GIGASTACK

Gigastack Phase 2: Pioneering UK Renewable Hydrogen

Public Report

Department for Business, Energy & Industrial Strategy

ITM POWER

Ørsted

PHILLIPS 66

elementenergy
an ERM Group company

Executive Summary

Gigastack is the UK's flagship renewable hydrogen project, led by a consortium of ITM Power, Ørsted, Phillips 66 Limited and Element Energy. Funded since 2019 by BEIS' Low Carbon Hydrogen Supply Competition[1], Gigastack is an ambitious multi-phase programme to prove economically viable renewable hydrogen at scale and demonstrate the full decarbonisation potential of offshore wind in the UK's largest industrial cluster.

Through Gigastack Phase 2, BEIS has funded two tracks of work to accelerate the expansion of the UK's renewable hydrogen sector by taking feasibility stage concepts through to a preliminary design for a $100MW_e$-scale electrolyser system which will use renewable power from Hornsea Two – the world's largest offshore windfarm – and provide renewable hydrogen to Phillips 66 Limited's Humber Refinery to replace refinery fuel gas within industrial-scale fired heaters:

1) Under Gigastack BEIS funding, ITM Power has progressed its next generation of electrolyser technology and production processes. Separately, ITM Power has also moved into its new Gigafactory in Bessemer Park, Sheffield, now the world's largest electrolyser production facility. These milestones represent a step-change in ambition and capacity which should enable a 40% reduction in costs for electrolyser stacks over the next three years.

2) Ørsted and Phillips 66 Limited have (i) developed the technical design for an industry-scale renewable hydrogen facility in Immingham, (ii) explored the current policy and regulatory landscape, (iii) identified barriers to developing industrial-scale renewable hydrogen production facilities, with potential solutions identified and (iv) developed a business case to map a pathway to an investable proposition. The levelised cost of hydrogen (LCOH) was calculated at £7.93/kgH_2 in the base case and between £5.11-5.44/kgH_2 in the low-cost case for this first-of-a-kind project. Gigastack will help to realise further cost reductions over the coming decade, with costs estimated to fall by around 47% to £2.80/kgH_2 by 2030 for N^{th}-of-a-kind deployments.

As a result of this funding, the Gigastack consortium has identified a pathway to a final investment decision by Q2 2023 and a commercial operating date by the end of 2025, subject to a supportive policy environment. Gigastack will support the decarbonisation

1 BEIS, Low Carbon Hydrogen Supply Competition, 2020

of the Humber region for sectors in which emissions cannot be reduced through direct electrification. Specifically, renewable hydrogen from the Gigastack facility will directly replace hydrocarbon-based fuels currently used in the Phillips 66 Limited Humber Refinery's industrial scale fired heaters. Renewable hydrogen is a key part of the industrial decarbonisation steps identified by Phillips 66 Limited at the Humber Refinery, under its "Refinery of the Future[2]" strategy. Subsequent expansion phases could then decarbonise other areas of the Humber Refinery, such as production of speciality graphite coke for electric vehicle batteries, as well as other sectors in the Humber region.

The Gigastack programme will send a strong signal to the UK manufacturing supply chain, stimulate UK-based jobs and act as a catalyst to the UK Government's ambition to deliver jobs and growth in order to 'build back better' in the recovery from the COVID-19 pandemic. Gigastack has already helped create more than 100 jobs at ITM Power's Gigafactory and this initial $100MW_e$ is projected to create an additional 180 jobs, predominantly focussed on equipment maintenance. An expansion to $1GW_e$ by 2030 could contribute up to £2.5bn GVA and 1,700 permanent jobs to Immingham's local economy through kickstarting a local hydrogen supply chain, including one of the UK's first Gigafactories. This ambition aligns with the UK Government's (i) hydrogen production targets of $1GW_{th}$ by 2025 and $5GW_{th}$ by 2030 in the "Ten Point Plan for a Green Industrial Revolution[3]", (ii) electrolyser specific support of up to $500MW_e$ by 2024 in the "Net Zero Strategy: Build Back Greener[4]" report and (iii) "Levelling Up" agenda with investment in the Humber region.

It is vital that the UK Government sends a strong signal of support to the renewable hydrogen sector to bring forward the opportunities to create jobs and supply chain benefits to the UK, enable system integration and decarbonise the Humber. The Gigastack consortium looks forward to continuing work with the UK Government from the end of Phase 2 to (i) secure support, both operational and development, and (ii) agree binding industry specific deployment targets for renewable hydrogen.

2 UKPIA, Future Vision, 2019
3 HMG, The Ten Point Plan for a Green Industrial Revolution, 2020
4 HMG, Net Zero Strategy: Build Back Greener, 2021

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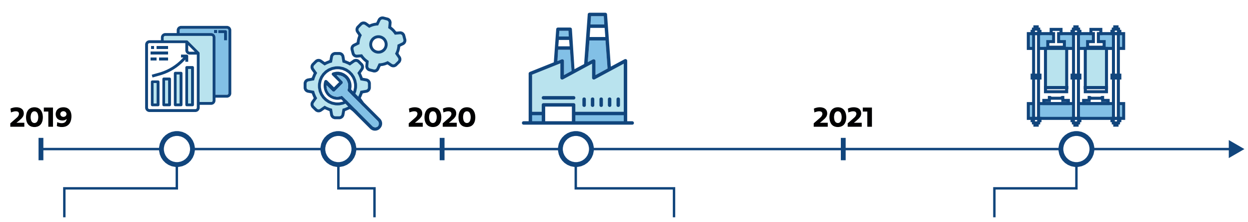
Acronyms

BEIS	Department for Business, Energy & Industrial Strategy
BSUoS	Balancing Services Use of System
CAD	Computer Aided Design
CAPEX	Capital Expenditure
CCC	Climate Change Committee
CCL	Climate Change Levy
CCUS	Carbon Capture, Utilisation and Storage
CfD	Contract for Difference
CM	Capacity Market
EC&I	Electrical Control & Instrumentation
EII	Energy Intensive Industries
FEED	Front End Engineering Design
FEL	Front End Loading
FID	Final Investment Decision
FOAK	First-of-a-Kind
GEP	Gigastack Electrolyser Platform
GVA	Gross Value Added
GW_e	Gigawatt Electrical
GW_{th}	Gigawatt Thermal
HHV	High Heating Value
HMG	Her Majesty's Government
HRS	Hydrogen Refuelling Station
ISCF	Industrial Strategy Challenge Fund
IDHRS	Industrial Decarbonisation & H_2 Revenue Support
KPI	Key Performance Indicator
kW_e	Kilowatt Electrical
LCCC	Low Carbon Contracts Company
LCOH	Levelised Cost of Hydrogen
MEP	Megastack Electrolyser Platform
MW_e	Megawatt Electrical
Ofgem	Office of Gas and Electricity Markets
OFTO	Offshore Transmission Owner
OPEX	Operational Expenditure
PEM	Polymer Electrolyte Membrane
PFD	Process Flow Diagram
P&ID	Process & Instrumentation Diagram
PPA	Power Purchase Agreement
TNUoS	Transmission Network Use of System

1 Introduction

The Gigastack project is led by a consortium comprising ITM Power, Ørsted, Phillips 66 Limited and Element Energy. Gigastack is a flagship project within the UK's decarbonisation portfolio since it is the most technically advanced large-scale renewable hydrogen project. Funded to date by BEIS' Low Carbon Hydrogen Supply Competition, Gigastack is a multi-phase programme which aims to take feasibility stage concepts through to a preliminary design for a $100MW_e$-scale electrolyser system, using renewable power. Gigastack has achieved these goals by bringing together an ambitious consortium to provide economically viable renewable hydrogen at scale, with an ambition to:

- Develop **electrolyser technology** to produce renewable hydrogen at large industrial scale.
- Couple the **largest offshore wind farm** in the world with the **largest industrial cluster** in the UK on a pathway to reduce carbon emissions to net zero.
- **Decarbonise critical national infrastructure** within the UK's largest industrial cluster



Gigastack Phase 1

Feasibility study

Developed designs for a low-cost $5MW_e$ next generation electrolyser stack

Explored electrolyser-wind farm synergies to access low-cost renewable H_2 production

Market analysis and $100MW_e$ electolyser business models

Gigastack Phase 2

FEED & Stack Development

Start of $100MW_e$ FEED Study for supply of renewable H_2 to Philips 66 Humber Refinery

Further designs for $5MW_e$ electrolyser stack including testing

Installation & trial of semi-automated electrolyser manufacturing equipment

ISCF

Green Hydrogen for Humber

Feasibility for industrial fuel switching to renewable H_2 in the Humber Region

Cost of industrial fuel switching to renewable hydrogen

Business models for industrial fuel switching to renewable hydrogen

Business models for industrial fuel switching to renewable hydrogen in the region

Conclusion of Gigastack Phase 2 Concept at Advanced Stage

Prepared for an electrolyser deployment in the region, subject to supportive policy

Blueprint created for deploying large-scale electrolysers in the UK

Enables export of UK designed and built electrolyser equipment to global market

Figure 1-1: Gigastack Timeline Overview

1.1 Gigastack Phase 1

ITM Power, Ørsted and Element Energy collaborated in Gigastack Phase 1[5] to deliver a feasibility study[6] in 2019. This study explored the delivery of bulk, low-cost renewable hydrogen through Gigawatt scale polymer electrolyte membrane (PEM) electrolysis, manufactured in the UK. Phase 1 led to:

- Development of the design for ITM Power's next generation of stack technology.
- Planning of a new electrolyser Gigafactory, including calculation of throughput and identification of the optimal layout.
- Analysis of wind farm-electrolyser synergies that could deliver a reliable supply of low-cost renewable hydrogen.
- Assessment of the business case for renewable hydrogen at an industrial cluster.

1.2 Gigastack Phase 2

The results of this feasibility study supported the consortium's efforts in preparing for Phase 2 of BEIS' Low Carbon Hydrogen Supply Competition and further development of the Gigastack programme.

Gigastack Phase 2 began in November 2019 and involved a consortium of ITM Power, Ørsted, Phillips 66 Limited and Element Energy. The main objectives for Phase 2 of the Gigastack Project were:

- Preparation for the manufacture of stacks in the world's largest electrolyser factory, Bessemer Park, in Sheffield.
- Installation and trial of ITM Power's next-generation electrolyser stack and the semi-automated manufacturing machines required for large-scale and high-volume manufacture of these new large low-cost stacks.
- Collaboration on a 100MW_e electrolyser Front End Engineering Design (FEED) study for the supply of renewable hydrogen to the Phillips 66 Limited Humber Refinery.
- Highlighting the regulatory, commercial, and technical challenges to be overcome, developing a **blueprint for deploying scalable electrolyser technology across the UK.**

5 Funded by BEIS' Low Carbon Hydrogen Supply Competition in 2019
6 Gigastack, Bulk Supply of Renewable Hydrogen, Public Report, 2019

- Development of the business case for deploying renewable hydrogen at the Phillips 66 Limited Humber Refinery, supporting industrial scale decarbonisation of a high complexity facility.

1.3 Report Objectives

This report concerns Phase 2 of the Gigastack programme, highlighting the impact of BEIS' Low Carbon Hydrogen Supply Competition. This competition has provided the Gigastack consortium with the opportunity to address the challenges of scaling up the supply of renewable hydrogen through the development of new technologies, business cases and working relationships.

In this report:

- The benefits of renewable hydrogen within the context of the UK's net zero future are described. Gigastack, as the UK's flagship renewable hydrogen project, provides a blueprint and tangible pathway to scaling up the technology.
- ITM Power describes the advances and development of its next generation electrolyser stack and associated semi-automated manufacturing process. Advancing this world-leading innovative technology will enable the UK to become a global manufacturer of hydrogen technology and North-East England as a hub for hydrogen excellence.
- Ørsted and Phillips 66 Limited illustrate the work undertaken in the FEED study. The concept supports Gigastack as a key contributor to the Humber's wider decarbonisation ambitions, as well as proving major benefits to the local community, stimulating the growth of high-skilled jobs in the region, and developing local supply chains.
- Led by Ørsted and Element Energy, and supported by Phillips 66 Limited, a business case analysis has been developed which highlights the technical concept and the challenges that remain for this and other electrolyser deployments. This includes calculations of the Levelised Cost of Hydrogen[7] (LCOH) opportunities for first-of-a-kind (FOAK) projects in the UK and a pathway towards further cost reductions.

7 The Levelised Cost of Hydrogen (LCOH) is the discounted lifetime cost of building and operating a production asset, expressed as a cost per energy unit of hydrogen produced (£/kgH2). It covers all relevant costs faced by the producer, including capital, operating, fuel and financing costs. (Source: BEIS Hydrogen Production Costs 2021)

2

UK Hydrogen

2 UK Hydrogen

2.1 Hydrogen in a Net Zero Economy

The UK Government is committed to efforts to keep global temperature rise since pre-industrial levels to well below 2°C and to pursue best efforts to limit the increase to 1.5°C as a signatory of the Paris Agreement. In June 2019, this commitment was extended, as the UK Government updated the Climate Change Act requiring a 100% reduction in net greenhouse gas emissions by 2050[8]. In December 2020, the UK Government enshrined a new target in law to reduce emissions by 78% by 2035[9], committing to reduce emissions at the fastest rate of any major economy.

According to the Committee on Climate Change's (CCC's) May 2019 report on net zero[10], such ambitious targets will require extensive decarbonisation across the UK's economy. This includes a transition from incumbent hydrocarbon-based fuel utilisation to low carbon alternatives. A range of technologies, energy sources and energy vectors are required for cross-sectoral decarbonisation.

The UK is among several countries and regions that recognise that hydrogen will have a critical role to play in the transition to a net zero energy future due to its many benefits, as shown in Figure 2-1. This was formally recognised in the UK Government's Hydrogen Strategy[11], published in August 2021. Industry is a large-scale producer and consumer of hydrogen, and this is currently generated using hydrocarbons a feedstock. However, attention is turning to lower-carbon production routes for cross-sectoral decarbonisation.

8 HMG, UK becomes first major economy to pass net zero emissions laws, 2019

9 HMG, UK enshrines new target in law to slash emissions by 28% by 2035, 2021

10 Committee on Climate Change. Net Zero: The UK's contribution to stopping global warming, 2019

11 BEIS, UK Hydrogen Strategy, 2021

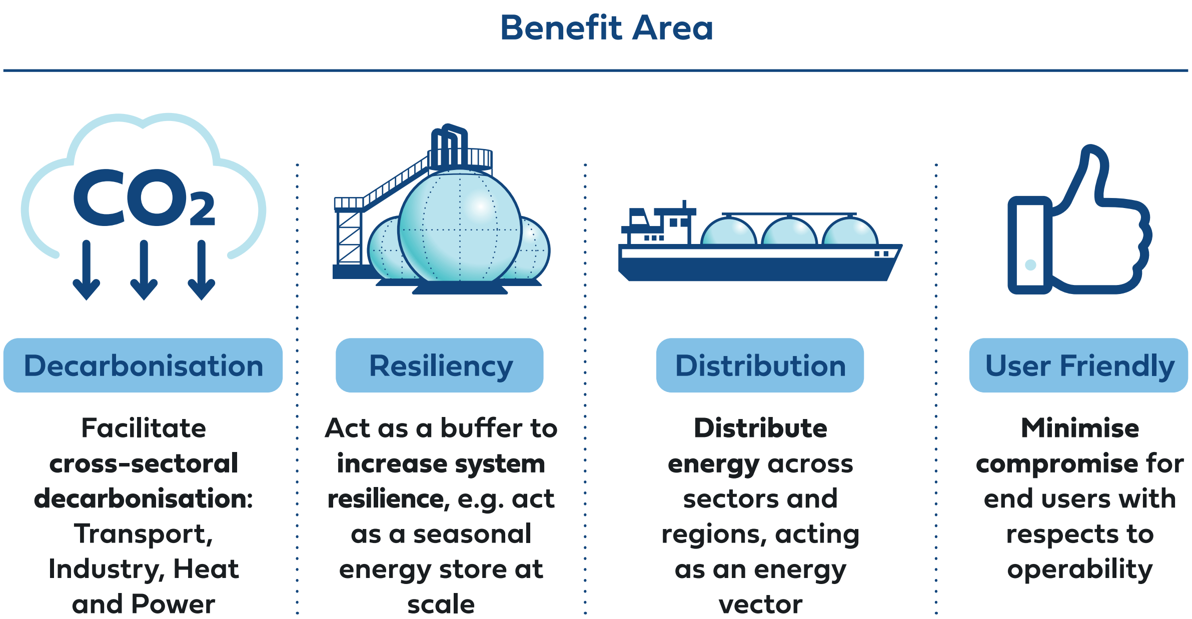


Figure 2-1: Benefits of low carbon hydrogen in a net zero economy

2.2 Renewable Hydrogen Contributes to a Net Zero Economy

Hydrogen produced with minimal emissions can decarbonise sectors where direct electrification is not viable (i.e., industrial processes, heavy-duty/long range transport, and some heating networks).

There are two main lower carbon hydrogen production options:

- Renewable hydrogen: Derived from renewable electricity and water (commonly known as green hydrogen)
- CCUS-enabled hydrogen: Derived from hydrocarbon-based fuels with carbon capture (commonly known as blue hydrogen)

Renewable hydrogen is produced by splitting water into hydrogen and oxygen in an electrolyser using renewable electricity, for example from a wind farm. This ensures that there are no emissions associated with the production process. Renewable hydrogen provides several benefits to the energy system, whilst also bringing major benefits to the UK economy, as described in Figure 2-2.

Integration of renewables and flexible demand	✓ Offers a solution to support the integration of renewables and alleviate potential system stress. Can flexibly adjust the renewable hydrogen output by varying the load factor to respond to external signals, such as flexible demand requirements
New market for renewables	✓ Enables renewable energy developers to diversify their offer and not rely exclusively on the electricity market for all revenue
Decentralisation and scale	✓ Offers ability to be utilised in diverse locations and applications. Clear opportunity to scale for some projects (like Gigastack)
Rapid deployment	✓ Does not depend on CO_2 transport and storage system and so deployment can be accelerated and geographically widespread
Supply chain and technology export	✓ Presents the UK with first mover opportunityin developing renewable hydrogen infrastructure with current expertise. Clear opportunitiesto export technology and renewable hydrogen, subject to domestic success and market development
Higher outlet purity	✓ Has a higher purity at teh point of production than CCUS enable hydrogen (e.g., less CO and water impurities), making it advantageous for direct use in fuel cells

Figure 2-2: Benefits of renewable hydrogen to the energy system

Renewable hydrogen also helps facilitate the UK's net zero energy future. Balancing the UK's electricity supply within a system with an increasing proportion of weather-dependent generation and ever-changing consumer behaviour is becoming increasingly challenging. Renewable hydrogen production can support renewable electricity generation over short time frames by responding to changes in demand in sub-second time and can support inter-seasonal energy variation by flattening demand and supply curves using long-term storage of hydrogen. This is vital to ensure the security of the UK's energy supply in an increasingly variable future, reducing dependency on imports of natural gas. Renewable hydrogen's ability to balance the UK's electricity supply and utilise long-term storage remain areas of ongoing research and demonstration, external to the Gigastack project.

2.3 Scaling Up Renewable Hydrogen in the UK

To date, renewable hydrogen has helped to decarbonise small passenger car and bus fleets as well as small scale gas grids through demonstration projects. To get the UK to net zero, it is imperative that renewable hydrogen production is scaled up providing opportunity to decarbonise those sectors that cannot be directly electrified, these include industry, heavy-duty/long ranging transport, and the UK's gas network.

The UK should therefore support the increase in scale from MW_e to GW_e installations. This requires increasing electrolyser capacity, electrolyser production capacity and the rate of electrolyser installations. These increases will drive industrialisation of the supply chain and provide major reductions in cost.

Renewable hydrogen is now experiencing a period of unprecedented momentum in political discourse in the UK. The UK's target of $5GW_{th}$ of low carbon hydrogen production by 2030 is a step change in ambition that is beginning to drive industrial activity. However, this is less ambitious and less technology specific than other key European countries which have set electrolyser-specific targets, namely Germany ($5GW_e$), France ($6.5GW_e$) and the Netherlands (3-$4GW_e$).

The UK Government has highlighted the importance of renewable hydrogen production, bringing new economic opportunities and growth in jobs across the UK, with the Gigastack project itself referenced in both the UK Energy White Paper[12] and the "Ten Point Plan for a Green Industrial Revolution[13]". The "Ten Point Plan for a Green Industrial Revolution" sets a UK Government low carbon hydrogen production milestone of $1GW_{th}$ by 2025 and $5GW_{th}$ by 2030. The 2025 timeframe is likely not viable for deployment of CCUS and, by default, is a target that can only met by timely support for renewable hydrogen. The "Net Zero Strategy: Build Back Greener[14]" report has begun to address this with the launch of the "Industrial Decarbonisation and Hydrogen Revenue Support" (IDHRS) scheme which will support up to $500MW_e$ of electrolyser capacity by 2024. Gigastack can contribute to these targets not only in deployment capacity but also by demonstrating how such an approach can be replicated and scaled elsewhere, thereby also supporting the $5GW_{th}$ 2030 target.

Gigastack is of increased importance as the flagship UK renewable hydrogen project, creating a blueprint for deploying scalable electrolyser technology.

12 BEIS, Energy White Paper Powering Our Net Zero Future, 2020

13 HMG, The Ten Point Plan for a Green Industrial Revolution, 2020

14 HMG, Net Zero Strategy: Build Back Greener, 2021

The activities in Gigastack are helping to develop:

- The next generation of electrolyser stack – to reduce the underlying cost of manufacture
- Electrolyser manufacturing capacity – to reduce costs through economies of scale, and reduction of lead times
- Offshore wind farm – electrolyser synergies – to increase overall system efficiency and ensure as low as possible a price for input electricity
- Technical and commercial understanding of how renewable hydrogen can be used in a large-scale industrial facility

Gigastack Phase 2 demonstrates the benefits of and potential for renewable hydrogen derived from offshore wind, utilised on an industrial scale in a refinery. Through the 100MW_e electrolyser FEED study and ITM Power's product development, the consortium has detailed the actual design of a hydrogen production system connected to a wind farm and industrial off-taker, including a first visualisation of a renewable hydrogen plant in the Humber. The rapid deployment of Gigastack will contribute to early CO_2 emission reductions at the Phillips 66 Humber Refinery as part of "Humber Zero[15]" and synergise with the wider decarbonisation activities in the Humber region, coordinated by the Humber Industrial Cluster Plan[16].

The activities in Gigastack Phase 2 have demonstrated and further advanced the potential for renewable hydrogen as an important component in the UK's future energy system, contributing to the UK's ambitious emission reduction targets and providing new economic opportunities.

15 Humber Zero

16 Humber Industrial Cluster Plan

3

Next Generation Electrolyser Technology

3 Next Generation Electrolyser Technology

3.1 ITM Power Electrolysers

An electrolyser is a piece of process equipment which takes water and electricity as inputs and makes hydrogen and oxygen gases as outputs. This process is enacted by electricity which splits the water into hydrogen and oxygen. When the electricity comes from a renewable source, the hydrogen is termed "renewable hydrogen".

ITM Power builds polymer electrolyte membrane (PEM) electrolyser technology. PEM electrolysis operates at a high-current density (thus creating more hydrogen relative to the physical size of the unit) and responds almost immediately (known as rapid response) to any change in input power profiles. This enables efficient operation which synergises with the intermittent nature of renewable energy.

3.2 Scaling up in Gigastack

Prior to Gigastack, ITM Power had designed and supplied PEM electrolysers stacks with a capacity of 0.7MW_e and systems with a capacity of 2MW_e (three-stacks); and identified an aggressive cost reduction plan involving the reduction of stack costs by upscaling electrolyser stacks. Achieving this involved moving, expanding and semi-automating production in the new Bessemer Park "Gigafactory", described in Section 4. This is forecast to reduce the unit cost of electrolysers by 40% over the next three-years and will maintain ITM Power's position as a leading supplier of electrolysis equipment.

With the growing demand for and interest in renewable hydrogen, ITM Power has continued to invest in new products to meet increasingly ambitious and ever-growing market demands. The work to pioneer this new technology involves the design of a 5MW_e electrolyser module; the Gigastack Electrolyser Platform (GEP). The GEP uses two 2.5MW_e stacks to form a 5MW_e system. These can be grouped together as required to allow end users to deploy the technology in different and scalable settings.

The Gigastack electrolyser stacks are bigger than any of the previous generation, with a hydrogen output 2.5 times larger than ITM Power's previous state of the art electrolyser module. To do this, ITM Power is increasing the number of electrolysis membranes within the stack by making them thinner, the more membranes per unit height, the greater the hydrogen output. In addition to having more cells per stack, GEP cells are of increased size, which provides a larger active area for electrolysis to take place. Accordingly, a much greater hydrogen production rate can be achieved within a given footprint for the same power input, when compared to earlier electrolyser modules.

This work has required:

- Representative testing of the new system at the 150kW$_e$ level
- New electrolyser designs for both lab-scale testing and 100MW$_e$ facility installations
- Establishing new supply chains

This allows ITM Power to build and deliver the new world-leading 5MW$_e$ system to an expanding market.

3.3 System Design and Prototype 150kW$_e$ Stack Build

ITM Power's main focus was on technology development for the GEP in the Gigastack project. The outcome from this task demonstrates that ITM Power is able to continue building on its previous successes and push the boundaries for electrolyser technology. This journey is illustrated in Figure 3-1 which shows the increase in scale from individual 2MW$_e$ skid to a 5MW$_e$ skid. A comparison with the state-of-the-art technology is given in Table 3-1. This work has involved tasks in the following technical delivery areas:

1. **Overall Concept Design** – including cell plate area confirmation and supply chain set-up[17];
2. **Electrolysis Cell Plate Development** – including mould flow analysis as well as cell, tool and sinter design;
3. **Skid Development** – including skid and end plate design as well as loading calculations and manufacture of I-beams;
4. **Single Block Electrode** – including all component procurement as well as skid and stack assembly;
5. **Detailed Computer Aided Design (CAD) Model** – CAD drawings of prototype, manufacturing plan, EC&I panel and software development;

17 Expanding supply chains, with a global range, to meet ITM Power's production expectations, especially regarding sinter (and sinter-forming) suppliers, continuous casting machine (CCM) suppliers, and injection mould suppliers.

6. **Stack Current Density Improvements** – including new membrane and material purchasing, scientific assessment of new materials;
7. **Test Bench Creation** – full balance of plant understanding and specification, parts purchasing, design suite (PFD, P&ID, etc), instrumentation, risk assessments, testing;
8. **Assembly and operation of new 150kWe prototype** – including safety documentation, test plans, data logging, test parameters, sign-off parameters by end of September 2021.

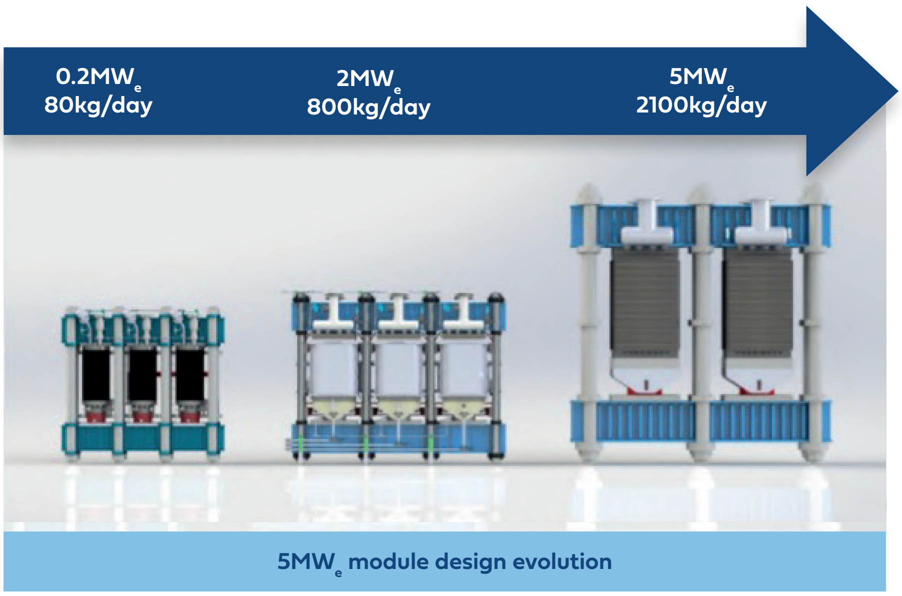


Figure 3-1: ITM Electrolyser Development

Technology	Units	MEP	GEP
System Size	MW_e	2.0	5.0
System Efficiency	% (HHV)	68.0%	73.0%
Hydrogen Production Capacity	kgH_2 / hour / system	34.5	92.6
Water Consumption	litres / kgH_2	20	17
Degradation Rate	% / 1,000 hours	0.08	0.08

Table 3-1: Performance comparison between ITM Power's Megastack Electrolyser Platform (MEP) and Gigastack Electrolyser Platform (GEP)

This large scope of work, from initial design to parts ordering, has enabled ITM Power to build and test a representative prototype system. Further in-depth testing of the prototype will allow ITM Power to successfully scale to the full $5MW_e$ GEP stack technology and better understand how the stack works. Figure 3-2 shows a CAD drawing of the completed stack, skid, and container with balance of plant alongside the initial skid build for the GEP.

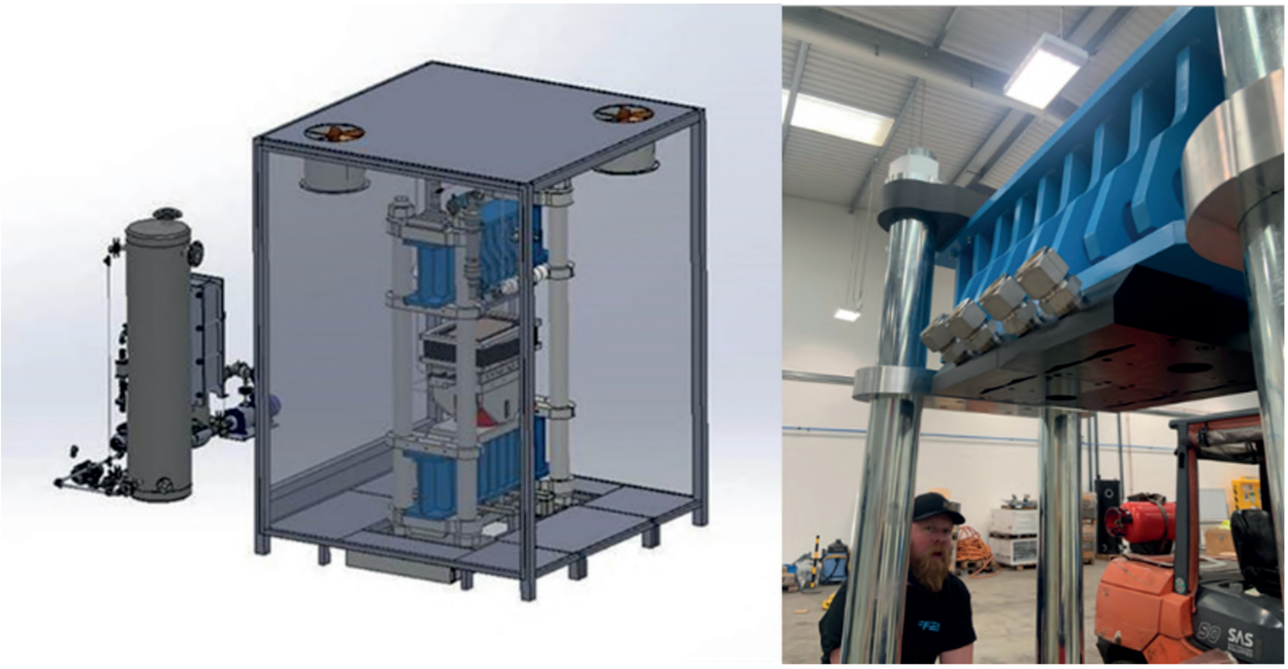


Figure 3-2: CAD Drawing of Prototype Test Rig (inclusive of skid, stack and immediate BoP) - Left | Initial Skid Build – Right

3.4 Stack design for FEED Study

ITM Power was also a major contributor to the $100MW_e$ FEED, led by Ørsted, as described in Section 5. This included designing the fully-fledged $5MW_e$ module which will be placed in the $100MW_e$ facility. Twenty of these systems will make up the full $100MW_e$, plus two additional systems included for redundancy and to allow continuous operation at $100MW_e$ during maintenance activities.

This work also included designs for the $100MW_e$ facility itself and how the electrolyser systems tie into the rest of the plant safely and efficiently. The Gigastack $5MW_e$ module is a "plug-and-play" hydrogen production-unit (target <26 m^2 footprint). This is comprised of the Gigastack electrolysis skid (including 2x 2.5MW$_e$ ITM Power GEP stacks) and the core balance of plant. An initial 3D rendering and CAD drawing of these systems is given in Figure 3-3.

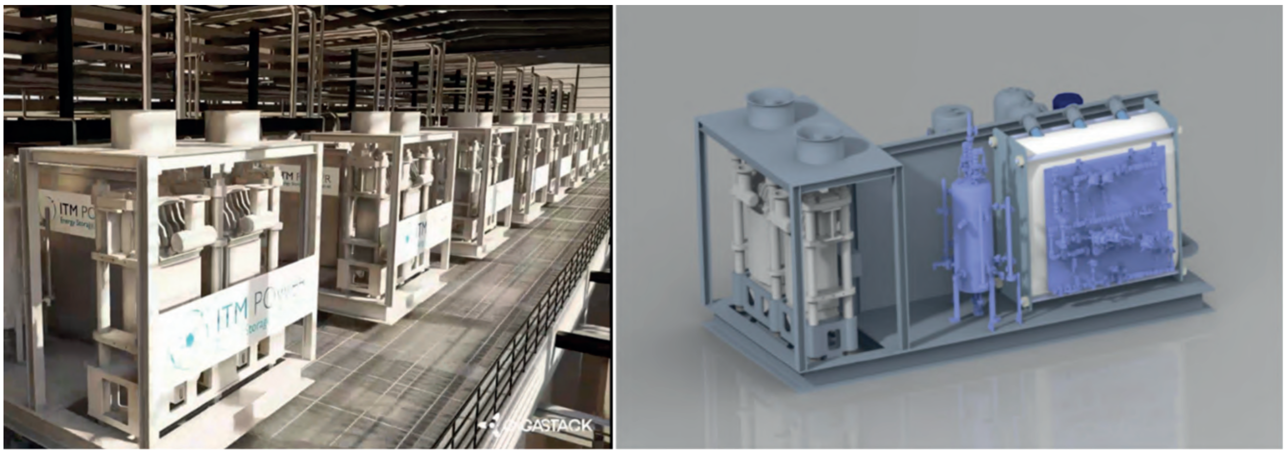
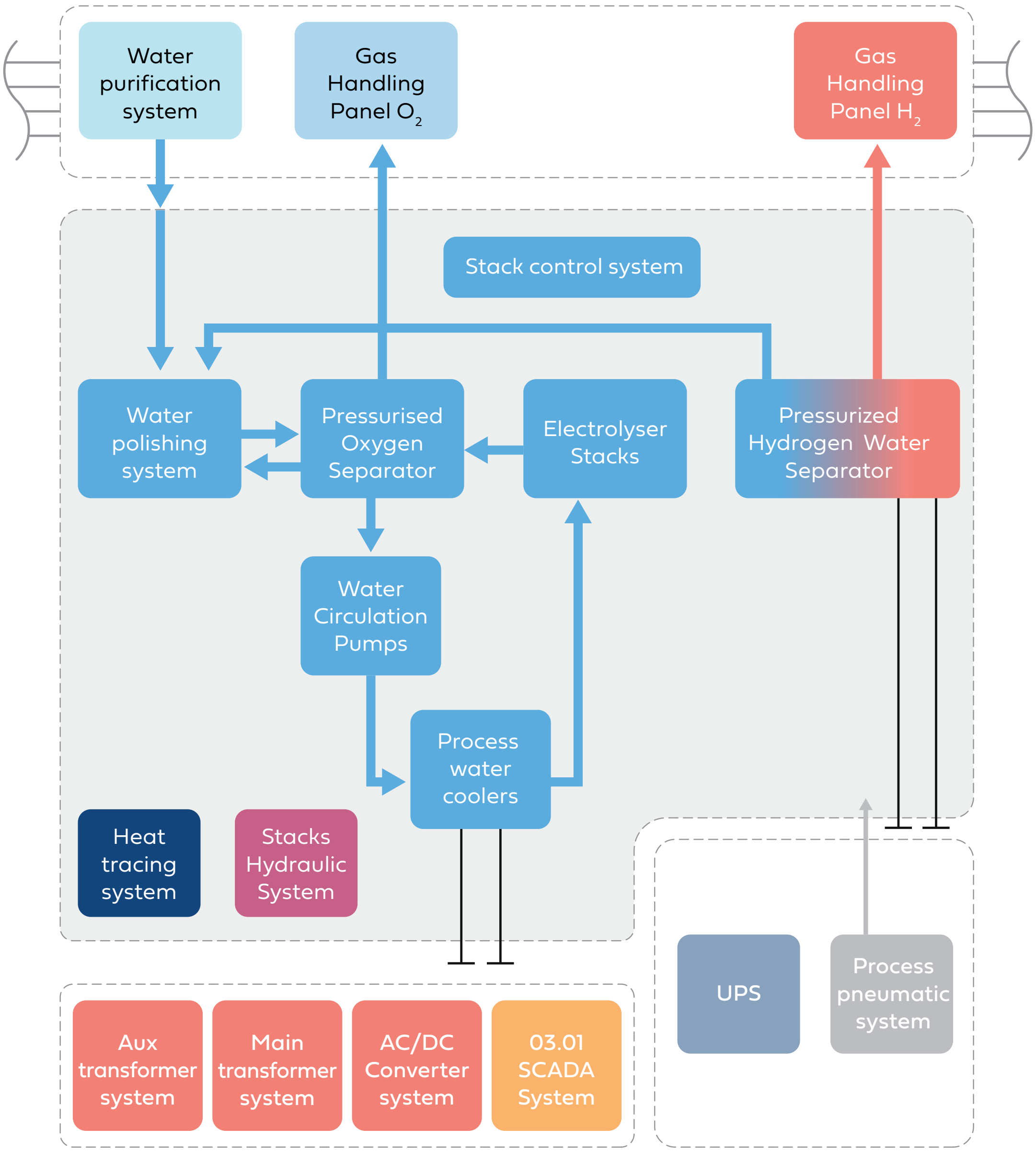


Figure 3-3: Visualisation of 5MW$_e$ GEP module within the Gigastack 100MW$_e$ facility - Left | Visualisation of 5MW$_e$ module core balance of plant - Right

The boundary limits of what's contained within the electrolyser module system are shown in Figure 3-4 (grey dashed area).



Top: Reactants, Products, Tray Services
Middle: Process
Bottom: Support

Figure 3-4: 5MW$_e$ Module core BoP

4

British Manufacturing

4 British Manufacturing

4.1 Developing the world's largest PEM Electrolyser Gigafactory

To meet the growing demand for renewable hydrogen and electrolysis, ITM Power moved into a new, state-of-the-art, electrolyser production facility at Bessemer Park in Sheffield, UK, in January 2021. Through this strategic move to a much larger manufacturing facility (134,000 square feet), electrolyser output capacity was increased up to $1GW_e$ ($1,000MW_e$) per annum, based on being ready to commence manufacture of the next generation GEP from the end of 2022. Funding from BEIS was used for Gigastack room preparation, installing and commissioning semi-automated manufacturing equipment for the Gigastack module as well as some manufacturing trials.

Figure 4-1: ITM Power Gigafactory at Bessemer Park

Bessemer Park is scheduled to reach its full manufacturing capacity of $1GW_e$ per annum by the end of 2023. When producing at full capacity, installed electrolysers from Bessemer Park will be able to produce enough renewable hydrogen to abate 2 million tonnes of carbon dioxide per year[18]. This is equivalent to the carbon emissions of charging 255 billion smart phones, or the carbon sequestered in one year by 2.6 million acres of forest.

This move represents a step change in the capacity of the electrolyser manufacturing business. The factory should facilitate cost reductions of nearly 40%, over a 3-year period, delivered through increased automation, product standardisation, economies

18 This assumes all electrolysers are powered entirely on renewable energy and the resulting renewable hydrogen is used to displace existing hydrogen produced from hydrocarbon-based fuels without carbon capture (Source: ITM Power, ESG Report, 2020)

of scale and increased minimum levels of stock held to reduce lead times and maximise throughput.

The ITM Power Gigafactory also delivers a blueprint for a high capacity, semi-automated PEM electrolyser manufacturing facility. The blueprint is readily replicable, enabling a local facility to be planned and rapidly deployed in response to large order volumes.

Figure 4-2: Sub-assembly preparation area

4.2 Infrastructure for Manufacturing Trials

To build the prototype stack and skid, described in Section 3.3, ITM Power needed to develop several physical areas within the new Gigafactory. These areas had space for the fabrication, production and manufacture of larger equipment. ITM Power's work covered the following:

1. Build Cell Membrane Printing and Sub-assembly Rooms
2. Build Negative Pressure Room
3. Manufacturing Areas Set Up

Preparation and construction of all factory areas were completed by October 2020. ITM Power is now completely confident in the ability of this new facility to build and test any prototypes. Plans are now in place to ramp up the capacity of the factory to deal with all future 5MW$_e$ Gigastack builds, meeting the project timeline for Gigastack shown in Section 5.

4.3 Installation and Commissioning of the Manufacturing Test Line

For ITM Power to manufacture the items that comprise the electrolyser stack itself, it needed to install several items of capital equipment. The manufacturing line works akin to any other factory and follows a process from A-B-C.

As such, within Gigastack Phase 2, ITM Power (i) developed and tested the Electrode Robotic Welding Process and (ii) worked on the installation and commissioning of the Electrodes Electroplating Process, the Membrane Hot Press and the Visual Measuring Machine.

ITM Power's factory is now set up to manufacture the the GEP module, comprising the electrolytic cells, stacks and skid as well as the balance-of-plant assembly within the module.

Figure 4-3: (1) Precious Metal Coating Electro-Deposition | (2) Visual Measurement Machine | (3) Precious Metal Coating Electro-Plating | (4) Robotic Welding Process | (5) Hot Press

4.4 Job Creation and Renewable hydrogen Economy Benefits

The expansion of ITM Power's production facilities and the opportunity to demonstrate the benefits of a large-scale deployment will have wider benefits than just decarbonisation. Job creation and value creation in the expanding lower carbon economy are just some of these benefits.

4.4.1 ITM Power Production Facilities

With ITM Power's increase in scale with market demand, the headcount at the new facility has also increased. ITM Power has actively recruited several new project managers and a tranche of highly skilled product design- and electrical-engineers to work on the Gigastack project. These new hires are supplemented by research engineers, manufacturing roles, and production capacity, all in aid of delivering the new technology as safely and rapidly as possible. It is envisaged that, as the company continues to grow, further recruitment will happen within the Sheffield region, as well as across the UK, to attract the best people in the country for the requisite positions.

Figure 4-4: High-skilled jobs at the ITM Power Gigafactory

4.4.1 Macro-Economic Impact

The Humber region offers the ideal place to host the Gigastack project as it brings together a consortium which specialises in each delivery element to make this flagship project a success. The deployment of electrolyser equipment and associated balance of plant will create demand for jobs immediately in supply chains and the construction centre whilst also ensuring that operational jobs are both created and protected at the production and end use case sites.

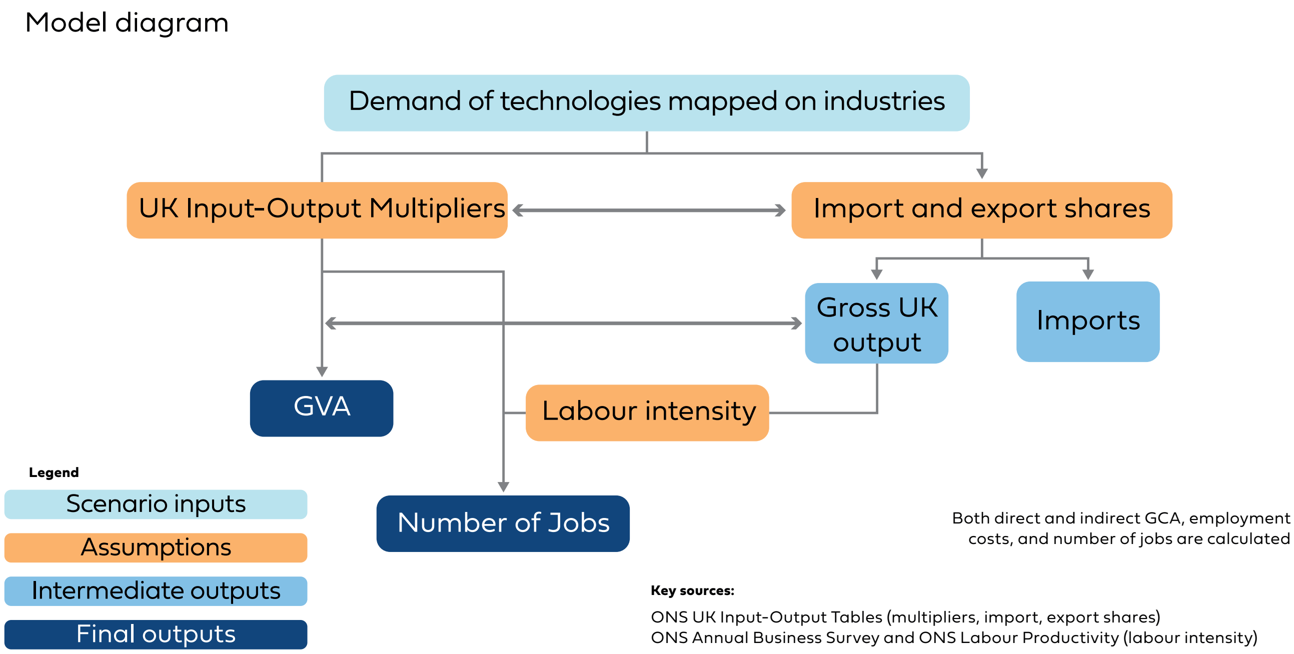


Figure 4-5: Element Energy macro-economic impact assessment analysis

To assess these opportunities, Element Energy led a macro-economic impact assessment within the Gigastack project. This considered:

- **Scenario specific hydrogen demand** | This focussed on the Humber region out to 2030 and UK wide out to 2050. This includes hydrogen demand from industry, mobility and heat networks.
- **The investment profile** | This focussed on electrolyser installations, downstream equipment (such as hydrogen refuelling stations), the upstream wind farm capacity required to meet the power demand and associated ongoing operational costs (such as maintenance and stack replacements)
- **Job and value creation** | Finally this culminated in Gross Value Added (GVA) and job creation using UK input-output tables and various business surveys produced by the Office of National Statistics.

Two periods and geographical regions were considered in this analysis to demonstrate how the Gigastack project can act as a catalyst for the creation of a renewable hydrogen economy in the UK. The potential for export to Europe was considered separately.

Gigastack – Humber Region Deployment

The period from 2021 to 2030 focussed on the Humber region and the Gigastack deployment described in this report. Three scenarios were considered:

1. **100MW$_e$** | This focussed solely on the Gigastack 100MW$_e$ concept for the Phillips 66 Limited Humber Refinery and led to 180 jobs created / safeguarded as well as £270m GVA by 2030
2. **400MW$_e$** | This focussed on growing demand from the Humber Refinery as well as mobility applications associated with the local port and led to 510 jobs created / safeguarded as well as £736m GVA by 2030
3. **1GW$_e$** | This focussed on wider industrial uptake within Immingham as well as aggressive mobility targets and led to 1,670 jobs created / safeguarded as well as £2.5bn GVA by 2030

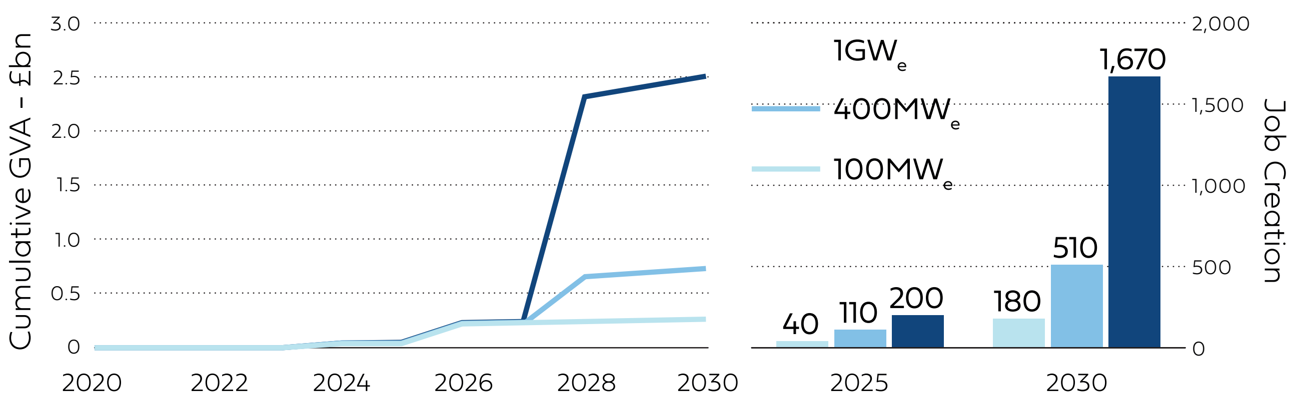


Figure 4-6: Cumulative GVA (£bn) - Left | Job Creation - Right

UK Renewable Hydrogen Economy

The period from 2030 to 2050 considered the entirety of the UK hydrogen economy and the associated opportunities for renewable hydrogen. Four scenarios were considered in this analysis, (i) Restricted Scenario (where there is no more renewable hydrogen activity outside the Humber region), (ii) Low Uptake, (iii) Central Uptake and (iv) High Uptake. Only the Central Uptake case is shown here.

The 136TWh/yr of renewable hydrogen demand (which aligns with the CCC's renewable hydrogen estimates in the Tailwinds Scenario[19]) creates £78bn of cumulative GVA, 44,000 direct jobs and 29,000 indirect jobs (73,000 in total) by 2050. These benefits could more than double where the UK has a market share in the region of 20-30% of the EU's envisaged imports market, based on Hydrogen Europe's 2x40GW$_e$ scenarios[20].

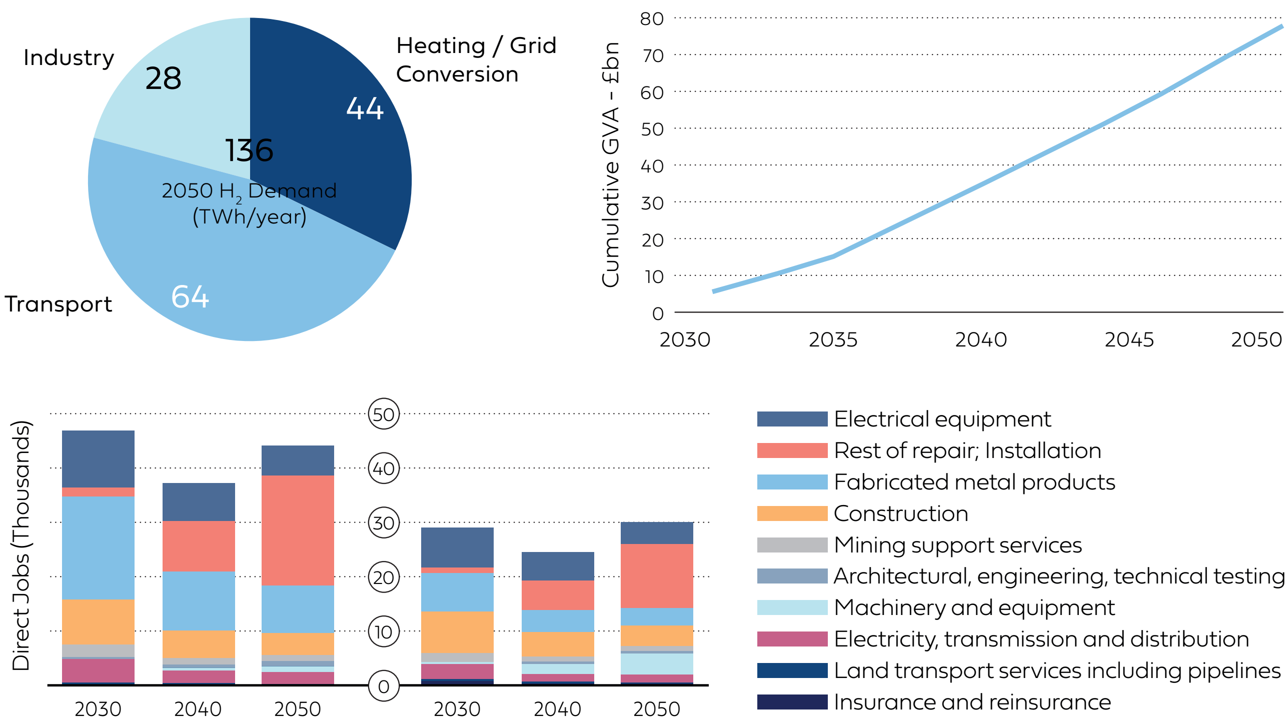


Figure 4-7: Renewable hydrogen demand in 2050 (TWh/yr) - Top Left | Cumulative GVA (£bn) - Top Right | Direct and Indirect Jobs by Sector (Thousands) - Bottom

19 The Sixth Carbon Budget, The UKs Path to Net Zero, December 2020

20 Hydrogen Europe, Green Hydrogen for a European Green Deal A 2x40 GW Initiative

5

Decarbonisation of the Humber Region

5 Decarbonisation of the Humber Region

The Humber region is the UK's largest industrial cluster with associated carbon dioxide emissions of 12.4Mtpa. This is due to the high density of energy intensive industries such as refineries, power stations and steel works that flank the banks of the Humber, traditionally receiving their hydrocarbon-based fuel feedstocks and exporting products via the ports. Decarbonisation of the Humber region is vital, not just for the UK's net zero greenhouse gas 2050 target, but in support of the UK Government's 'Levelling Up' agenda.

Alongside other decarbonisation solutions, renewable hydrogen provides a decarbonisation pathway for industries that cannot reduce emissions through direct electrification alone. A sustainable transition needs to occur in these industries to maintain the economy upon which the region depends. Gigastack will demonstrate how renewable hydrogen can fit within Phillips 66 Limited's plans to decarbonise the Humber Refinery, by commercialising a transformative technology and replacing hydrocarbon derived fuel gas currently used in industrial scale fired heaters as well as offering the potential to support the expansion of specialty graphite coke production, linked to demand for its use as an essential component in the manufacture of lithium-ion batteries for electric vehicles. This is further described in Section 5.4. This aligns with the regional Humber Industrial Cluster Plan under development through the Industrial Strategy Challenge Fund.

The FEED study has developed a concept and visualisation of the requirements for the design, construction and operation of a $100MW_e$ electrolysis facility supplied with renewable electricity from Ørsted's Hornsea Two wind farm, using ITM Power's GEP electrolyser technology and supplying hydrogen to the Phillips 66 Limited Humber Refinery.

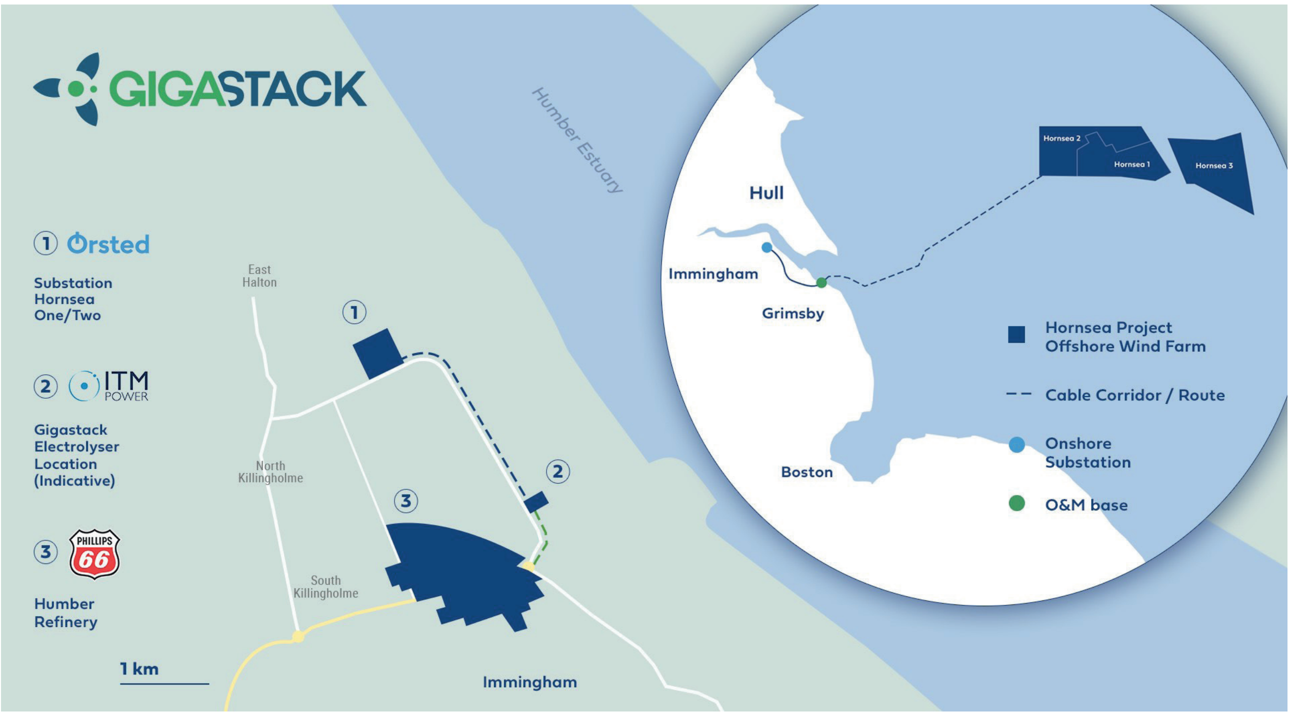


Figure 5-1: Gigastack concept with indicative location

This concept involves the following process pathways:

- Renewable electricity generated at Ørsted's Hornsea Two wind farm is delivered to an onshore substation in Killingholme via a sub-sea underground cable.
- The electricity is delivered from the substation to the Gigastack electrolysis facility via an underground cable located approximately 2km away.
- The renewable electricity splits water into renewable hydrogen and oxygen at the electrolyser facility.
- This renewable hydrogen is transported to the Humber Refinery, substituting refinery fuel gas, an energy source similar to natural gas for the generation of heat in the refinery processes. Renewable hydrogen could also be used to meet new demand associated with an expansion of Phillips 66 Limited's electric vehicle (EV) battery coke production. The refinery is already an industrial scale producer and consumer of hydrogen (derived from catalytic naphtha reforming), used in various manufacturing processes and is already a component in refinery fuel gas.

All technical work has been undertaken collaboratively between the consortium members. Ørsted led the activities, supported by Phillips 66 Limited (bringing in-depth knowledge for operating large plants and processing water and hydrogen at industrial scale) and ITM Power (providing technical input from developing the new electrolyser design). Engineering services provider Worley was subcontracted to support the consortium with the plant design.

This work has produced a visualisation of the technical concept for an electrolyser facility in the Humber, shown in Figure 5-2. A detailed overview of the technical concept, including key aspects from the FEED phase, is given in the Appendices.

Figure 5-2: Visualisation of the technical concept for the electrolysis facility

5.1 FEED Study Activities and Responsibilities

The FEED study developed a concept design for an electrolysis facility with ITM Power stacks at the heart of the plant. This includes associated balance of plant such as water purification and integration into the electricity transmission and refinery pipeline systems.

Highlights

FEED study at advanced stage with FID achievable by Q2 2023:

- Technical concept selection is well advanced to the level where the team has an overview of outer boundary limits for Gigastack including: the water and power supply, the hydrogen production, and the requirements for electrical infrastructure from the Hornsea Two wind farm as well as for piping and systems with the Phillips 66 Limited Humber Refinery.
- Commercial, financial, and regulatory challenges are clearly defined, and the consortium is working with stakeholders to overcome issues.
- Ready to take the Final Investment Decision by Q2 2023 once project definition is complete and revenue support is secured from the UK Government. Project timelines are given in Figure 5-3.

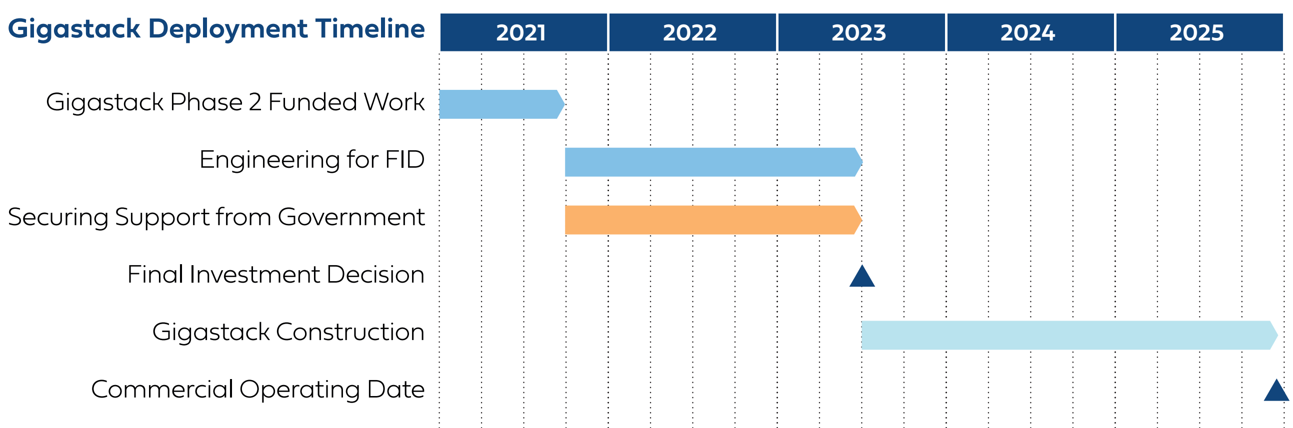


Figure 5-3: Indicative Gigastack project key timelines and milestones to deployment

Gigastack offers a scalable, renewable hydrogen project in a key industrial region:

- Gigastack is rapidly-deployable and will industrialise renewable hydrogen production, driving down costs and creating further economic opportunities in the Yorkshire and the Humber.
- A 100MW$_e$ deployment, with opportunity to expand further. This is further discussed in Section 7.2.

- Opportunity to further develop and integrate renewable hydrogen into the Humber Industrial Cluster Plan[21]. The consortium has investigated options for both power and water supply, which have been some of the key drivers and risks identified on this project.

5.2 Key learnings

The FEED study has enabled the consortium to gain an in-depth understanding of the requirements for the construction of an electrolysis facility at scale and the challenges that lie ahead.

Several challenges have been investigated in detail, such as access to water supply in an industrial area,

integration of a high voltage electrical substation a few miles away, integration into a complex refinery, the approach to planning and permitting for a first of a kind project and plant design using a technology currently in its development ramp-up phase. These challenges have been uncovered and now de-risked with solutions and key considerations for the next phase. The consortium intends to further optimise the design based on the learnings gained.

Water

Renewable hydrogen requires water as a feedstock. This poses a challenge for industrial zones, as operators are required to minimise their use of water, and further restrictions may be imposed in an environmentally sensitive area where borehole extraction is limited. The Gigastack concept explored additional supply, recycling effluent waste-water from the Humber Refinery and desalination. The technical team opted to use effluent waste-water from the Humber Refinery based on a cost benefit analysis. This ensures that there is no increase to the industrial water demand in the region and provides an innovative way of recycling refinery effluent water.

Power

The power will be supplied via the Hornsea 2 onshore substation at 220kV. The substation is designed specifically to export electricity generated by the windfarm to the National Electricity Transmission System and is already energised. Ørsted has

21 Humber Industrial Cluster Plan

built and energised the substation, its wind farm will soon produce its first power, and the divestment of the transmission system (a regulatory requirement[22]) will soon commence.

Scaling Up

Expanding the electrolyser technology from MW_e-scale plant to GW_e-scale also requires a significant change in the design to the balance of plant (i.e. water treatment, power and cooling), including the transition from containerised to industrialised solutions as well as how to operate and maintain the site.

The project has provided a robust technical concept and helped the partners to understand the key focus areas required to take Gigastack through development and into detailed design and construction. The learnings of this FEED can be used not only for Gigastack but will also contribute to wider cluster decarbonisation and the UK hydrogen strategy.

5.3 Outlook for Gigastack

Design

The FEED developed in the Gigastack project has focussed on the core processes, reaching a technical stage based on the electrolyser scope. From power coming in, to hydrogen going out and ending up with a conceptual design. The conceptual design provides an overview of the power, water consumption, hydrogen produced, and all the utility installations needed for supporting the core production as well as an initial cost prediction.

Based on this, the conceptual design containing technical areas such as footprint, technology types, and approximate required bill of materials, is now ready to be taken into the next design phase, which will mature the conceptual design to a final engineering stage before reaching a +/-10% capital expenditure

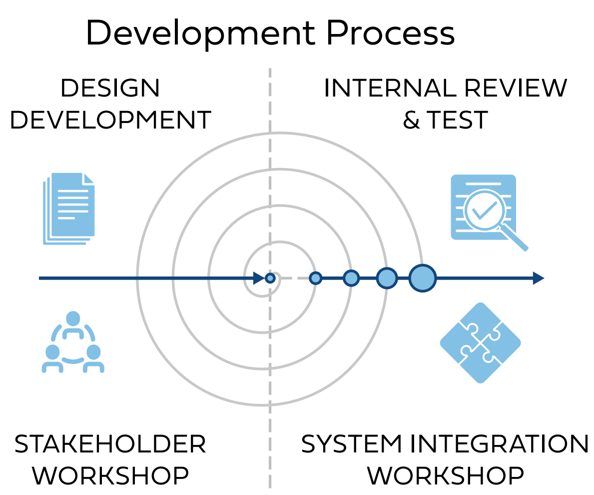


Figure 5-4: Spiral model

22 OFTO, Ofgem

(CAPEX) accuracy for total installed cost, ready for construction. The generic design process adopted by the Gigastack project follows a spiral model, Figure 5-4, that matures the design in steps. The Gigastack FEED has completed two full rounds of the model during the project's lifetime.

At every loop, the developed design was re-evaluated with the design team and stakeholders to ensure that no system was forgotten and all systems were properly integrated towards the other systems. Phillips 66 Limited has engaged its Major Project Group in the US to peer review the design work on Gigastack. This group oversees design and deployment of Phillips 66 Limited's world-scale projects, which are often in excess of £1bn.

The design process will continue to follow this approach to ensure a design that is safe and optimal for construction and operation.

Consents and Permitting

In support of the FEED study phase, a consenting strategy has been developed. This establishes an understanding of the consents required for the project and identifies key consenting risks, regulatory barriers and opportunities to take into the next phase for delivering the project. Key consents identified include the requirement for planning permission and environmental permitting with associated environmental studies. Programme milestones have been developed, incorporating the approach for stakeholder engagement; scope and delivery of environmental surveys and assessments; integration and interaction with the design development; schedule for planning permission and environmental permitting delivery; and site selection process, including cable and pipeline routing for connecting assets.

Feedback from work carried out to date demonstrates that the deployment of Gigastack in the Humber region is feasible with broad policy support, suitable site development opportunities based on initial environmental and land studies and a clear strategy for consent delivery.

This Gigastack FEED enabled the project to gain a strong insight into the key focus areas to deliver on the consenting requirements for the project, including:

- Finalising the connection routes (electrical cable, water and hydrogen).
- Carrying out environmental surveys and assessments to support the consent applications.
- Integrating assessment outcomes into the final design and layout, such as landscaping, noise mitigation, building design appearance and drainage.
- Engagement with stakeholders on the proposals including the local authority, the Environment Agency, Natural England, the Health and Safety Executive and the local stakeholders.
- Delivering robust consent applications which provide for flexible deployment of the Gigastack project.

Site Selection

Alongside the consenting strategy and in support of the FEED study phase, Ørsted undertook a rigorous site selection process. This aimed to identify land plots which could support the project, proposed asset routing, and statutory undertakers and private assets owners with which Gigastack's assets may interact. This also included a detailed study of the land ownership and required rights of way to fully understand any existing restrictions that may prohibit the use of the site as well as cable and pipeline routes.

This has enabled the project to rule out several sites and establish a preferred site location with routes for the required electricity cable, hydrogen pipeline and water assets. This process also identified all key stakeholders to be engaged and interacted with.

5.4 Phillips 66 Limited Humber Refinery

The Phillips 66 Limited Humber Refinery is the consortium's offtaker of renewable hydrogen. The Humber Refinery, one of Europe's most efficient refineries, has operated in the UK for more than 50 years. The Humber Refinery produces fuel for inland supply, employs 1,000 people and makes a significant contribution to the regional economy every year.

It is proposed that Phillips 66 Limited will switch hydrocarbon fuel for Gigastack's renewable hydrogen in their industrial fired heaters. The Humber Refinery has a long-history of producing and consuming hydrogen which is used in various processing units and as fuel gas and understands the molecule's properties and requirements well. This technology choice is based on previous work done within the BEIS Industrial Strategy Challenge Fund[23] programme that identified that the optimum route to industrial decarbonisation was through a combination of direct carbon capture and hydrogen refuelling. Hydrogen refuelling is a critical tool for decarbonising the Humber Refinery's heaters where it is impractical and inefficient to install carbon capture due to their geographic spread and lower individual capacities. Phillips 66 Limited has identified that high-percentage blends of hydrogen can be used in the heaters. As part of "Refuelling the Humber Refinery" (a UK Government supported programme funded under the Industrial Energy Challenge Fund[24]) Phillips 66 Limited is currently assessing the onsite heater and piping modifications required to refuel with hydrogen.

Hydrogen is a critical decarbonisation pathway for the Humber. Phillips 66 Limited has identified a pathway to 90% reduction of direct refinery emissions where up to 25% is expected to be abated through the use of both renewable and CCUS-enabled hydrogen. Gigastack's 100MW_e is expected to reduce refinery CO_2 emissions by 0.1Mtpa by switching refinery fuel gases with hydrogen.

The Gigastack project complements Phillips 66 Limited's ambitions of making the Humber Refinery the "Refinery of the Future". This concept includes four key tranches of work which Phillips 66 Limited is actively developing and engaging with the UK Government on:

1. Lower carbon sustainable feedstocks and products – this includes major investments in processing of biogenic waste oils into fuels. The Humber Refinery is also the UK's only at-scale producer of Department for Transport approved "Development Fuels" – biofuels created from advanced feedstocks.

2. Products needed for the energy transition – the Humber Refinery is Europe's only producer of synthetic graphite coke, which is a key component in the electric vehicle and consumer electronics battery market. The Humber Refinery is one of the world's largest suppliers of this specialist product and well positioned to support the UK's future electric vehicle ambitions, with potential to anchor regional manufacturing supply chains.

23 UKRI, Industrial Strategy Challenge Fund
24 BEIS, IETF Phase 1, 2020

3. Industrial decarbonisation of the Humber Refinery – Working within the BEIS Industrial Strategy Challenge Fund (ISCF) program, Phillips 66 Limited has developed a plan to reduce refinery emissions by more than 90%. This includes the Humber Zero project which has received FEED funding through the ISCF Phase 2 project.
4. Hydrogen fuel switching at the Humber Refinery – Phillips 66 Limited is actively working with the Gigastack consortium to develop industrial scale hydrogen production for the provision of fuel to the refinery, reducing consumption of hydrocarbon fuel and lowering CO_2 emissions.

Renewable hydrogen is a key part of Phillips 66 Limited's Refinery of the Future plans and has the potential to fit into all four of these categories. For example, it can be used in hydrotreating processes in the production of development fuels and in synthetic graphite coke production. Externally to the Humber Refinery, renewable hydrogen can be used in at-scale vehicle fuelling, either directly or in the form of hydrogen carriers such as ammonia.

6

Hydrogen Policy and Regulations

6 Hydrogen Policy and Regulations

Gigastack Phase 2 has achieved its objective to identify and highlight regulatory, commercial and technical challenges for real applications of industrial-scale renewable hydrogen systems.

Several policy and regulatory barriers to development were identified, with potential solutions laid out. These barriers and solutions are detailed below alongside a description of ongoing work for the consortium.

6.1 Step One: Regulatory Barriers

Barrier 1 – Clarity on Grid Connection Compliance Requirements

The current "Grid Code"[25] and approaches to "Bilateral Connection Agreements"[26] do not provide clarity on how the existing rules can be applied to co-locating and connecting a FOAK electrolyser project (a demand user) with an offshore wind farm (a generator) and onshore grid via the offshore transmission network.

Solution: Further clarity is required to identify the compliance and testing regime that the electrolyser would be subject to.

Status Update: Extensive engagement has taken place with National Grid throughout the project to work through areas of uncertainty and clearly define the processes and requirements that apply to Gigastack. The complexities are not necessarily company or project specific, and as such can be applied to any development looking to co-locate assets. Therefore, work to address this – and all barriers – will have a positive net effect on future deployments and enable innovative technologies to be brought through. Work on this barrier is ongoing.

Barrier 2 – Bringing Co-Located Assets into the OFTO Framework

The current Offshore Transmission Owner (OFTO) framework, which governs the required divestment of offshore transmission assets that offshore generators build, is based around a single offshore wind farm connecting into the offshore transmission assets. As a result, the installation of additional assets connecting into the offshore transmission network requires further regulatory development.

25 National Grid ESO, Grid Code

26 National Grid ESO, How can I connect?

As an initial step, Ofgem's current Cost Assessment methodology for OFTO assets should be examined. At present, the introduction of new innovative solutions and new assets into the divestment presents a high risk of cost disallowance. This increases the level of risk to developers. The pricing in of new assets by potential OFTO bidders also requires consideration.

Furthermore, determining the appropriate apportioning of the Tender Revenue Stream between the offshore wind farm and the electrolyser will require a robust methodology to ensure that incentives given to the OFTO are properly calibrated. Late-life issues may also materialise if the lifetimes of the offshore wind farm and electrolyser deviate.

Solution: For these issues, information is crucial to both Ofgem and to potential bidders. To avoid cost disallowance risks before costs are sunk into the project, an 'approval in principle' process should be implemented so that Ofgem can approve of works and provide assurance to developers.

Status Update: OFTO related issues have been raised with Ofgem – which regulates and operates the OFTO divestment framework – through consultation and discussion. The issues are also being considered within the Offshore Transmission Review, via the Early Opportunities workstream, and it is hoped that conclusions will be reached by the end of 2021

Barrier 3 – Uncertainty in Network Charges

The electrolyser is liable for network charges applicable to transmission connected users if it imports power from the grid (which is expected). This includes costs associated with the Transmission Network Use of System (TNUoS) and Balancing Services Use of System (BSUoS). These charges currently face a high level of uncertainty given that they are undergoing significant reform.

Solution: When network reforms are finalised, the project will have a greater level of certainty. However, the charging environment is not static and future changes are likely to follow. The choice of metering arrangements can limit exposure to some of these charges.

Status update: Some further clarity has been provided following decisions on The Targeted Charging Review; however, a level of uncertainty remains. Proposed charging changes from Ofgem and National Grid are being tracked. Technical solutions are also being explored to mitigate against network charges, given that the electrolyser will effectively be taking 100MW_e of generation off the system. This work is being carried out in tandem with Barrier 4.

Barrier 4 – Clarity on Metering to Unlock the Full Value of Negative Hours

The current metering framework presents an issue whereby the power from the offshore wind farm flowing into the Total System would disincentivise the offshore wind farm from supplying power to the electrolyser during negative price periods[27]. These could occur in more than 400-hours from 2024, 5% of the year[28]. Power that enters the Total System is subsequently priced, meaning that negative hours would represent a cost to the offshore wind farm.

Solution: If a solution can be developed to simulate a behind the-meter scenario during negative-priced hours, allowing the offshore wind farm to continue to generate and enabling the electrolyser to capture lower priced electricity this would unlock further value to the electrolyser and to consumers,

Status Update: Technical solutions are being explored, both externally – via relevant stakeholders such as Elexon[29] – and internally. Further discussion with Elexon is expected to explore the feasibility of using a Trading Unit function to link the settlement metering of the Wind Farm and Electrolyser. This would avoid unnecessary curtailment and ensure the assets are used optimally.

6.2 Step Two: Further Policy Support for Renewable Hydrogen

Gigastack has investigated the barriers to the wider uptake of renewable hydrogen. Some approaches to support schemes have been proposed and implemented across international markets with the aim of incentivising growth in hydrogen. Not all support scheme approaches are suitable for renewable hydrogen, as they may impose barriers. These barriers along with solutions are detailed below.

27 This includes pre- and post-AR4 contracts where prices are negative for longer than 6-hours

28 Current News, What's on the Horizon for horizon for negative prices in GB? 2019

29 Administer the Balancing and Settlement Code (BSC) and provide and procure the services needed to implement it

A Mechanism to Aid the Transition to Renewable Hydrogen

As the UK Government begins to establish policy to meet climate change goals and achieve net zero climate neutrality, it is exploring ways of increasing the deployment of low carbon hydrogen. Grants and other mechanisms to provide capital expenditure support are initially helpful for early technology demonstrators. However, for rolling out new and enduring methods of producing hydrogen, ongoing revenue support schemes covering operational expenditure costs will be essential to ensure low carbon hydrogen is competitive against incumbent and carbon-intensive methods of hydrogen production. This is particularly important in the Humber region since one in ten jobs depend on energy intensive industries[30], therefore a sustainable transition is necessary to avoid economic shock.

Solution: For renewable hydrogen, end-user obligations and Contract for Difference (CfD) mechanisms are likely to be most appropriate, given the initial small scale and overall low number of renewable hydrogen projects in the market. These mechanisms provide revenue support that will enable investment in early projects, which in turn will help to drive down costs as future projects scale up. The consortium is engaged with the UK Government on these issues through ongoing bilateral discussions, participating in the Hydrogen Advisory Council[31], and by responding to the UK Government's Hydrogen Strategy consultations, with a focus on the hydrogen business model[32] and Net Zero Hydrogen Fund[33] consultations.

Development and Deployment of a Hydrogen Network.

Scaling up hydrogen will require the UK Government to deploy the mechanisms mentioned previously to drive initial demand for a network. Large-scale installations will then require the development of hydrogen networks that will transport the product to different end users. This will create a virtuous circle where greater connectivity leads to increased demand for further scaling up hydrogen production capacities since (i) the accessible market grows larger, (ii) there are opportunities to increase sales volumes and revenues and (iii) transportation costs are lowered. These factors will also result in an overall lower unit cost of hydrogen production. A scheme which supports this expansion would also allow electrolysers to be sized to the total accessible market and be more compatible with the size of offshore wind generation. This maximises future opportunities for projects like Gigastack, where having alternative end use options might allow the project to respond to market conditions and consider additional routes to market.

30 Humber LEP, Humber Clean Growth, Local White Paper, 2019
31 BEIS Hydrogen Advisory Council
32 BEIS, Consultation on a Business Model for Low Carbon Hydrogen, 2021
33 BEIS, Designing the Net Zero Hydrogen Fund Consultation, 2021

Solution: It could be beneficial to explore transitional schemes or adjustments to support scheme parameters that would enable first-wave producer-user specific projects like Gigastack to be developed to capture future market opportunities. These projects would typically be sized to the needs of a single off-taker, located at customer sites and would need some physical adjustments and adaptations to the Business Model to capture broader market opportunities. Exploring the retrofitting of the distribution network or providing new infrastructure to connect supply and demand is needed. As an accessible network becomes a feasible option, greater options around size and location of projects can be considered.

Demonstration of Renewable Power Input

At the same time as developing mechanisms for support, it is also important to ensure that the provenance of the electricity being provided can be demonstrated and the power consumed in the production of the hydrogen is genuinely low carbon. This needs to come from the low carbon hydrogen standard[34] that the UK Government released for consultation in August 2021, which recognises renewable hydrogen as zero-carbon when the power.

is generated from renewable generators, such as offshore wind. This would validate the hydrogen produced and create more commercial opportunities, warranting additional deployments of offshore wind in the North Sea. Consideration needs to be given to direct connection to renewable power generators and power purchase agreements. This would allow the full value of these projects to be unlocked and not funnel projects into requiring dedicated, off-grid solutions – a certification scheme that demonstrates the environmentally friendly credentials would facilitate future routes to market that would enable greater levels of commercial optimisation.

Solution: An evidenced renewable power supply should be able to demonstrate the environmentally friendly credentials of renewable hydrogen projects. This could be in the form of a Power Purchase Agreement (PPA) that provides a contractual route showing the electrolyser's power source.

Coordination between Support and Carbon Price

Lastly, it is important to re-emphasise the difference in development lead times between offshore wind farms and electrolysers. For first wave projects that are not

34 BEIS, Consultation on a UK Low Carbon Hydrogen Standard, 2021

coordinated from inception with co-location in mind, the timing of support schemes for the offshore wind producer and electrolyser may not be aligned, and therefore there may be a need to examine the efficiencies of how the two schemes interact.

Solution: Implementation of effective metering and PPAs would allow projects to evidence production data that can satisfy support scheme requirements. The UK Government's Hydrogen Strategy is also exploring the ability to layer subsidies to make deploying hydrogen project more viable

Policy support status update: Regular discussions have been held regarding support for Renewable hydrogen, primarily with BEIS – but also Ofgem, the Low Carbon Contracts Company (LCCC), and others. Advocacy work will continue, with a focus on the development of an appropriate mechanism to enable renewable hydrogen.

Additional Policies to Further Support Renewable Hydrogen

The list below includes, at a high-level, an additional set of policies, financial incentives and commercial mechanisms which can further support renewable hydrogen:

- Implement a subsidised revenue business model, ensuring that it aligns with any relevant carbon accounting practices.
- Provide formal standard definitions based on the carbon intensity of hydrogen production methods, as launched in the low carbon hydrogen standard consultation[35] in August 2021.
- Define capacity and production targets beyond 2030 based on both technology and supply, as done in other countries.
- Support for hydrogen projects coordinating end-to-end solutions, including hydrogen storage to manage swings in renewable power supply and aligning hydrogen distribution infrastructure from blue projects with renewable projects to bring about a distribution network that can serve all production technologies.
- Further promotion of R&D, especially to maximise IP for electrolyser technology.
- New market creation: synthetic fuels via CCU, lower carbon / recycled carbon chemicals such as ammonia etc.

35 BEIS, Consultation on a Low Carbon Hydrogen Standard, 2021

7

Business Case

7 Business Case

7.1 Purpose of Business Case Modelling

The Business Case Analysis activity helps the consortium and wider stakeholders understand the costs of production of renewable hydrogen for this FOAK project, demonstrating:

- Achievable cost reductions when upgrading electrolyser technology from existing PEM electrolyser technology to Gigastack via reductions in CAPEX and in electricity and water consumption.
- Further areas of cost reduction achieved via private-public collaboration on technical development and creation of optimal regulatory environments to minimise project risks.
- The total policy intervention required to enable the project investors to take a Final Investment Decision (FID), for a rapid deployment enabling a commercial operations date in 2025.

The Business Case Analysis workstream quantified the cost of delivering renewable hydrogen to the Phillips 66 Limited Humber Refinery. This includes the cost of electrical connections to the substation, supply of water, the electrolyser facility, downstream pipelines and associated operational costs. This does not include the conversion costs within the Humber Refinery as these are the same for both renewable and CCUS-enabled hydrogen. Costs are reported on a £/kgH_2 basis. Further information is given in the Appendices. These costs are specific to this FOAK project, with significant cost reductions envisaged over the coming decade, as highlighted in this Section.
The model was informed by assumptions developed by the consortium throughout Gigastack Phase 1, Gigastack Phase 2 and Green Hydrogen for Humber[36] (funded under ISCF Phase 1). These projects have:

- Advanced technology and manufacturing readiness levels, thereby reducing cost and increasing readiness for electrolyser installation.
- Calculated the EPC costs associated with the phased build out to a degree of certainty to meet FID requirements.
- Identified and developed solutions for technical barriers (i.e., water supply) and regulatory barriers (i.e., OFTO regime).

36 ITM Power, Green Hydrogen for Humber, 2020

This section identifies a route to low-cost renewable hydrogen for a FOAK project and the size of the support gap that needs addressing for FID. This gap is based on a counterfactual fuel cost for natural gas (51p/therm or 1.74p/kWh[37]) plus carbon price (£20.50/tCO_2)[38]. This is given on an energetically equivalent basis of £0.85/kgH_2. It should be recognised that this counterfactual price will vary proportionally with the price of natural gas. Assumptions are given in the Appendices.

7.2 Scenario Descriptions

Two scenarios are presented in this report, reflecting the different electrolyser operational modes[39] and the complete 100MW_e electrolyser facility (around 1,850kgH_2/h) build. These scenarios are defined to ensure that a reliable and rateable supply of hydrogen is supplied to the Humber Refinery, displacing incumbent hydrocarbon-based fuels. Hydrogen storage can meet this demand and was analysed in the Gigastack project but is not shown here. As a result, the hydrogen supply must be dependable. These scenarios represent the phasing of the Gigastack deployment.

Future electrolyser deployments will involve low electrolyser load factors to benefit from more volatile power price periods and cheaper system CAPEX. However, for FOAK deployments and even under support schemes, it is important to run the electrolyser at or near to baseload operation to maximise hydrogen sales, thus reducing the £/kgH_2 specific fixed costs, as well as meeting fixed demand (desirable for stable industrial heater operation) in the absence of large-scale storage systems (both chemical and electrical). This requires the electrolyser to operate near to every hour of the day and every day of the year; this minimises the CAPEX cost component (and hence the required Capex support) and reduces demand for expensive storage.

Electrolysers and wind farms can employ different PPA terms and configurations. Here, two PPA terms and their impact on the LCOH are explored.

The options are shown here, portrayed for the 100MW_e case:

- **As Produced** – The electrolyser will have access to a capacity of the wind farm equal to that of the electrolyser (100MW_e). The electrolyser's consumption of "green" power from the wind farm is equal to its anticipated capacity factor of 54%. The remaining 46% of power comes from the grid to meet baseload operational requirements, leading to an almost even split between wind and grid power consumption.

37 BEIS, 2019 Fossil Fuel Price Assumptions

38 BEIS, Green Book, 2021

39 Previous work investigated including storage infrastructure in the system, an operational mode where there is a one-way grid connection which never imports power from grid and a high degree of flexibility from the end user. These have not been further explored here as they lead higher specific CAPEX for this FOAK project or reduce the hydrogen production, harming the LCOH.

- **Oversized PPA** – The electrolyser has a greater fraction of its power coming from the wind farm. Ørsted allocates a fixed, to-be-determined tranche of power above 100MW$_e$ from the wind farm to the electrolyser. Depending on how oversized the PPA is, the amount of "green" power consumed by the electrolyser could grow to circa 80%, reducing grid power requirements from 46% to 20% relative to As Produced.

Therefore, the difference between the options above is the proportion of total power which is "low carbon" power; with the total power consumption being identical in both options. Critical to the choice of the PPA is the policy environment that the electrolyser operates in. It must be noted that in the Oversized PPA scenario there is the added complication and likely cost of managing the excess volume when the contract is delivering more than 100MW$_e$. This can be managed under the PPA but needs to be considered and would see this structure being more expensive than the simple As Produced (however additional costs not accounted for here). However, if the electrolyser only receives support when it is consuming low carbon power, then the Oversized PPA is essential to maximise the amount of time during the year during which operation is subsidised. For all scenarios, the final LCOH includes three main components:

- **Energy Costs**: Cost of electricity sourced from the wind farm and grid.
- **Energy Charges and Tariffs**: Grid charges, levies and other regulatory costs.
- **Equipment Costs**: CAPEX and fixed OPEX, including stack replacement.

7.2.1 Gigastack Technology Improvements and Phased Deployments

Technology Improvement

ITM Power's next generation technology facilitates an increase in scale, cost reductions and efficiency improvements. Cost reductions are attained through:

- Reduction in electrolyser system CAPEX from circa £1,500/kW$_e$ to less than £600/kW$_e$.
- Improvements in electrolyser system efficiency from 68%$_{HHV}$ to 73%$_{HHV,}$ reducing electricity demand to 54kWh/kg H_2 at start of life at nominal capacity.
- Reducing refinery effluent water consumption from 25 litres/kgH_2 to 17 litres/kgH_2.

Work through private-public cooperation is warranted to narrow the gap between the LCOH and the natural gas counterfactual. The possible reductions of LCOH attainable through cooperation, and the comparison of the resulting LCOH with the counterfactual is shown in Section 7.3.

7.2.2 Private-Public Cooperation

Public-private cooperation to reduce Gigastack endogenous (within control of consortium) and exogeneous (outside of control of consortium) risks is vital for timely project delivery. This cooperation can reduce the LCOH directly through policy mechanisms and indirectly by facilitating an increased appetite for risk. Closing the gap can be achieved through:

- Further project optimisations, including lower cost wind power (which in turn is dependent on the UK Government's commitments and guarantees), identifying synergies with other offtakers (i.e., local hydrogen transport) and materialising additional sources of revenue.
- Reducing regulatory burdens, including minimising the cost of grid charges and reducing renewables obligations i.e., remaining green levies following 85% Energy Intensive Industries (EII) exemption[40]
- A supportive policy regime, where Gigastack receives an operational support and a capital grant, which are prerequisites for a successful project FID.

Select risks and cost drivers which were modelled are discussed below. Further cost reductions and risks to be considered but not analysed here include:

- Technical design and performance optimisation
- Supply chain engagement
- Low-cost financing
- Support from the UK Government to guarantee renewable hydrogen offtake
- Carryover of definitions for renewable hydrogen and policy regimes for assets installed or planned before changes are introduced and clear communication of changes for future deployments.

40 BEIS, Energy Intensive Industries, 2020

Green Levies

Green levies are a significant component of energy charges and tariffs. Reducing green levies is an endogenous cost driver, as eligible industries can claim an 85% rebate under the EII Exemption. This reduces energy charges and tariffs from approximately £55/MWh to £22/MWh (~60%). Removing the Green Levies completely is a UK Government decision and would reduce the energy charges and tariffs further to nearly £16/MWh. Countries such as Germany have already taken steps on this front to implement policies removing certain levies (albeit under strict conditions where no other subsidies are awarded).

Energy Charges and Tariffs

The primary cost driver for renewable hydrogen is the cost of power. In the 100MW$_e$ Oversized PPA base case, energy charges and tariffs costs associated with power consumption account for 16% of the total cost of power (excluding Green Levies). Working with Ofgem and other regulators to remove energy charges and tariffs costs for renewable electrolysis using power from offshore wind farms will help to stimulate the market. Rationale for removing these costs is based on the following:

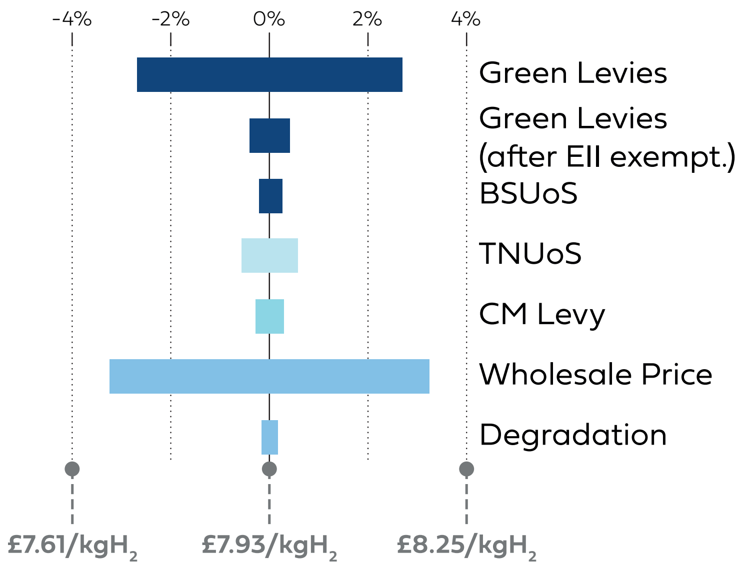


Figure 7-1: A ±10% variation in the cost components shown vary the final LCOH on for the Oversized PPA 100MW$_e$ scenario Base Case by up to 4%.

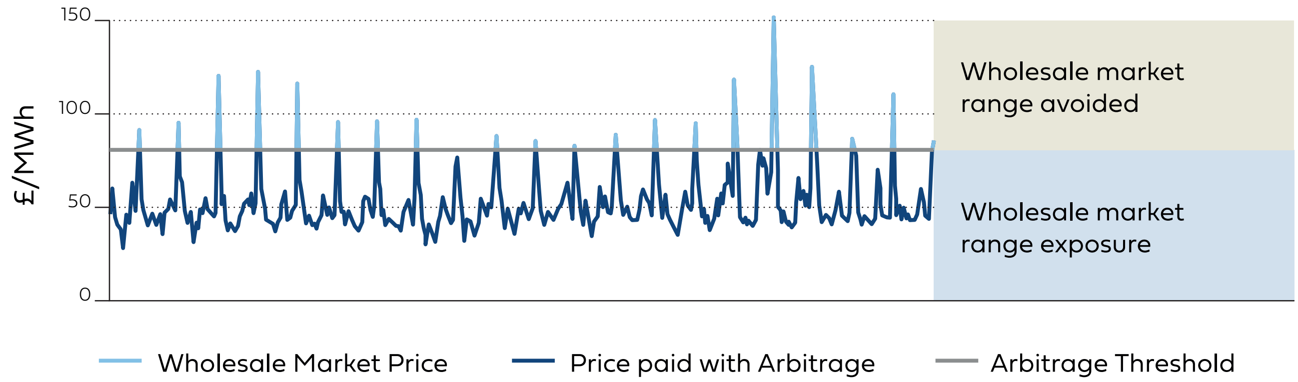
- Many of these charges relate to the regime for connection of offshore wind farms to the grid, which was not designed for renewable coupled electrolysers, as described in Section 6.1.
- There are considerable synergies available from electrolysers for the grid which could be realised through a waiver for certain charges.

It is also important that there is visibility on (i) energy charges and tariffs costs and (ii) the regulatory regime to allow for robust business cases. As shown in Figure 7-1, changes to the price of these costs (before any reductions are introduced) will influence the LCOH.

Day Ahead Arbitrage

Electrolysers can operate flexibly, responding to changes in price signals in sub-second time intervals. This allows for business case optimisation by turning the electrolyser down or off during expensive power price periods, however the offtaker would need to accept some degree of flexibility. This is not practical for most potential hydrogen consumers (whether industrial or for domestic heating uses), who require rateable supply. This practice improves the economics more as the capital cost of installations decreases and the impact of low capital utilisation diminishes[41].

With no PPA, wind power price is pegged to the wholesale market value, and an arbitrage limits the sourcing of power from the wind farm and wholesale market



A PPA fixes the commodity costs for power sourced from the wind farm, and an arbitrage threshold limits exposure only to wholesale market prices when wholesale power is needed

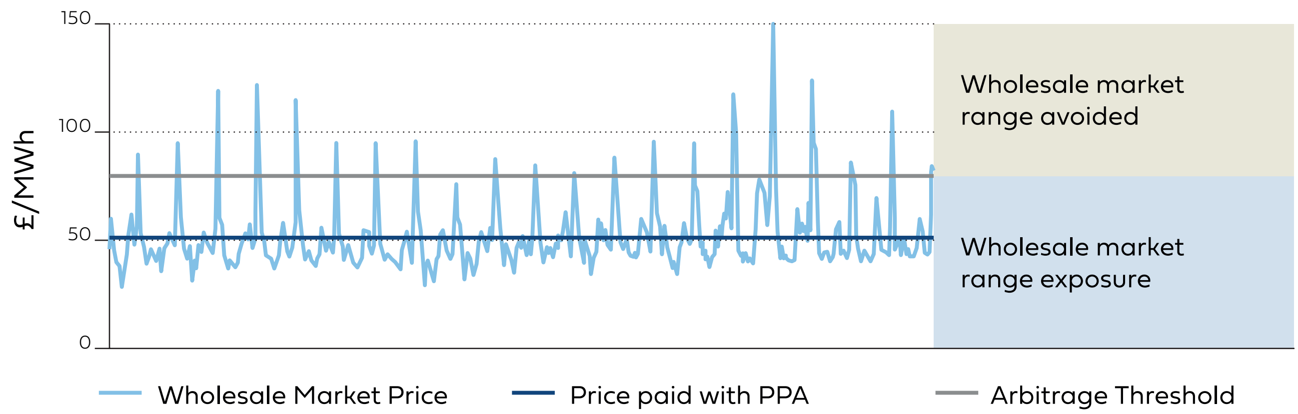


Figure 7-2: Arbitrage and PPA demonstration

41 Whilst not included in this report, the consortium is investigating additional sources of revenue for the business case via participation in the balancing mechanism and wholesale markets.

Power Purchase Agreements

As large and reliable offtakers of power, it is plausible to agree on attractive PPA terms. This can reduce the average power price. However, the terms of the PPA are also dependent on the UK Government's business models. Favourable CfD conditions will likely improve the PPA contractual terms, reducing the LCOH further.

Possible PPA terms are currently being explored and their value has not been included in this analysis. In the Oversized PPA scenario, which has a PPA greater than the $100MW_e$ electrolyser capacity, the complication and likely costs associated with managing the excess volume would need to be accounted for. Either the electrolyser or a paid third-party will need to bear this cost, hence adding an additional cost element to the Oversized PPA structure. Therefore, the Oversized PPA is shown as less expensive relative to a practical scenario.

7.3 Scenario Analysis

$100MW_e$ – As Produced

As shown in Figure 7-3, the pathway achieves a 31% cost reduction from the Base Case, and involves:

- Accessing the 85% EII Exemption, which reduces the cost of green levies by 85%.
- Minimising grid fees associated with power that is metered directly from the wind farm through public decision to remove energy charges and tariffs costs paid on wind farm power.
- Limited arbitrage approaches. It should be noted that reliable and rateable supply will be critical in order to ensure that renewable hydrogen is a viable alternative to natural gas within the UK's industrial decarbonisation. As seen in the figures below, a meditated arbitrage approach with no consumption of power priced above £100/MWh leads to further reductions in LCOH, whilst still meeting >98% of the rateable hydrogen demand.

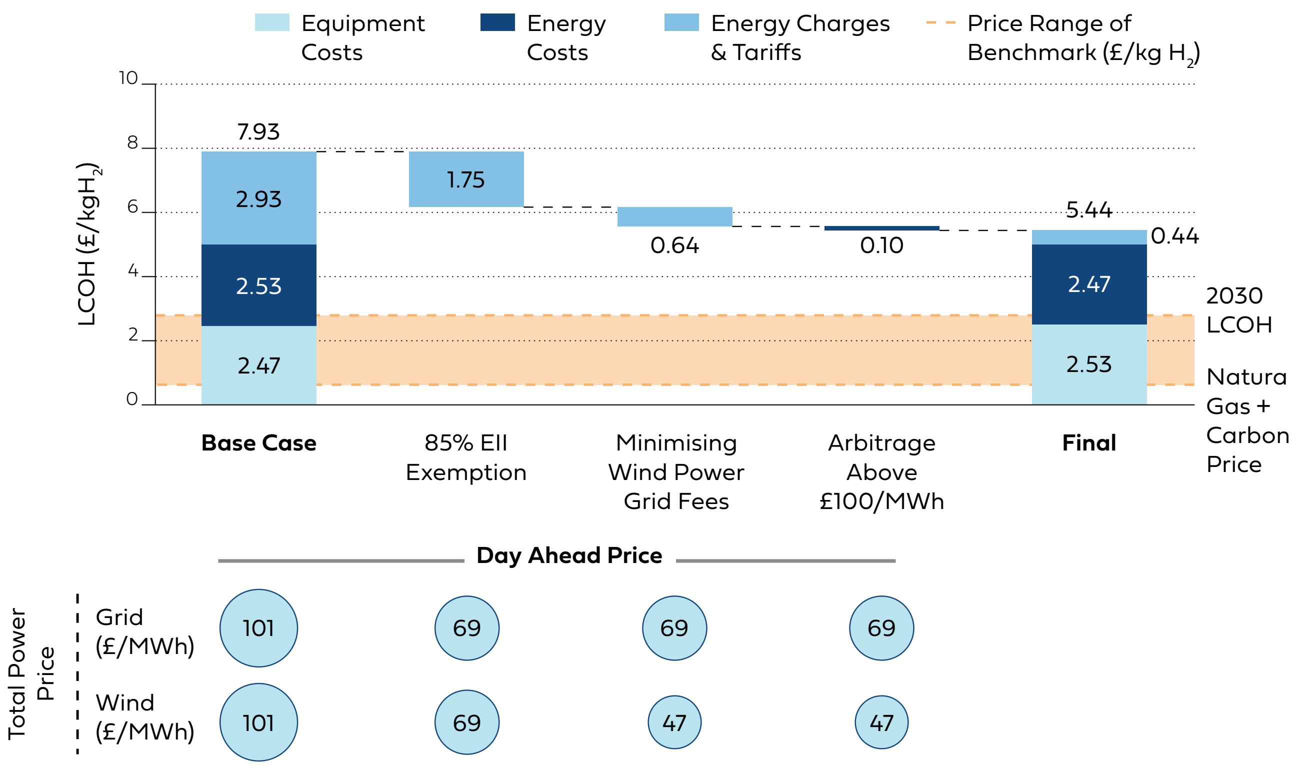


Figure 7-3: Contributions to the reduction of LCOH for As Produced (£/kg H_2)

100MW$_e$ – Oversized PPA

In the Oversized PPA scenario, the same cost reduction pathways and strategies are followed. Since a greater portion of power comes from the wind farm, in theory there should be greater cost reductions associated with the minimisation of grid fees from wind farm power. This leads to a 36% cost reduction on the Base Case. However, once the PPA pricing on managing the additional contracted volume is incorporated, the final LCOH will increase. The size of this green premium is as yet unknown, as discussed previously in Section 7.2.

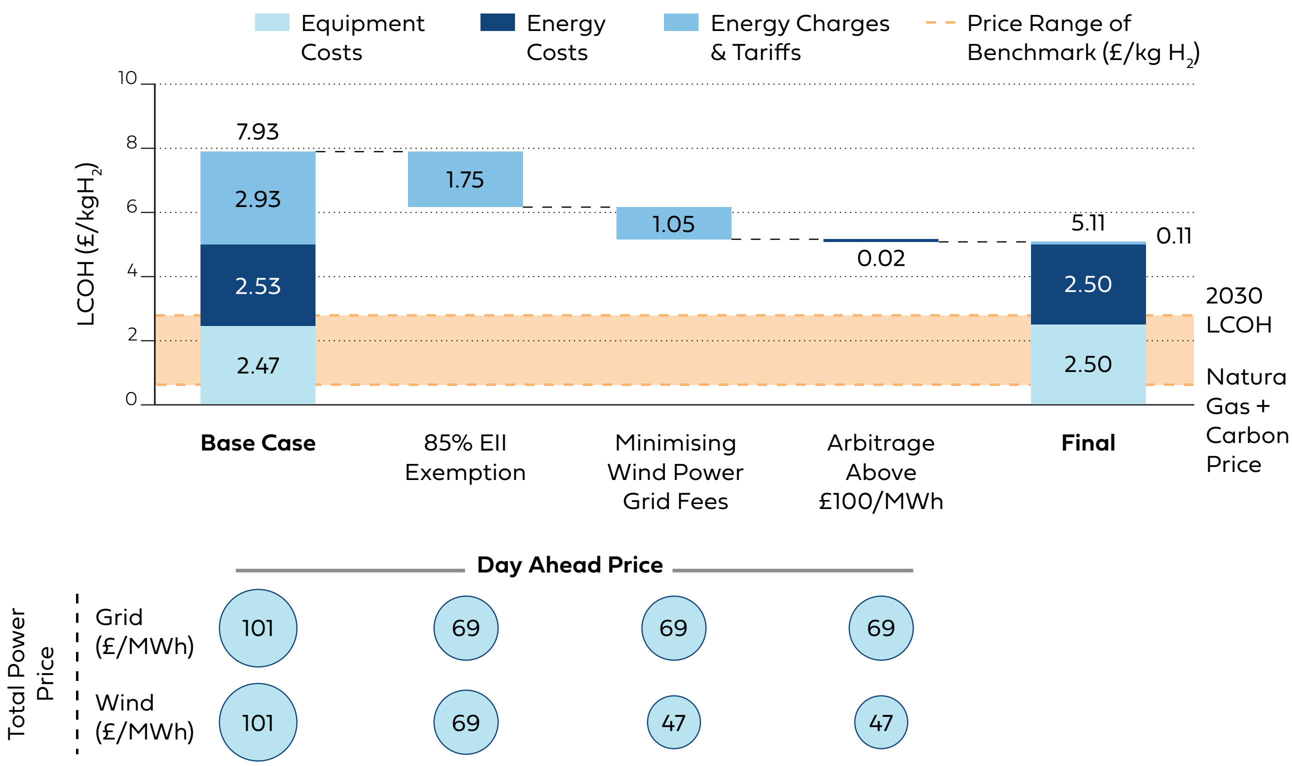


Figure 7-4: Contributions to the reduction of LCOH for Oversized PPA (£/kg H_2)

Figure 7-5 gives a more granular breakdown of the final LCOH of £5.11/kgH_2, including the cost associated with the electrolyser equipment, maintenance and power. The figure shows that the LCOH is dominated by the cost of power. However, cost reductions in areas such as engineering and construction are also important to reduce the LCOH. The CAPEX breakdown is discussed further in the Appendices.

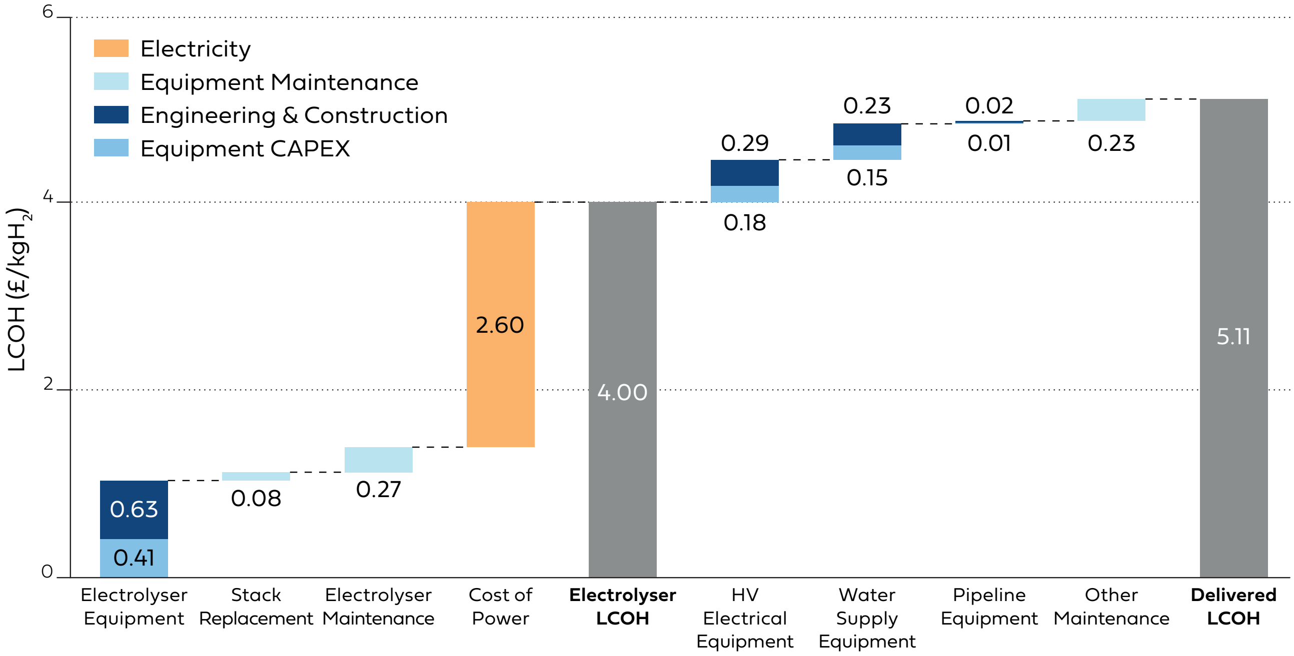


Figure 7-5: Granular breakdown of the levelised cost of hydrogen in the Oversized scenario

7.3.1 Policy Gap and Further Cost Reduction Opportunities

Gigastack has achieved valuable cost reductions on state-of-the-art renewable hydrogen costs, reaching close to £5/kgH_2 once energy charges and tariffs costs are minimised. However, a delta remains between these scenarios and the natural gas plus carbon price counterfactual, valued at £0.85/kgH_2. As mentioned, support from the UK Government is required to enable the consortium to take an FID decision. This support, £4.26/kgH_2 for Oversized PPA and £4.59/ kgH_2 for As Produced, will close the gap with the counterfactual. This support is expected to come in the form of both a capital grant, match funded by the private sector, and operational support. The consortium is working with the UK Government as part of the UK Government's Hydrogen Strategy consultations to bring best value to the UK taxpayer whilst delivering a transformational renewable hydrogen project.

7.3.2 Leveraging Accelerated Renewable hydrogen Support

Funding the renewable hydrogen project in the early 2020s will accelerate the maturity of the sector, enabling faster capital cost reductions and efficiency improvements. Future electrolyser deployments will therefore operate more flexibly, taking advantage of more volatile power pricing[42].

42 Growth of variable renewable electricity production assets as well as higher carbon prices are expected to increase the volatility of the short run marginal cost market (and thus wholesale electricity market).

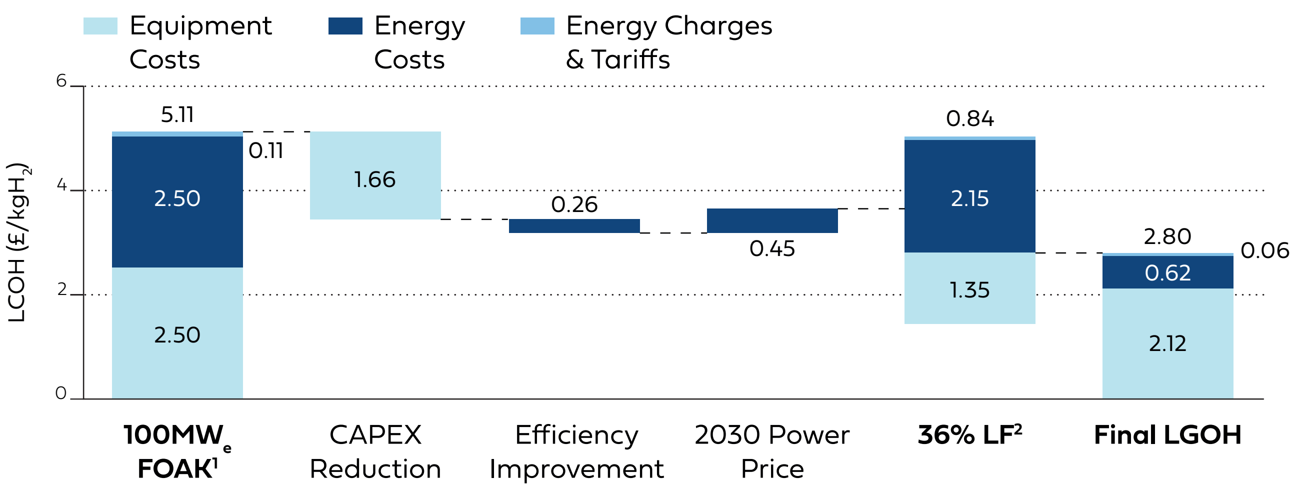


Figure 7-6: Transition to a low cost LCOH in 2030. Starting basis of comparison (first column) is 100MW$_e$ – Oversized PPA scenario before use of arbitrage LCOH reduction[43].

Figure 7-6 shows the transition from the 2020 FOAK Gigastack project to a new renewable hydrogen build which meets the same hydrogen demand[44] as Gigastack in 2030. LCOH reductions are achieved through (i) capital cost reductions to £800/kW$_e$ due to increased technology learnings, this is responsible for a 32.5% reduction, (iii) efficiency improvements from the GEP's envisaged efficiency of 73%$_{HHV}$ to 79%$_{HHV}$, this is responsible for an additional 5.1% reduction and (iii) accessing lowest-cost power periods in the 2030 wholesale using a load factor of 36%, this is responsible for a 7.6% cost reduction. Maintaining rateable hydrogen supply at a low load factor will be made possible by leveraging the UK's future hydrogen infrastructure and storage capability, which will require an additional storage premium. The overall pathway reduction of the LCOH is therefore of 45.2%, to £2.80/kgH$_2$. This pathway, combined with increasing carbon pricing, narrows the gap between renewable hydrogen and the natural gas counterfactual.

43 Figure 7-6 assumes same policy environment which led to LCOH reductions exhibited in 2020 (i.e. EII exemption, minimising wind power grid fees).

44 MW$_e$ capacity is increased when load factor is reduced to maintain annual hydrogen demand.

8

Conclusions and Next Steps

8 Conclusions and Next Steps

Since 2019, Gigastack has made significant advances to develop the concept for the production of bulk, low-cost renewable hydrogen through Gigawatt scale polymer electrolyte membrane (PEM) electrolysis, manufactured in the UK. This was made possible through the provision of funding from BEIS via the Low Carbon Hydrogen Supply Competition as well as the ambitions, collaboration and work of the consortium.

8.1 Final Investment Decision

The consortium's main goal is now to reach FID. FID could be delivered by Q2 2023 if the following aspects are realised on time and with positive outcomes. These will ensure the rapid deployment of the Gigastack project, which could be replicated across the UK.

Renewable Hydrogen Policy Support

The Gigastack activities to date have improved the accuracy of the assumptions used to model the business case for the project. This has allowed the consortium to identify a route to the production of renewable hydrogen for close to £5.00/kgH_2 for this FOAK project, falling to £2.80/kg for a N^{th}-of-a-kind project in 2030.

The activities listed below will further improve the accuracy of this calculation in preparation for FID. However, getting to and then taking FID itself will be contingent on obtaining funding support from UK Government. To get to FID, the consortium requires the following to progress with engineering, planning and permitting:

- Government demonstrating commitment to renewable hydrogen through dedicated production targets and ring-fencing funding in both the Hydrogen Business Model and Net Zero Hydrogen Fund
- Preliminary engagement with the UK Government on the Heads of Terms from the Hydrogen Business Model to increase confidence in attaining a finalised contract

To then take FID, the consortium needs a finalised bilateral CfD with the UK Government, via the IDHRS scheme, for the Gigastack project. Confidence in this decision will be further strengthened by support from the Net Zero Hydrogen Fund.

Gigastack Technology Commercialised

ITM Power has installed the semi-automated manufacturing equipment in their new Giga-Factory and is in the process of commissioning this equipment. The next-generation $5MW_e$ electrolyser system is undergoing representative testing at the $150kW_e$ scale in preparation for large-scale installations.

To prepare for the next phase of the Gigastack programme, ITM Power will prove the manufacturing capability of their factory by building the first $5MW_e$ Gigastack module. This will demonstrate their capability to mass manufacture such technology. ITM Power will then test this first $5MW_e$ system in representative loading conditions to prove its high technology readiness level and readiness for commercialisation and installation at the GW_e scale. These activities will be coordinated with the rest of the consortium to inform the final phases of the FEED study and ultimately the procurement and installation processes.

FEED Study at Advanced Stage

Through Gigastack Phase 2, the FEED study has advanced the technical stage based on the electrolyser scope. The project design and selection of the technical concept for the $100MW_e$ facility is in an advanced stage.

The technical team will now focus on developing preliminary designs for various systems within the technical concept alongside secondary systems. These activities will run alongside the consent and permitting activities needed for the chosen sites (upstream electrical cabling, electrolyser facility and downstream pipework).

Pathway to Resolution Identified for Regulatory Barriers

Gigastack Phase 2 has achieved its objective to identify and highlight regulatory, commercial and technical challenges for real applications of industrial-scale renewable hydrogen systems. Several policy and regulatory barriers to development were identified, with potential solutions laid out.

In the next twelve months (and beyond), the consortium will work to resolve and / or identify solutions for the barriers identified in the Gigastack project and those that emerge through continued project development and value engineering. Where solutions cannot be found in the near term, a long-term pathway or mitigating measures will be developed to provide sufficient certainty and confidence in the project to move to FID.

8.2 Development of a Renewable hydrogen Supply Blueprint

Beyond reaching FID and progressing to a procurement and build phase, the consortium will continue to disseminate information (such as that contained in this report) to facilitate sectoral knowledge sharing. This will help to form a robust blueprint for future renewable hydrogen projects and electrolyser deployments. These actions will reduce the cost of project delivery, thereby reducing the impact of policy asks on the UK Government and also facilitate the pathway to low-cost renewable hydrogen.

Beyond the direct project economics, the continued expansion of the sector will protect and create new highly skilled jobs in Yorkshire and the Humber region. This has the opportunity to transform this region into a centre of renewable hydrogen excellence and expertise whilst enabling the UK to become a global leader in exporting hydrogen technologies.

Finally, the acceleration of the renewable hydrogen sector due to the Gigastack project will reduce the uncertainties, cost and technical challenges in reducing carbon in sectors across the economy. Renewable hydrogen is the cleanest method of reducing carbon in those sectors that cannot easily be electrified and will have a significant role in the UK's energy future.

9

Appendices

9 Appendices

9.1 Business Case Assumptions

Operational assumptions:

- 100MW$_e$ installed in Year 1.
- Stack replacement: Every 9 years (two replacement periods).
- Lifetime: 25-years of operation.
- Some degree of flexibility accepted by the end user (98% supply); no storage of hydrogen is available – 1,850kgH$_2$/hr.
- Perfect foresight when arbitrage is implemented.

Natural gas valued at 1.74p/kWh (incl. Climate Change Levy (CCL)), converted to hydrogen with an equivalent energy density of 142MJ/kg (HHV). Carbon price valued at £20.5/tCO$_2$, extracted from BEIS' Green Book for 2021. Emissions factor for natural gas is 0.00215 tCO$_2$/m^3 at a density of 800g/m^3.

Description of Boundary Limits

The graphic below describes the modelling method used in the business case analysis and the boundary limits:

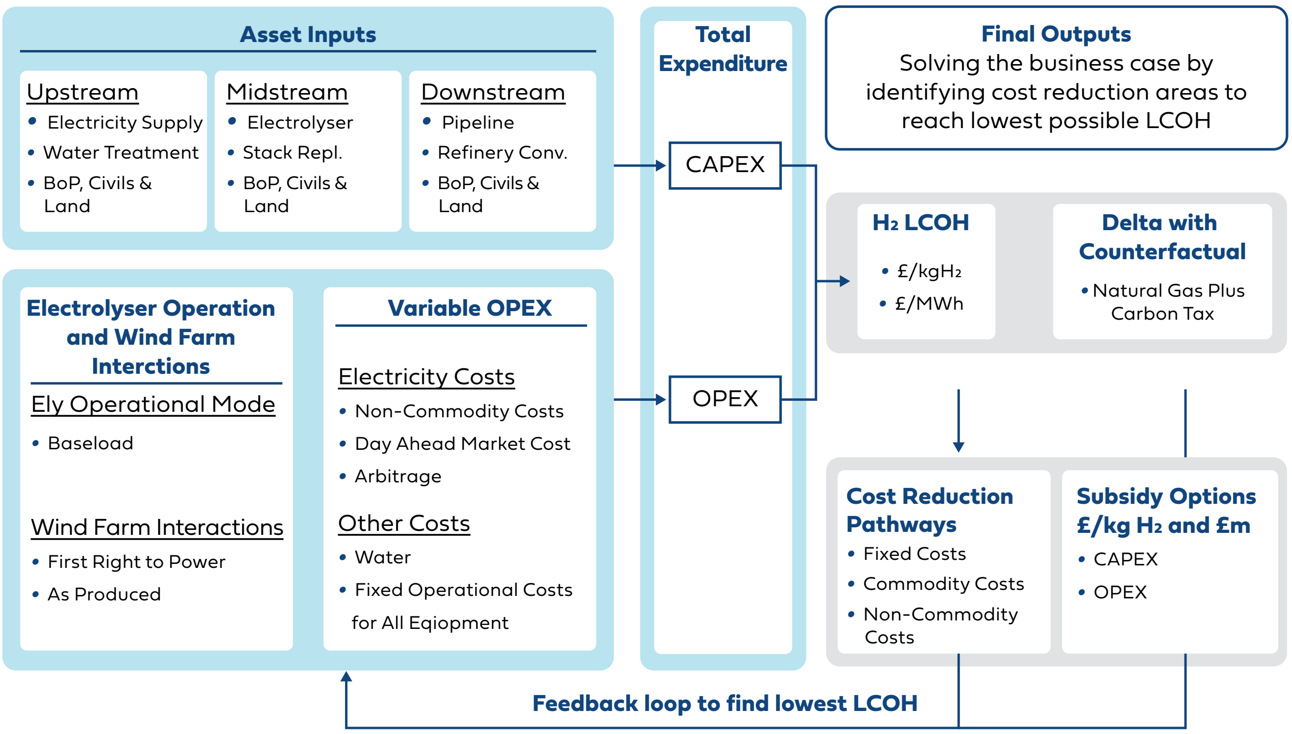


Figure 9-1: Model flow diagram for Gigastack business case analysis

CAPEX and Fixed OPEX

Item	Description	TIC (£m)	Source
Electrolyser	For full 100MW$_e$ deployment	57.0	ITM Cost Data (2021)
Substation Conversion & Electrical Cable	Engineering at wind farm substation and connection between substation and electrolyser	25.7	Unit costs for electrical cabling from National Grid & Element Energy Internal Assumptions
Water Supply	Purification trains for Humber Refinery effluent water	21.0	Gigastack ISCF Phase 1 Study
Pipeline	Connection to the Humber Refinery	1.6	HyNet and BEIS Data
Construction		70.0	Gigastack Programme
Engineering & Other Costs		30.0	Gigastack Programme
Contingency		64.0	Gigastack Programme
Total Installed Cost	-	269.0	

Table 9-1: Total installed cost by cost component

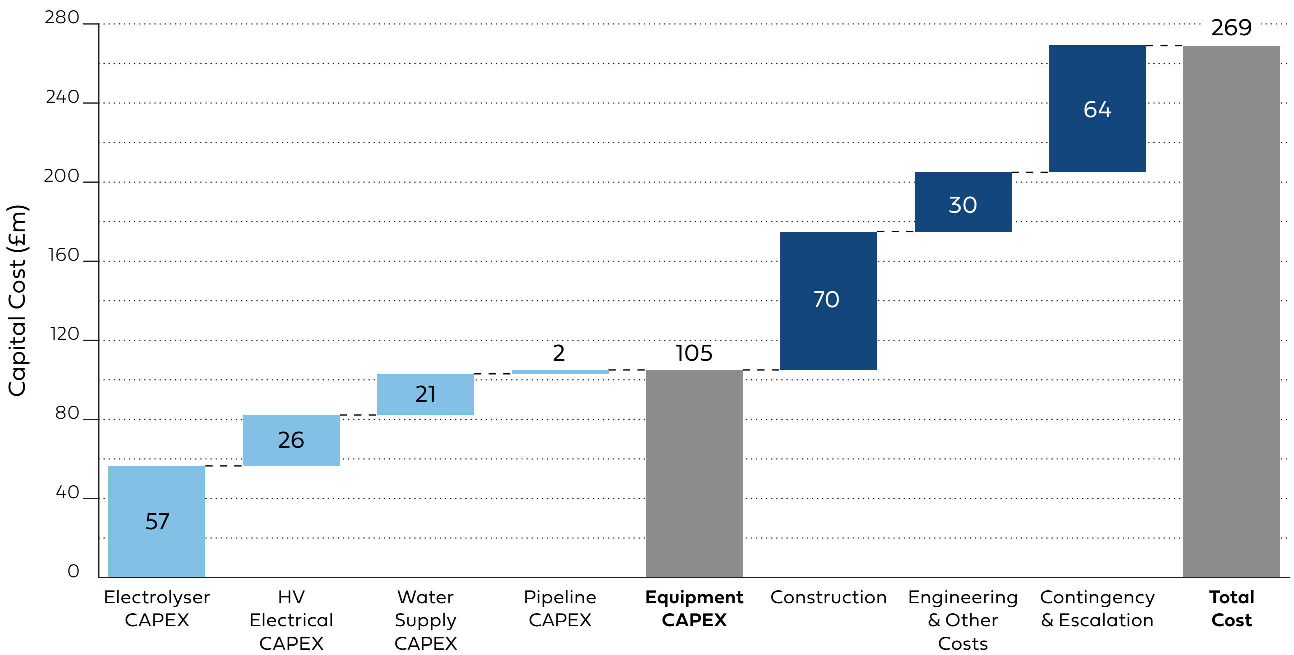


Figure 9-2: CAPEX breakdown by cost component

LCOH is equal to the sum of discounted expenditure divided by the sum of discounted hydrogen sold.

Costing assumptions:

- Fixed OPEX is assumed to be 3% of Total Installed Costs (TIC). Lang Factor: 145%
- Discount factor: 10%
- Decommissioning costs not included

The variable OPEX components (energy costs and energy charges and tariffs) and their public source are listed below:

- BSUoS is sourced from National Grid data and Supplier Margin is sourced from Ofgem data (2020)
- Day ahead wholesale data, (£47/MWh avg.), taken from internal Element Energy Analysis based on 2018 SRMC data
- TNUoS (National Grid ESO & Dukes, TNUoS Tariffs Five Year" & "Chapter 5 Electricity" (2019))

- CM Levy Costs and Green Levies from Gigastack Hydrogen Windfarm Modelling Outputs (2019)

System KPIs

- Please see Table 3-1 for electrolyser KPIs.
- The windfarm profile was sourced from Ørsted's Race Bank Wind Profile Data and manipulated to provide a capacity factor of 54%, as per forecasts for future wind farms[45].

9.2 Technical Solution in Brief Overview

In this section a brief overview of the Gigastack concept design is presented.

The plot plan shows quite clearly that the focal point for the design has been the electrolysis compound in the centre of the facility with all the supporting functions surrounding it.

Transportation routes around the main building is one of the main considerations for easy access to various parts of the plant during the construction phase as well as the operation life cycle of the facility.

Further details including a video of the 3D model can be found on the Gigastack website[46].

The whole concept has been scrutinised from process, constructability and safety aspects aimed at delivering a project that the partners would be confident to develop further and ultimately invest in.

45 Offshore Wind Industry Council, Solving the Integration Challenge, 2020

46 Gigastack Video – A Glimpse at the Future of Renewable Hydrogen

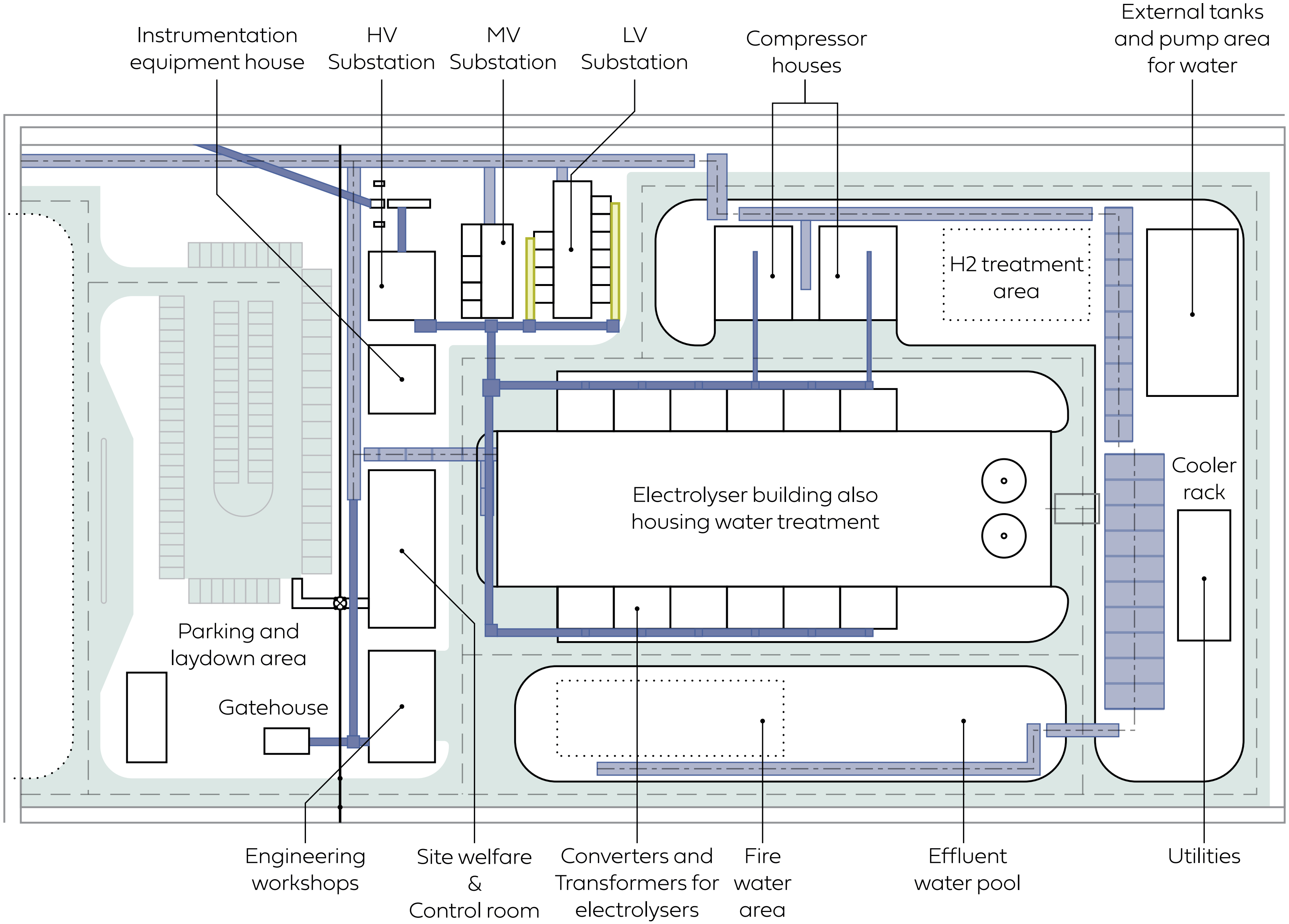


Figure 9-3: Plot plan outcome of the FEED phase of the GGII

GIGASTACK

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