the reliability and redundancy of supply in various ways. Firstly, to protect against any disruptions to the water supply and hence to the hydrogen production process, a water tank is used to ensure there is 2 days of uninterrupted water supply. Secondly, electricity sourced from 2x 3.3kV cables, with each electrolyser system being supplied by one of the cables. The electrical supply for the two 3.3kV cables is connected both nuclear reactors to ensure security of supply to the hydrogen production plant in the event of a planned or unplanned availability of one of the reactors. This concept design and the operational lessons gathered from the H2H project will be carried over into replicated projects.

[16] Cadent (2019) 'HyMotion Network-supplied hydrogen unlocks low carbon transport opportunities', (June), pp. 1–44.

4.3.7 Replicability and scalability

Achieving large scale hydrogen production across the UK will require a robust and scalable strategy. The successful construction and operation of the H2H hydrogen supply demonstrator will accelerate the development of bulk low carbon hydrogen by establishing a benchmark to be replicated at other nuclear power plants owned and operated by EDF Energy across the UK. EDF Energy's nuclear new build project, Sizewell C which is currently in development, could support the modular installation of large-scale electrolysers by taking it into consideration in the early stages of development. Hinkley Point C which is already in construction also presents the same opportunity.

The sizes of electrolysers are expected to scale up considerably within the next few years. A 10MW electrolysis plant is already underway at the Shell Rheinland refinery in Wesseling, Germany[17]. Upon completion it will be the world's largest PEM electrolyser installation. Scaling up further from that, a 100MW electrolyser plant is currently in development by electrolyser manufacturers based on the modular design of their technology.

4.4 Community Impact and Value Sharing

The Lancaster district region is very committed to decarbonisation and addressing the Paris '2 degrees Celsius' global warming target. Lancaster City Council recently declared a 'climate emergency' and are now formulating plans to work towards becoming a zero carbon district by 2030 (Climate Emergency, 2019). There is thus a strong local political drive behind developing a local hydrogen economy which would help decarbonise heat and transport in the region.

With regards to the local environment, the average carbon emissions of new the internal combustion engines (ICE) in 2016 was 117 gCO_2/km[18]. The hydrogen fuel cell vehicles produced no carbon emissions during operation when fuelled by low carbon hydrogen, and for hydrogen fuel cell vans, 1.5kg of hydrogen powers the vehicle for 100km. So, assuming 200kg of hydrogen from the H2H Demonstrator Project is used to fuel a fleet of hydrogen fuel cell vans, that would correspond to over 1,500kg of CO_2 emissions avoided in the Lancashire area, when compared to a similar fleet of ICEs.

The Lancashire area is one of the largest economies in the Northern Powerhouse, with 52,350 businesses generating added value and supporting thousands of jobs in the manufacturing and engineering sector[19]. The siting of a low carbon hydrogen plant at Heysham will be of National importance and attract a lot of attention form business's wanting to invest in the region. During the feasibility study, there was strong interest from organisations in the transport sector, gas distribution grid, port operations and manufacturing, all of whom can see local business opportunities in the hydrogen sector. In the leisure sector organisations such as Eden North and Cumbrian hotels could benefit from market opportunities surrounding the provision of low carbon transport and heating options to visitors.

The Lancaster City Council economic development team are also very excited about the opportunity to build a local centre of excellence for hydrogen technology deployment and research using the pilot plant as an

[17] https://www.itm-power.com/news-item/shell-rheinland-refinery-update
[18] EEA, Monitoring CO2 emissions from new passenger cars and vans in 2016, Report n°19/2017
[19] Lancashire Enterprise Partnership, (2018), Lancashire Enterprise Partnership Annual Report 2017/18

initial focus point. The local area has for many years hosted four nuclear reactors, however by 2035 it is expected that these will all have been taken offline. Siting a pilot Hydrogen plant at Heysham could be the start of journey to develop Heysham as nationally significant low carbon hydrogen manufacturing facility, especially if linked with the very large existing offshore wind farms (and future round 4 farms) that make landfall there. Such a development could ensure that any high skilled jobs lost as a result of the nuclear plant decommissioning plan are retained in the region.

Finally, the level of interest and cooperation shown in this pilot project by local business, academia and local government is a testament to the potential for shared value growth in the region.

5 Local Hydrogen Market

5.1 Heysham Geographical and Historical Context

Heysham is a large coastal village six miles to the west of Lancaster with excellent road, rail and sea transport connections. There are direct links the West Coast mainline railway and the M6 motorway, both of which connect London to Glasgow via the Midlands. The motorway connection was recently enhanced by a £100m link road 'Bay Gateway', connecting the Port of Heysham with the M6 at a new Park and Ride facility at Junction 34. Heysham has several international passenger and freight airports within an 80km radius, as well as sea freight links with the Isle of Man, Northern Ireland and the Republic of Ireland, through the Port of Heysham.

As shown in Figure 5 below, Heysham is centrally located in the UK. EDF's other nuclear power stations, which will be assessed for future hydrogen production are spread evenly around the coast. This good geographical spread would minimise transport and logistics costs for any scale up plans post the initial H2H Demonstrator Project.

Heysham, Lancaster and Morecambe form the 'Lancaster City Region' with a population of 138,000. The city region is the home of the University of Cumbria and Lancaster University. Lancaster University is home to world class researchers in the energy sector; both on the supply and demand side and are host to the Centre for Transport Logistics (CENTRAL), the Centre for Mobility Research (CEMORE) and the recently formed Lancaster Hydrogen Hub, a group of stakeholders aiming to develop a local hydrogen economy in the region.

The wider Lancashire area (in which Heysham is situated) is one of the largest economies in the Northern Powerhouse, with 52,350 businesses generating £29bn of Gross Value Added (GVA) and supporting over 85,000 jobs in the manufacturing and engineering sector. Lancashire is number 1 in the UK for aerospace, with over 500 supply chain companies and also has key strengths in advanced engineering and manufacturing, automotive and energy industries. (Lancashire Enterprise Partnership, 2018).

In terms of the region's commitment to decarbonisation and the Paris 2 degrees Celsius global warming agreement, Lancaster City Council recently declared a 'climate emergency' and are now formulating plans to work towards becoming a zero carbon district by 2030. There is thus a strong local political drive behind developing a local hydrogen economy which will help decarbonise heat and transport in the region.

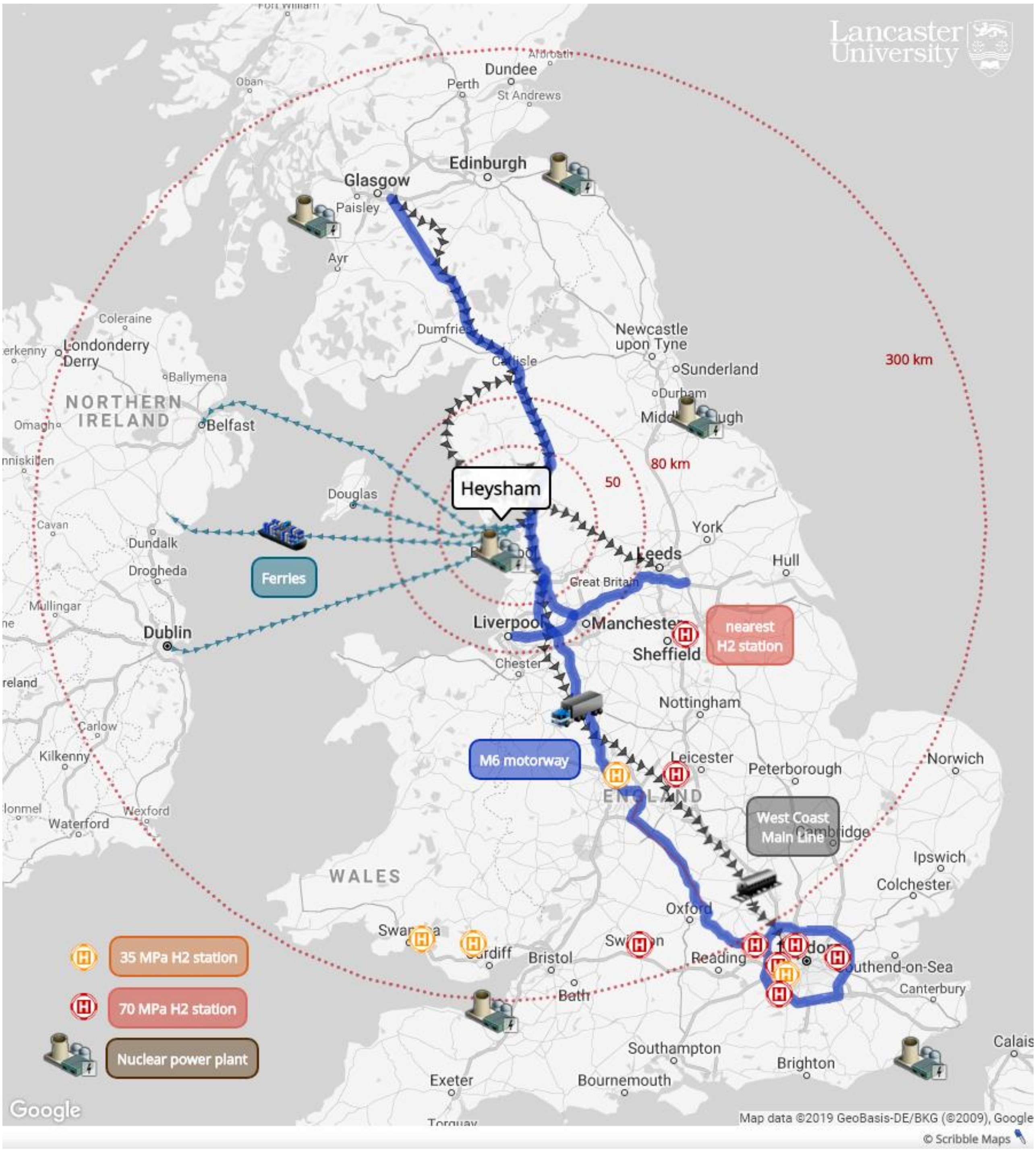

Figure 5 Heysham's connections to the UK transport network and some of the existing Hydrogen infrastructure

5.2 Heysham as a Transport Hub

The Hydrogen Council[20] and Connected Places Catapult[21] have both identified that early adaptors of hydrogen as a fuel are likely to be in the materials handling sector and the passenger bus sector, followed by HGV trucks and possibly trains (on non- electrified low speed lines). The introduction of clean air zones (Gov.UK, 2019)**,** will act as a catalyst for both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs).

Heysham is located close to Liverpool, Manchester and Leeds and would be in a strong position to supply low carbon hydrogen to any of these cities operating hydrogen vehicles. Within an 80km radius of Heysham are some of the country's largest freight distribution centres clustered around the M6, M61 and M62 motorways.

Heysham Port, owned and operated by Peel Ports, is at the heart of the Irish Sea Roll on Roll off (RoRo) ferry operations. There are six ships operating out of the port with seven daily sailings to the Isle of Man, Belfast, Warren Point and Dublin. There are fork lift trucks and tractor trailers units operating at the port which could be converted to hydrogen. Heysham port could become a focal point for early fuel cell HGV operators with easy access to the planned HRS at the adjacent H2H project site.

The Connected Places Catapult have identified opportunities for hydrogen trains on non-electrified routes with rolling stock speeds of less than 75mph. This suggest that there are several opportunities in the local area for hydrogen trains to be introduced.

In terms of passenger buses, the Lancaster district bus depot is located just off the 'Bay Gateway' about 3 miles from Heysham. The bus fleet from this depot travel a total of 3.3M miles per annum, with 32 buses operating between Lancaster town centre and the University covering 1.9M miles per annum. These 32 buses would be ideal candidates for conversion to a hydrogen fleet and would benefit the University's green transport agenda and the City Councils 'climate change emergency' strategy.

It is clear that the Heysham, Morecambe and Lancaster areas are ideally suited to the development of a nationally significant hydrogen cluster, encompassing low carbon hydrogen production from the H2H project at HYB, a world class research capability at Lancaster University and a wide range of first adopter business opportunities in the area covering industrial, power and transport (road, rail and air) opportunities. A graphical concept map of the 'Lancaster Hydrogen Hub' is shown in Figure 6.

[20] https://hydrogencouncil.com/en/
[21] https://cp.catapult.org.uk/

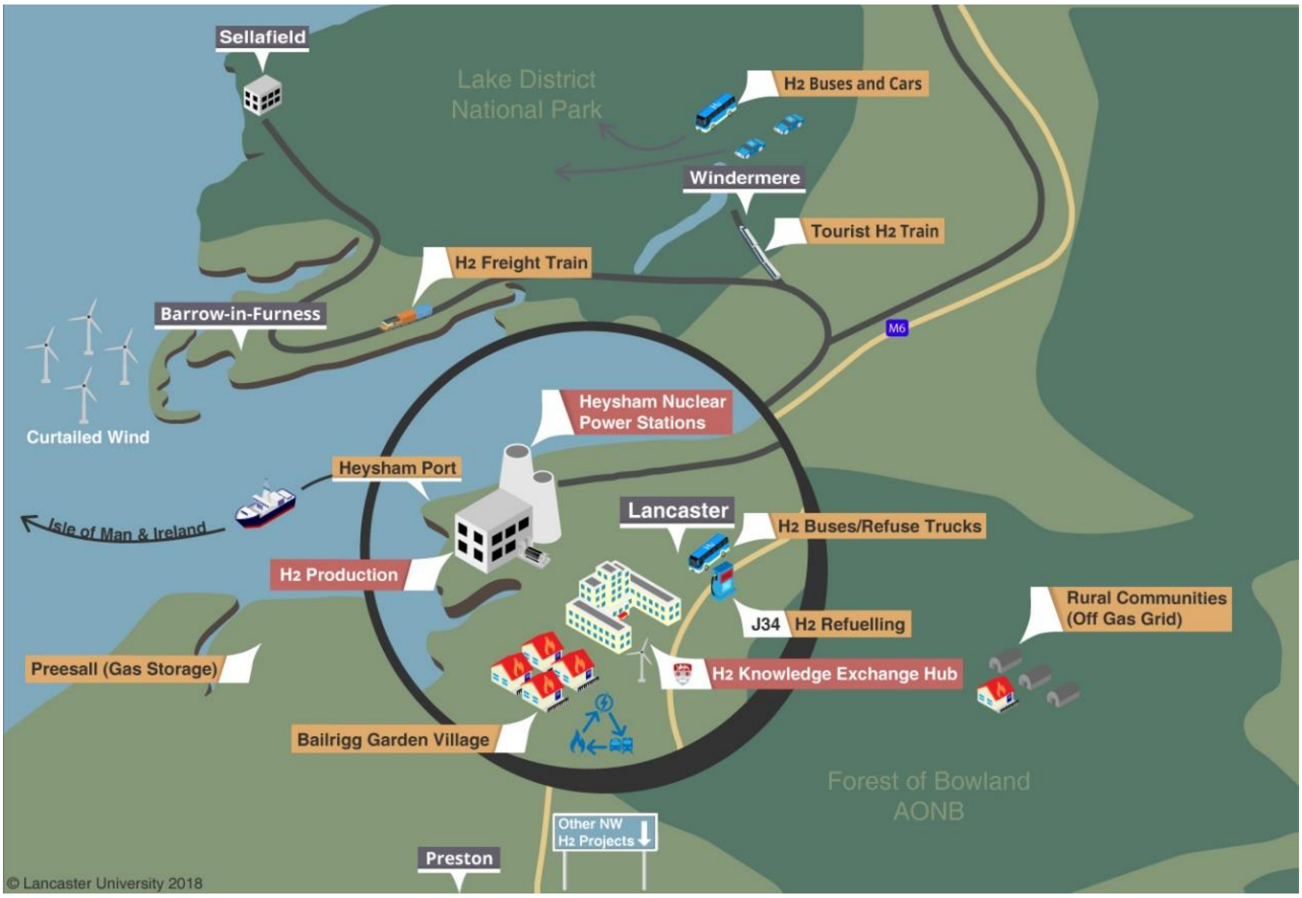

Figure 6 Lancaster and Heysham Hydrogen Hub

5.3 Social acceptance of Hydrogen

A key question is how people can be enabled to practice low carbon living with hydrogen? A survey of over 50 articles and book chapters and their key findings have been evaluated through a mixed methods approach, combining a pilot empirical study with analysis of past transitions and existing, more system-oriented studies in other areas. At a high level, the public has a lack of knowledge about hydrogen, and positivity about hydrogen is lower in the UK than in other EU countries; however, there is an appetite for genuine low carbon hydrogen.

6 Scale up and Replicability

The feasibility study confirmed that the H2H project is technically feasible and further development of this hydrogen supply solution could contribute to the UK Government's commitment to net zero carbon emissions by 2050. This section of the report discusses how the H2H project could be replicated at other EDF nuclear power stations to implement a large scale hydrogen supply solution.

The Heysham power stations as the first potential end user of H2H will benefit because it will ensure a stable and reliable supply of locally produced low carbon hydrogen and oxygen which are vital to its operation activities. A scale up of the H2H site is to be considered as the demand for hydrogen should grow within the Lancashire area.

In preparation of the decommissioning of HYA, the potential uptake of hydrogen for the local onsite logistic, as well as the rail opportunity for defueling, will be studied and evaluated during the operation phase of the H2H project. This would define if there is a need to upscale the H2H plant at Heysham. The decommissioning could benefit from the locally produced, low carbon and low cost hydrogen for the use in vans and forklifts, as well as defueling trains used in the decommissioning village, with decommissioning work commencing on site at HYA from 2024.

Lessons learned from H2H will be studied ensuring that key challenges and barriers addressed during the project can benefit further developments of low carbon hydrogen projects. A close collaboration with preferred technology suppliers will ensure this is aligned with the development of the technology, mainly stacking up the maximal capacity of electrolysers.

Beyond the benefit of low carbon electricity from nuclear generation, EDF Energy is a major developer of wind farms across the UK. The flexibility of the PEM electrolyser will be tested during the H2H project at HYB to provide experience to potentially couple the intermittent renewable energy with the PEM electrolyser. This could help flatten the intermittency of renewable sources and support the grid with ancillary services.

The longer term development plan for EDF Energy is to deploy large scale, low carbon hydrogen in the UK, which will benefit from the major infrastructure of the EDF Group, both nuclear and renewables, as well as storage capabilities. EDF Energy currently operates 33 onshore wind farms and 2 offshore wind farms in the UK, benefiting from the expertise of the whole EDF Group.

The second part of the longer term development plan is the upscaling across the UK. Nuclear new builds currently in development could ensure long term, low carbon, pre grid electricity supply to electrolyser for the next decade. The development of large scale electrolysers (20-200MW) could ensure the bulk supply of hydrogen for the local and national applications beyond 2024.

The upscale will commence with the development of 20MW electrolysers at other nuclear power stations from 2024. The design, construction, installation and commissioning will be prepared for an upgrade up to 200MW by 2030. At full generating capacity and for the full upscaling (2x 200MW), the hydrogen production plants at new nuclear builds would generate enough hydrogen to meet a significant portion of the forecasted demand in the UK.

The foreseen cost reduction of the CAPEX for the electrolyser technologies will support a more cost effective business case and enable the scaling up. Figure 7 shows the overview of the development plan bulk low carbon hydrogen supply.

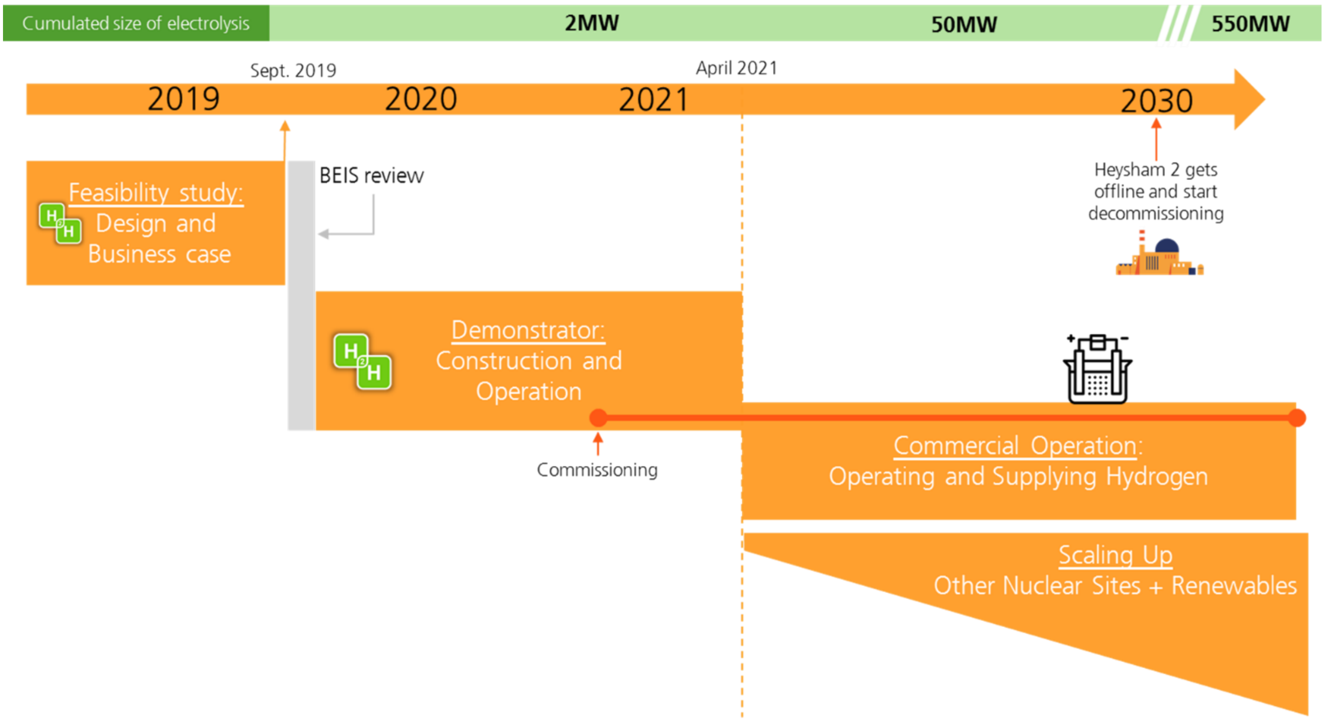

Figure 7 Overview of the development plan for bulk hydrogen supply

7 Conclusion

The Hydrogen to Heysham (H2H) project seeks to demonstrate a path to bulk low carbon hydrogen supply, supporting the UK Government's commitment to net zero carbon emissions by 2050. The Phase 1 feasibility study involved EDF Energy working in collaboration with Hynamics, Lancaster University, EIFER and Atkins to implement a solution for low carbon bulk hydrogen supply for industry, power, transport and gas injection. EDF Group sees hydrogen as an integral part of its 2030 strategy, and the H2H project presents a novel approach in the production of low carbon hydrogen by connecting an electrolyser system directly to the Heysham nuclear power plant to produce hydrogen from low carbon baseload electricity.

In feasibility study, a concept design was carried out for a 2MW electrolyser system (1 x 1MW Alkaline and 1 x 1MW PEM) capable of producing up to 800kg of hydrogen per day. The project presents a unique opportunity to study the similarities and differences in operational parameters of Alkaline and PEM electrolysers. The H2H project will also assess the use of the by-product oxygen from the H2H project, for on-site use at the Heysham power stations or any further applications. In addition to the local environmental benefits of the use of low carbon hydrogen, the H2H project could also attract investment into the Lancashire area. By creating a small nucleus of first adopters in the Lancashire region, the project aims to achieve a critical mass that could open up other local and regional hydrogen supply markets.

The feasibility study and integrated concept design work undertaken confirmed the technical feasibility of the production of hydrogen coupled with nuclear generation and that it meets the relevant nuclear safety and industrial regulatory requirements (including health and safety and air quality). The innovative approach of this system enables production of low carbon hydrogen with flexible supply for various applications. The system could be scaled up at other nuclear power stations to meet the future demand for low carbon hydrogen and supports a flexible electricity system and UK ambition for net zero.

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