element energy

Gigastack

Bulk Supply of Renewable Hydrogen

Public Report

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Disclaimer

1 Executive Summary

The Gigastack feasibility study was funded by the BEIS Hydrogen Supply Competition to demonstrate the delivery of bulk, low-cost renewable hydrogen through Gigawatt scale polymer electrolyte membrane (PEM) electrolysis, manufactured in the UK. This study brought together; ITM Power, a developer and provider of world-class electrolyser hydrogen systems; Ørsted, the global leader in developing, building and operating offshore windfarms; and Element Energy, a low carbon, sustainability and consumer behaviour consultancy and engineering practice. The consortium has delivered the following primary conclusions:

- ITM Power has furthered the designs of its next generation of innovative stack technology. The new 5MW stack will enable the development of the 100MW electrolyser systems that are required to meet the UK's legally binding net zero target by 2050. These installations will come at a fraction of today's cost, with the installed electrolyser system costing less than £400/kW.

- These stacks will benefit from cost reductions due to ITM Power's new Giga-Factory at Bessemer Park, Sheffield[1]. This will come about due to standardisation and industrialisation. As a result of the capacity modelling and machine analysis, the factory will manufacture 60 stacks per year from 2023 (300MW/yr), tending towards 200 stacks per year in the mid-2020s (1GW/yr).

- The most significant contributor to the cost of renewable hydrogen is the cost of the electrical input. Work by Element Energy and Ørsted assessed siting the electrolyser in innovative locations and exploiting electrolyser-windfarm configurations to reduce these costs. Today, the cost of renewable hydrogen from grid-connected electrolysers is more than £8/kg. The pathways analysed here for the new 5MW electrolyser and power supply, without full exposure to grid fees, could deliver a produced renewable hydrogen relative cost saving of more than 50%. With further regulatory intervention, commercial optimisation, industrialisation and increased production volumes of electrolysers the results of the feasibility study show further potential cost reductions of up to 50% (scenario dependent).

- Combined the reduced stack cost, increased manufacturing capacity and the innovative technical configurations enabled the consortium to identify viable business cases for supplying hydrogen to industry and transport end-users. This is enabled through cost competitive renewable and high purity hydrogen at a range of scales, not possible for reformers with carbon capture and storage (CCS) due to the high purification costs and inflexibility in build capacity.

- An analysis of the hydrogen demand from target markets for renewable hydrogen (i.e. industry, transport, hydrogen for heat) both nationally and internationally from 2020 to 2030 validates ITM Power's proposal decision to ramp-up to a factory capacity of 1GW/yr over an accelerated timeframe. In all scenarios considered, the hydrogen market deemed accessible to ITM Power's new 5MW stack far exceeded their production rate of 1GW/yr from 2025. The High Ambition scenario even demonstrated that two additional factories of similar capacity would be required to satisfy the accessible demand by 2030.

[1] https://www.itm-power.com/news-item/new-factory-update-and-senior-production-appointment

2 Introduction

2.1 Hydrogen in a Net Zero Economy

As a signatory to the Paris Agreement, the UK is committed to contributing towards efforts to keep global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. This was further enforced in June 2019 with the UK Government's introduction of primary legislation committing the UK to reaching a 100% reduction in greenhouse gas emissions, commonly known as Net Zero, by 2050. This legislation was based on the recommendation of the Committee on Climate Change's (CCC's) May 2019 report on net zero[2].

The CCC's report recognises that, to achieve these targets, extensive decarbonisation across the UK's economy is required along with a transition from incumbent fossil fuel utilisation to a low carbon system. A wide variety of technologies, energy sources and energy vectors are required to meet these targets and ambitions. Both the CCC[3] and bodies such as the International Energy Agency[4] recognise that "*the time is right to tap into hydrogen's potential to play a key role in clean, secure and affordable energy future*". Hydrogen has the potential to decarbonise sectors across the UK economy including industrial process, transport and heat. It is this wide range of applications that makes hydrogen such an exciting prospect in the future of the UK's energy system.

Currently, there are two primary pathways that are used for hydrogen production; (i) the reformation of natural gas and (ii) electrolysis. Reformation, typically steam methane reformation, converts a stream of natural gas and steam into hydrogen and carbon dioxide using a specialised catalyst. Electrolysis, meanwhile, splits water into hydrogen and oxygen using electricity. Electrolyser technologies are divided between polymer electrolyte membrane (PEM) electrolysis and alkaline electrolysis; this study focusses on PEM electrolysis.

The reformation of natural gas, whether it be "Steam Methane Reformation" or "Auto-Thermal Reformation", currently produces the majority of the world's hydrogen. However, for these pathways to play a role in a net zero scenario, they will require large scale carbon capture and storage (CCS). Conversely, with the prospect of much greater supplies of low-cost renewable electricity (especially in nations with large renewable resources such as the UK), the production of hydrogen via electrolysis offers a means for carrying renewable energy into the energy system and, in doing so, minimising carbon emissions and CCS requirements. Electrolysis has come to the fore because of the combined potential of renewable hydrogen as an energy vector and electrolysers as flexible electrical loads.

Renewable hydrogen (i.e. that produced using renewable electricity; a windfarm for example), has a number of benefits that makes it attractive despite its higher cost than reformed hydrogen

- Reformation is carbon intensive. For each kilogram of hydrogen produced, circa 10kg of CO_2 is released without CCS[5]. Even with CCS, the capture rate is not 100%. This limits the applicability of this solution in achieving the objectives of Net Zero. Carbon emissions from electrolytic hydrogen, however, are only associated with the carbon intensity of the electricity used to produce it. To meet the UK's legally binding target of net-zero, clean technologies such as electrolysis are required. Where renewable electricity is used to split the water, the hydrogen product is termed *renewable hydrogen*.

[2] Committee on Climate Change. (2019). *Net Zero: The UK's contribution to stopping global warming*.
[3] Committee on Climate Change. (2018). *Hydrogen in a low-carbon economy*.
[4] IEA. (2019). *The Future of Hydrogen*.
[5] H21, Northern Gas Networks, Equinor, & Cadent. (2018). *H21 North of England*.

- The hydrogen purity from an electrolyser is inherently higher than that from fossil fuel reformation, which require expensive and inefficient purification steps for high grade purity. This makes it attractive to markets such as hydrogen for transport since high purity hydrogen is required to avoid poisoning the vehicle's fuel cell.

- The only resources required to produce electrolytic hydrogen are water and electricity. An increased UK portfolio of electrolysers would decrease our dependency on imports of foreign natural gas and, thereby, increase the security of our national energy supply.

- Finally, hydrogen production from electrolysers is inherently flexible. This means that; (i) the electrolyser can respond to changes in the setpoint in sub-second time frames, allowing it to follow the generation profile of variable renewable energy sources; (ii) the asset can operate at a wide variety of load factors; and (iii) the 5MW modular stack design enables the electrolyser to be built at a variety of capacities to suit the use case.

2.2 Scaling-Up Electrolysis

Despite these benefits, the majority of hydrogen demand currently comes from industry and requires a bulk supply. The deployment of electrolysers on such a large scale to deliver the hydrogen needs for the UK's net-zero target has not been possible. Electrolyser deployments to date have consisted of sub one-Megawatt (MW) installations for transport and power-to-gas systems, with plans for up to 10MW in the pipeline for refineries (Refhyne[6]). These projects show that electrolyser technology is commercial but is not currently scalable for the required bulk scale energy applications in excess of 100MW.

Large scale deployment requires low-cost stack modules which are easily integrated into larger electrolyser systems. Furthermore, the largest electrolyser factories globally are capable of less than 30MW of electrolyser capacity output per annum. For electrolysers to have any impact on the energy system at a bulk scale, this must be increased in the order of GWs of electrolyser output per year (in a similar fashion to the recent expansion in solar and wind manufacturing facilities). This requires an increase in throughput and hence the use of automation to reduce unit manufacturing costs.

In addition to low capacity stack modules and low manufacturing rates, the commercial viability of electrolytic hydrogen is further hampered by high electricity costs associated with grid electricity. The price of electricity can contribute up to 85% of the total cost of producing the hydrogen. Accessing lower cost electricity requires large scale systems to create bankable business cases for energy suppliers, to warrant issuing attractive power purchase agreements, and innovative siting to gain access to configurations that enable the desired electricity price reductions.

A number of industry reports are concluding that renewable electrolytic hydrogen will be an important component in the UK's future energy system and will be vital in decarbonising a number of sectors to meet the UK's 2050 legally binding net zero target. The development of this sector will also bring significant economic benefits. Increased renewable hydrogen activity will lead to growth and investment from the entire hydrogen supply chain. Hydrogen Europe has forecasted that hydrogen could create an accumulated investment of €52bn and 850,000 new jobs across Europe[7]. The UK, therefore, has a significant opportunity to become a centre of excellence in and global exporter of innovative hydrogen technologies and practices. To deliver this

[6] http://www.itm-power.com/project/refhyne
[7] Hydrogen Europe. (2018). *Hydrogen, Enabling a Zero Emission Europe*.

future however, activity and support is required today to resolve these problems and to develop a trajectory to the bulk supply of renewable hydrogen.

2.3 BEIS' Hydrogen Supply Competition

The BEIS' Hydrogen Supply Competition provides consortia with the opportunity to address these outstanding issues through the development of new technologies, business cases and working relationships. The first phase of this competition funded, amongst others, the Gigastack project. Work on this project was concluded in September 2019 by a consortium comprised of ITM Power, Ørsted and Element Energy.

ITM Power, an AIM-listed company registered in England, has grown from a basis in hydrophilic ionic polymers to that of a hydrogen systems developer and provider over the last seventeen years. Over the last ten years, ITM Power has greatly contributed to the hydrogen technology space through the development of products for market, rigorous scientific testing, product design and development, CE marking and safety compliance. This is made possible through their first-class team of engineers and scientists based at their two facilities in Sheffield.

ITM Power is committed to the development of clean fuel systems for fuel cell electric vehicles (FCEVs), hydrogen energy storage, hydrogen gas injection and hydrogen systems for synthetic natural gas production. It is for these reasons that ITM Power has allocated significant resources to the Gigastack programme and the development of renewable hydrogen.

The **Ørsted** vision is a world that runs entirely on green energy. Ørsted is the global leader in offshore wind, including US, Asia and Europe. In the UK, Ørsted develops, constructs and operates offshore wind farms as well as battery storage and innovative waste-to-energy solutions. Ørsted has invested £8 billion in the UK to date, with eleven operational wind farms. A further £4 billion investment is planned by 2020.

Ørsted has worked with ITM Power and Element Energy through the Gigastack project to identify the potential synergies that exist between windfarms and electrolysers, enabling Ørsted to explore the potential for renewable hydrogen. This could potentially lead to greater investment in UK activities by accessing a new market.

Element Energy is a low carbon, sustainability and consumer behaviour consultancy and engineering practice providing strategic advice, computational modelling, software development and engineering consultancy across the buildings, transport and power sectors for a broad range of clients.

Element Energy has been involved in hydrogen technology since its formation in 2003 and the company's directors have worked on hydrogen engineering projects since 1999. With two decades' experience in hydrogen mobility, Element Energy has particular expertise in initiating and coordinating ambitious hydrogen energy projects throughout the UK and Europe. They are coordinating the FCH JU's major deployment projects for fuel cell cars and buses (H2ME, ZEFER, JIVE), which together receive €124m of FCH JU funding. Element Energy are also active in initiating early deployment projects in areas which are of importance to the low carbon transition.

3 Gigastack Feasibility Study Aims and Activities

Achieving the aims of the Gigastack feasibility study precedes the consortium's greater ambitions for large-scale electrolysis in the UK. Through this first project and subsequent phases of development, the consortium will work to resolve the barriers to the bulk supply of renewable electrolytic hydrogen enabling reliable production of low-cost, renewable electrolytic hydrogen via Gigawatt (GW) scale PEM electrolyser deployments. This work will also benefit the UK's export potential and hydrogen technology supply chains (through job creation and upskilling) which will help the UK to become a centre of excellence for hydrogen technologies and innovation internationally.

Specific to the feasibility study, the consortium worked to:

i. Develop the designs for ITM Power's next generation of stack technology that decreases the cost of the 5MW stack cost on a £/kW basis by more than 40% and enables the ramp up to 100MW deployments. This will reduce the capital cost contribution to the cost of hydrogen on a £/kg basis.

ii. Create a factory capacity model to calculate factory throughput and to identify the optimal factory layout and number of jobs created.

iii. Analyse and assess windfarm-electrolyser technical configurations that deliver a reliable supply of low-cost renewable hydrogen. This also considers the practicalities of these configurations, as defined in Section 3.3, and the timescales over which they could be implemented.

iv. With these windfarm-electrolyser configurations, assess the business case for hydrogen (in the scope of an industrial cluster) in the industry, transport and heat sectors. Through this process, the roll-out strategy and target markets for hydrogen were also identified.

The results of this feasibility study will support the consortium's efforts in preparing for Phase 2 of BEIS' Hydrogen Supply Programme and the further development of the Gigastack programme.

3.1 Next Generation of ITM Power Electrolyser Stack

The first aim of the project was for ITM Power to create computational designs for their fourth generation of stack, which will have a capacity of 5MW, and to finalise the material specifications for the stack itself. This design will increase the stack capacity, reduce material costs and make the stack compatible with semi-automated manufacturing. This will contribute to a system cost of less than £400/kW.

The targeted stack capacity is an order of magnitude increase on ITM Power's third generation of stack which has a capacity of 0.67MW. This would reduce the number of stacks required for a 100MW deployment from 150 to 20. An example of such a facility is shown in Figure 1. This step change will decrease the installed cost of the electrolyser systems. This, in combination with the aforementioned material specification and compatibility with the semi-automated manufacturing will minimise the contribution of the Capex and maintenance to the hydrogen cost.

A stack of this size is not required for today's commercial requests of 1-10MW. BEIS funding is, therefore, required to warrant the development of this system for the market of the future and that renewable electrolytic hydrogen is a viable component of the net-zero requirements of the UK.

ITM Power finalised the designs for the next generation 5MW stack using computational techniques and physical tests. This design work included specifying the required stack materials, preliminary stack dimensioning, stack volume, stack design pressure, the pressure equipment directive requirements for the stack, hazard assessment and the stack availability.

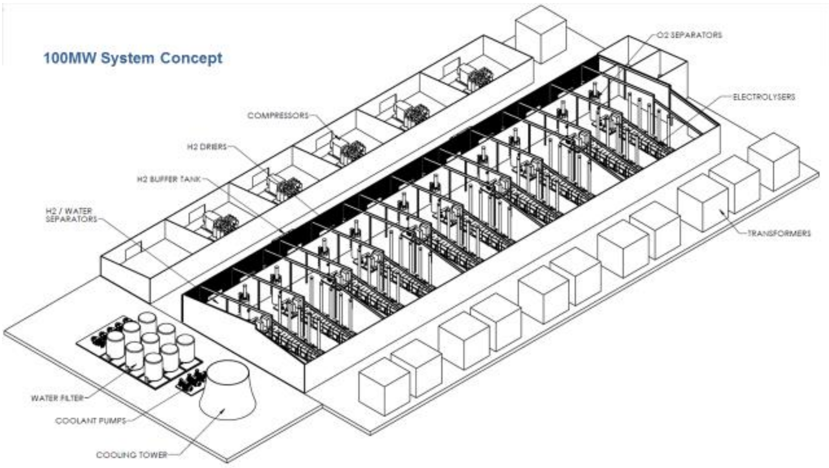

Figure 1: ITM Power 100MW electrolyser facility concept

This design work also considered new processes and policies which reduce stack cost. These included; bringing some processes in-house, such as platinum coating on the surface of electrodes; the use of titanium electrode welding; recycling waste material; and reductions in order costs through bulk procurement.

Furthermore, physical tests were also completed. For example, new polymer electrolyte membranes were tested to improve stack efficiency and lower costs. To do this, membranes of different chemical formulae and varying material thicknesses were tested across 1,500-hour testing period.

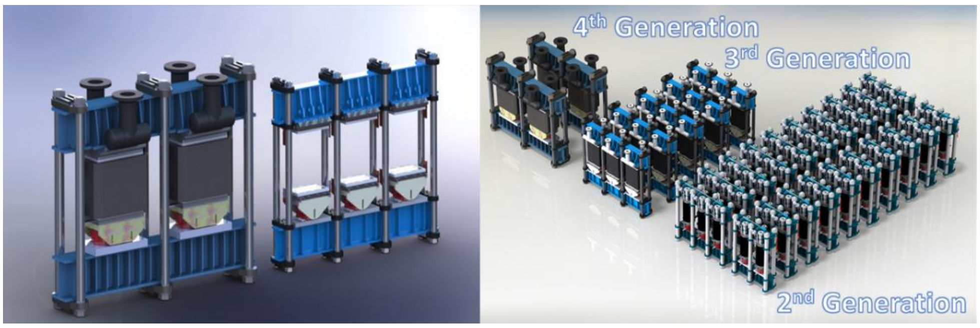

Figure 2: New 5MW module (*left*) and footprint comparison with the 3rd and 2nd generation of ITM Power electrolyser modules

As a result of this work, ITM Power has developed designs for a stack with a 30-bar hydrogen production capacity an order of magnitude greater than their incumbent technology (2.1 tonnes per day versus 350 kilograms per day). Additionally, the system will also produce oxygen at pressure.

ITM Power also demonstrated, through this testing and material specification, that the targeted cost reduction in excess of 40% at the stack level could be achieved, as shown in Figure 3. Out to 2020, these changes will be introduced and will reduce the stack cost accordingly. When combined with improvements in the balance of plant, economies of scale and reduced labour costs, the cost of a complete installed electrolyser is reduced to less than £400/kW.

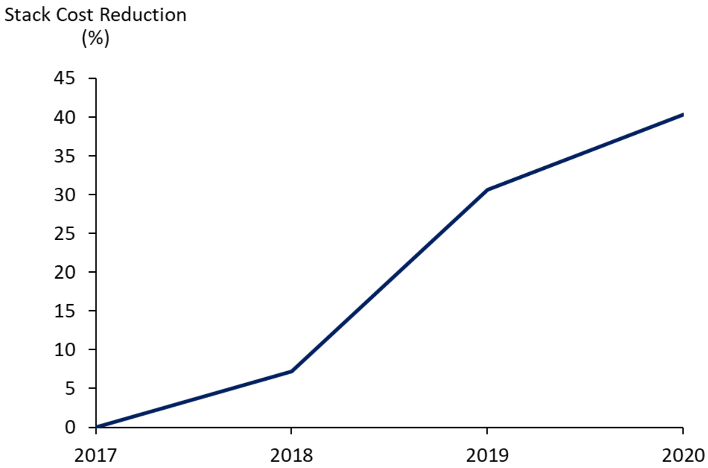

Figure 3: Stack cost reductions through time due to industrialisation, material specifications and specialised manufacturing techniques

In addition to cost, there have been a number of other stack improvements. Figure 2 shows the number of systems required to deliver a 10MW electrolyser system. This highlights the significant balance of plant improvements that have greatly reduced the footprint of the electrolyser system. Furthermore, the tests on the new stack membranes yielded an efficiency of 82% (HHV)[8]. Other KPIs, such as stack degradation, are also within the FCH JU's targeted ranges out to 2030, as shown in Table 1.

Table 1: FCH 2 JU Multi-Year Annual Work Plan (MAWP) targets with ITM Power targeted performance

FCH 2 JU Multi-Year Annual Work Plan Targets		State of the Art (2017)	2020	2024	2030	Gigastack
KPI1	Electricity Consumption @ Nominal Capacity (kWh/kg)	58	55	52	50	54
KPI2	Capital Cost (£/kW)[1]	1,090	820	640	450	300-400
KPI3	Degradation (%/1,000hrs)	0.25	0.19	0.125	0.12	0.09
KPI4	Hot Idle Ramp Time (s)	10	2	1	1	<1
KPI5	Cold Start Ramp Time (s)	120	30	10	10	<30

1: Assuming €1.10/£
KP4 & KP5 shall be considered as optional targets to be fulfilled according to the profitability of the services brought to the grids thanks to the addition of flexibility and/or reactivity (considering also potential degradation of the efficiency and lifetime duration.

Along with these improvements, existing benefits of hydrogen production via electrolysis remain. For example, the hydrogen purity will still comply with the most stringent standards (Grade D of the upcoming ISO 14687, being developed by ISO TC 198).

3.2 Developing the World's Largest Electrolyser Manufacturing Facility

The second aim of the project was for ITM Power to develop its "Giga-factory" which will enable an increase in production capacity up to 1GW/yr through a stream-lined semi-automated manufacturing process. This

[8] System efficiency is expected to be lower, with a targeted efficiency of 73% at a 100% load factor.

factory, based at Bessemer Park in Sheffield, will manufacture electrolysers at a large-scale with a footprint of 134,000 square feet, as shown in Figure 4.

In this work, ITM Power aimed to accelerate the development of the factory and assess innovative processes; this is only made possible through funding from BEIS. Specifically, ITM Power aimed to:

- Validate their factory throughput, factory layout and the number of jobs required through computational modelling.

- Assess the semi-automated manufacturing assets required to deliver the increase in production capacity

- Assess production flow software, never before used in electrolyser manufacturing

Figure 4: ITM Power's Giga-factory exterior (*left*) and modelled interior (*right*)

ITM Power developed a factory capacity model. This model lays out the physical space required for manufacturing these stacks up to the 300MW/yr and 1GW/yr levels. Additionally, the model also identified the workforce required to operate the factory alongside the increase in production capacity through time.

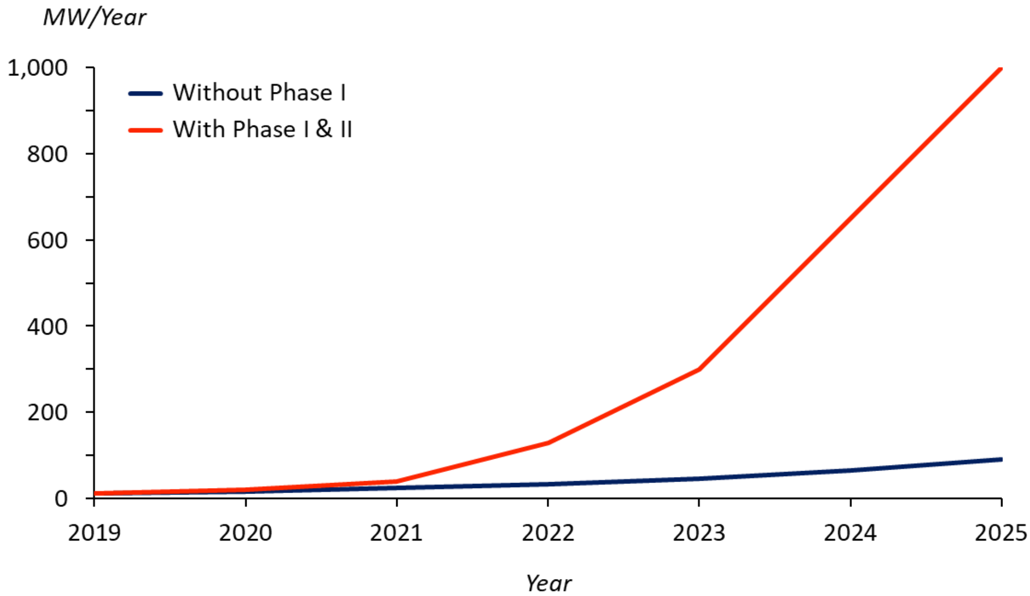

Figure 5: Increase in factory electrolyser capacity out to 2025 with and without BEIS funding

ITM Power also identified the manufacturing assets needed to deliver the targeted throughput of electrolyser stacks. This was done through a series of expert consultations and tests which assessed both the cell and stack manufacture. Where existing processes were insufficiently capable (i.e. too slow), ITM Power sourced or developed the necessary solutions. A production management solution has also been assessed to deliver state-of-the-art just-in-time (JIT) management of the high throughputs of stacks.

Through its work on the capacity model, ITM Power was able to optimise the layout of their new factory. At the end of the study, the architectural design for the factory was frozen. The final design and factory capacity model will enable ITM Power to ramp-up to 300MW/yr by 2023, as shown in Figure 5 and expand to 1GW/yr by 2025. Figure 5 also highlights the additionality of funding from BEIS; funding of Phase 1 (and an eventual Phase 2) allows ITM Power to accelerate the expansion of their Gig-factory such that, by 2025, the production capacity of the factory by a factor of more than ten.

The model also identified a total of 78 new full-time employees (FTEs) for manufacturing at the 300MW/yr level and a trajectory for FTEs required out to the 1GW/yr level. This is shown in Figure 6.

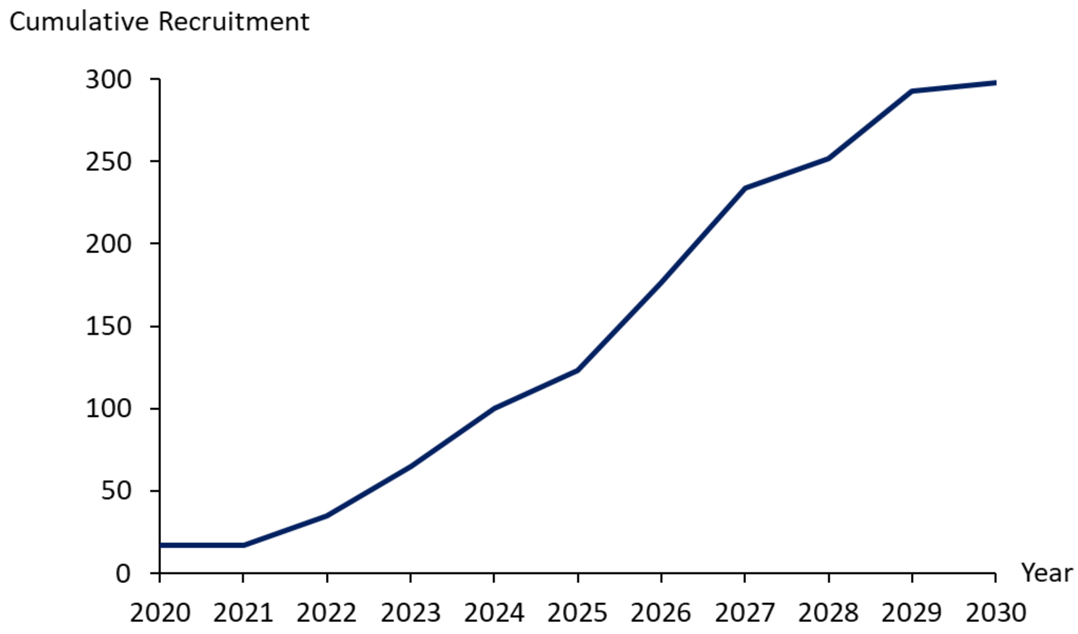

Figure 6: Cumulative recruitment for the Gigastack factory out to 2030

Amongst these manufacturing solutions, ITM Power also identified the necessary machinery (where available and appropriate) and developed innovative designs for bespoke equipment. Through this process, the following items were identified: injection moulding, precision edge stamping, electrode edge finishing, CNC electrode pre-assembly, fully automated inspection vision system and cutting-edge surface deposition. The introduction of these semi-automated manufacturing processes over the incumbent manual ones will be transformative. Some of these automated processes will reduce material wastage and will remove bottlenecks in the manufacturing process.

Finally, ITM Power chose a lean production flow control system called an Andon system. This has never before been used in electrolyser manufacturing. A manual equivalent was trialled in Phase 1 including staff training and reporting. This will minimise disruption when transitioning to the new factory.

This work has enabled ITM Power to reach a manufacturing readiness level of five / six (Capability to Produce Prototype Components in a Production Relevant Environment / Capability to Produce a Prototype System or Subsystem in a Production Relevant Environment).

3.3 Synergising the UK's Windfarms with Electrolyser Technology

The third aim of the project was to analyse and assess a series of electrolyser-windfarm configurations that would deliver renewable hydrogen. Whilst ITM Power's work in this project focussed on developing technology and infrastructure that enables the deployment of 100MW electrolysers and reduces electrolyser system costs, the cost of electricity remains the most dominant component of the cost of hydrogen. It is therefore important to identify ways to reduce cost of electricity whilst ensuring a reliable supply of hydrogen for an array of end-users.

To ensure complete coverage of a wide variety of factors, four scenarios were created; see Figure 7:

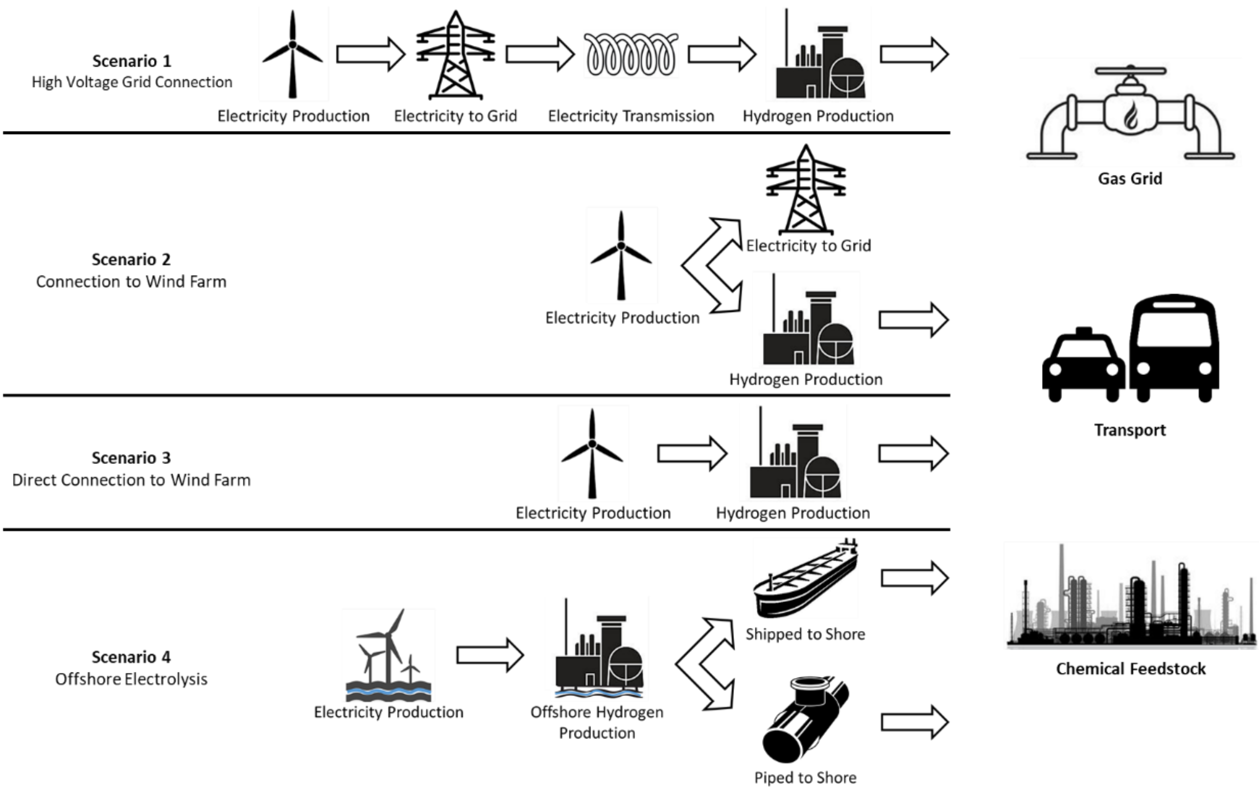

Figure 7: Scenario analysis for identifying a low-cost reliable supply of renewable hydrogen

- **Scenario 1:** The electrolyser is sited anywhere in the UK where it can form a high-voltage grid connection to the UK electricity network. To ensure the hydrogen is renewable, the electrolyser makes a commercial arrangement with a renewable energy generating asset (a windfarm in this case), thereby procuring the renewable electricity that the asset produces.

- **Scenario 2:** The electrolyser is sited upstream of the meter between the renewable energy generating asset and the electricity grid. In this way the electrolyser has access to electricity from the windfarm on a private meter and from the grid through the pre-existing meter. This scenario minimises impact on the transmission grid and includes reduced grid fees and tariffs (both transmission and distribution).

- **Scenario 3:** The electrolyser is built with and directly coupled to a new windfarm (i.e. both assets are built at the same time). The electrolyser has access to the levelised cost of the output power from the windfarm, as opposed to the market price.

- **Scenario 4:** The electrolyser is built offshore in close proximity to the offshore wind turbines. In this way, offshore electrical cables are avoided, and cheaper pipelines can be accessed. The electrolyser accesses the energy at a price equivalent to the levelised cost of the wind turbine.

Ørsted began this work by assessing the technical feasibility of these four scenarios. This included:

- Establishing the sub-scenarios based on variations to the underlying assumptions for each scenario.

- Identifying the possible operating profiles for the electrolyser in each scenario; as shown in Figure 8.

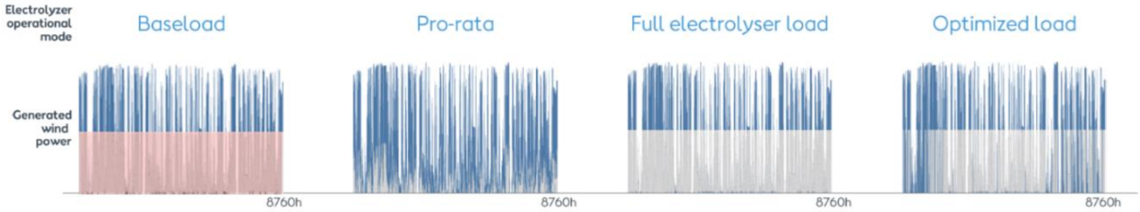

Figure 8: Electrolyser operating profiles

- An overview of the unit operations from electricity generation to hydrogen production; as shown in Figure 9.

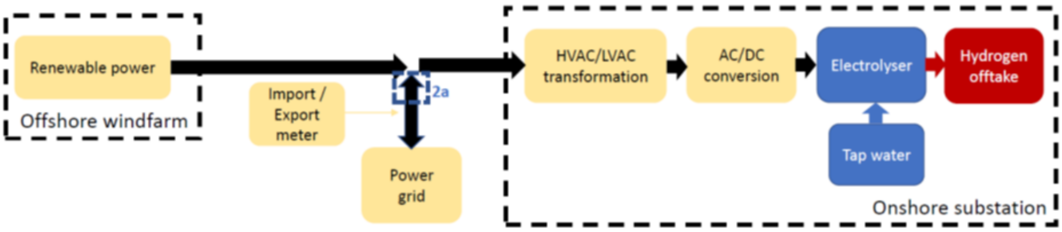

Figure 9: Overview of the unit operations for Scenario 2

- Identifying constraints on the electrolyser operation and / or capacity by the scenario configuration.

- The respective advantages and disadvantages of each scenario.

This analysis enabled Ørsted and Element Energy to work together to collect the required data points and assumptions to model each scenario and sub-scenario. The majority of this data was from public resources such as The Crown Estate Report on “A Guide to Offshore Windfarms”[9]. The calculation methodologies are shown in Figure 10 and 11 for Scenarios 1 & 2 and Scenarios 3 & 4 respectively.

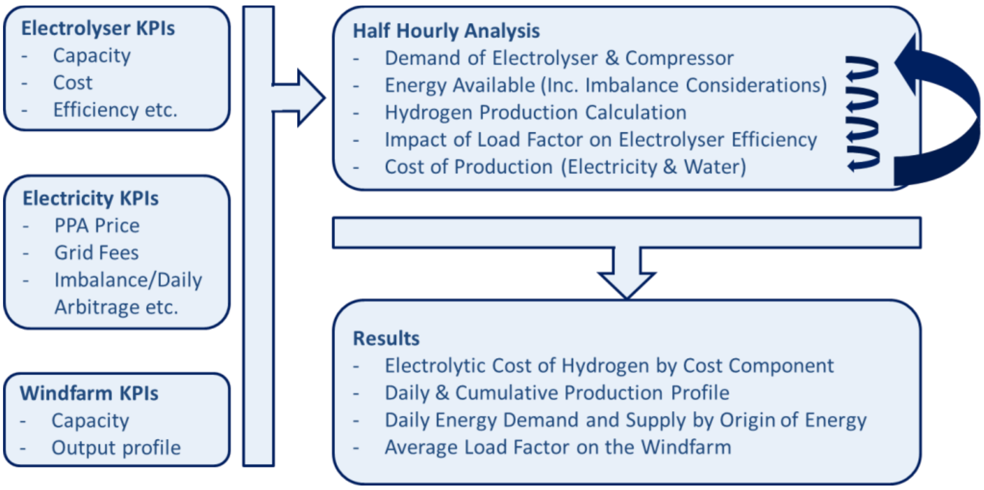

Figure 10: Process flow diagram for calculating the cost of hydrogen production and the production profile for Scenarios 1 & 2

These models allowed Ørsted and Element Energy to calculate and optimise the cost of hydrogen production (i.e. at 30 bar) and to assess the reliability of the production profile.

[9] BVG Associates. (2019). *Guide to an offshore wind farm*.

Scenarios 1 and 2 differ to Scenarios 3 and 4 in that they are grid connected, cost is therefore a function of market forces and regulations. The dominating cost elements are therefore the price of the electricity (whether that be the wholesale grid price or the price of the purchase power agreement) as well as grid fees and tariffs (both distribution and transmission). In all scenarios, a 75MW electrolyser was analysed.

These scenarios were optimised by:

- Testing the sensitivity to the price of the power purchase agreement
- Introducing daily arbitrage during expensive hours, i.e. turning off during red band hours between 4pm and 7pm to avoid expensive transmission and distribution charges
- Gaining access to policies like the "Energy Intensive Industries" exemption which allow consumers to waive up to 85% of the green levies
- Accessing the imbalance market to benefit from payments by National Grid to increase or decrease the operational set-point of the electrolyser
- For Scenario 2 only, to what extent the electrolyser is exposed to grid fees
- Any design improvements that come from siting the electrolyser in close proximity to the substation

Scenarios 3 and 4 focus on building the electrolyser with new windfarms. Scenario 4 is particularly innovative since the electrolyser is built offshore (either within the wind turbine itself or on a floating platform) and uses pipelines to transport hydrogen to shore. Since these scenarios access power prices at the levelised cost of the windfarm[10], the cost of hydrogen is dependent on windfarm system changes, industrialisation and the technological improvements in windfarm technology.

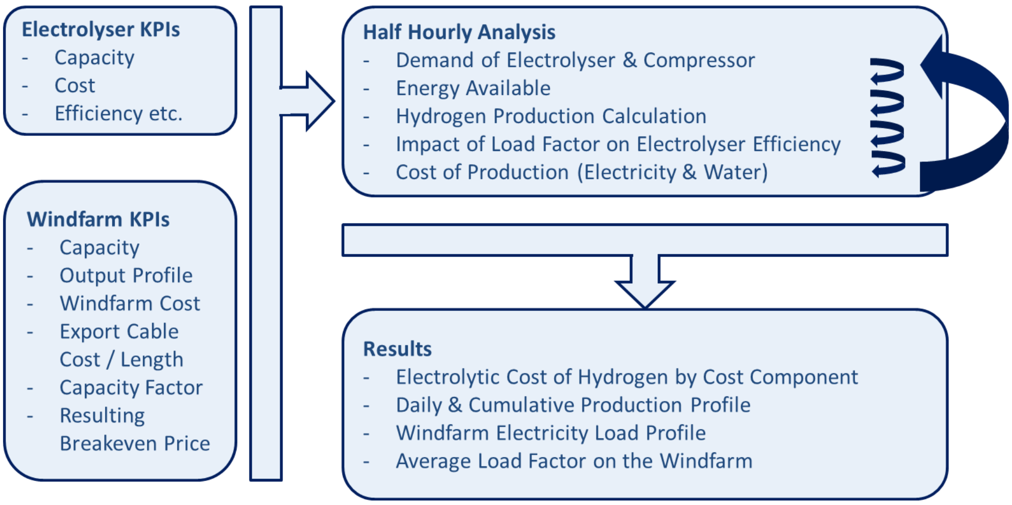

Figure 11: Process flow diagram for calculating the cost of hydrogen production and the production profile for Scenarios 3 & 4

These scenarios were therefore optimised by:

- Varying the length of the offshore electrical cable / pipeline
- Using learning curves to further reduce the capital and maintenance costs of the windfarm itself

[10] This is not based on the current contract for difference negotiations

- Recognising increases in the capacity factor of windfarms

- Introducing cost reductions brought about through the technological integration of electrolysers and windfarms

- Variations in windfarm capacity

Table 2 gives the cost of producing renewable hydrogen under Scenarios 1 through 3 using the state-of-the art stack technology and the Gigastack stack technology. These scenarios have not been optimised using the strategies identified above but instead demonstrate the cost reductions brought about by this innovation in stack technology. Whilst Scenario 4 showed significant promise, there is too much uncertainty surrounding the research and development costs to provide a credible hydrogen cost. Therefore, whilst the consortium considers it an exciting option for further development, the short-term focus must be on Scenarios 1 through 3.

Table 2: Hydrogen cost for Scenarios 1, 2 and 3 in the Base Case

Scenario	State-of-the-Art Stack Technology (£/kg)	Gigastack Stack Technology (£/kg)	Cost Reduction (%)
Scenario 1	8.37	6.93	17
Scenario 2	5.38	4.16	23
Scenario 3	7.68	6.74	12

Configurations similar to Scenario 1 are widely deployed in the UK today at hydrogen refuelling stations. Whilst some techniques are exploitable to reduce electrical costs, the full exposure to grid fees and tariffs dominates the cost of production. This leads to the highest production cost of the three scenarios. However, there are no restrictions (beyond daily arbitrage) that Scenario 1 experiences; therefore, the production profile is flat.

Like Scenario 1, when choosing to supplement electricity from the windfarm with electricity from the grid, the hydrogen production profile is flat. Furthermore, Scenario 2 allows the operator to minimise exposure to grid fees and tariffs by ensuring that the majority of the electricity is from the windfarm; 82% for a 75MW electrolyser and a 573MW windfarm with a 42% capacity factor. Completely avoiding electricity from the grid further reduces this cost, but the reliability of the production profile suffers as a result.

Scenario 3's production profile is more variable since the electricity is solely derived from the windfarm. However, this ensures that 100% of the hydrogen is renewable. The cost of hydrogen under this scenario comes down considerably with the anticipated improvements in windfarm technology.

With further regulatory intervention, commercial optimisation, industrialisation and increased production volumes of electrolysers the results of the feasibility study show further potential cost reductions of up to 50% (scenario dependent); a "best case". Reaching these costs is highly dependent on accessing challenging mechanisms that enable these cost reductions. For Scenario 2, this requires low-cost power purchase agreements, no grid fees behind the meter on electricity from the windfarm and access to the "Energy Intensive Industries" exemption. For Scenario 3 meanwhile, significant windfarm cost reductions and increases in the capacity factor are required. It is therefore reasonable to expect the cost of hydrogen to tend towards this "best case" through time as more of these mechanisms are accessed and / or realised.

Hydrogen valuation varies by sector due to differences in the incumbent fuel supply, i.e. diesel for passenger cars versus natural gas for heating. To evaluate the hydrogen costs concluded through this work, the business cases for each sector (industry, transport and heat) need to be assessed. Whilst these hydrogen costs enable the beginnings of commercial discussions for bulk supplies of renewable hydrogen, further support is still required for full commercialisation; this is the point of discussion in the subsequent section.

3.4 Developing the Business Case for Renewable Hydrogen in the UK

The fourth aim of the Gigastack project was to assess the business case and roll-out strategy for hydrogen produced from the Gigastack stacks. This work was carried out by Element Energy.

In preparing the business case, the analysis considered an electrolyser deployment in an industrial cluster. The UK government has set out an "Industrial Clusters" approach to create net zero carbon industrial clusters by 2040[11]. This enables significant potential for renewable hydrogen produced via electrolysis to support these clusters whilst also supplying hydrogen to local urban areas for transport purposes and for hydrogen injection into the gas network in a supportive policy environment (whether that be a blend of natural gas and hydrogen or a dedicated hydrogen network).

To evaluate the business case for these three sectors, the costs of producing, distributing and, for transport, dispensing the hydrogen were considered. This was done for Scenarios 1, 2 and 3. It was assumed that, for Scenarios 2 and 3 that the electrolyser would be built in close proximity to an existing onshore substation for an existing / new windfarm respectively.

This analysis demonstrated that, even when including the costs of accessing different markets, there are a range of end users for which the cost of hydrogen supplied using the Gigastack scenarios leads to a plausible overall case for a switch from their incumbent source of fuel to renewable hydrogen.

Three **industrial customer** types were considered; refineries, who have the potential to benefit from government schemes such as the Renewable Transport Fuels Obligation (RTFO); industries which use hydrogen as a chemical feedstock, i.e. steel manufacturing or ammonia production; and those who would use hydrogen as a source of heat. Since industry is expected to provide the baseload demand for electrolyser installations, siting electrolysers in close proximity to these end-users is most appropriate. This ensures that the cost of distributing the hydrogen through a pipeline is near zero. The end user therefore has access to the cost of produced hydrogen.

There are a number of ongoing projects that suggest that hydrogen has a future as a feedstock for chemical processes in industry. However, further development of regulatory frameworks are required for these end-users to be incentivised to use renewable hydrogen and decarbonise their processes.

- For refineries, the current RTFO is under constant review and could support the blending of renewable hydrogen into refineries. The

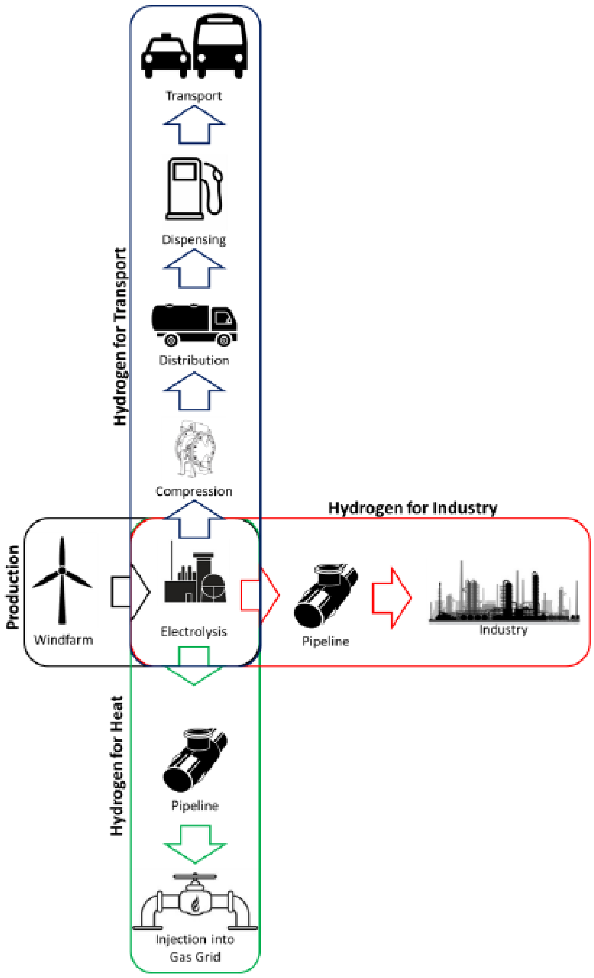

Figure 12: Process flow diagram from hydrogen production to the end-user

[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/803086/industrial-clusters-mission-infographic-2019.pdf

exact criteria for this are not fully tested, but it is clear that the upcoming Renewable Energy Directive II (RED II) supports the use of renewable hydrogen as a refinery input. This is perhaps the most mature sector in terms of having a supportive regulatory environment which could promote industrial decarbonisation using renewable hydrogen.

- Other industries which use hydrogen as a chemical feedstock will rely on either carbon accounting or new industry specific incentives to generate the case for hydrogen uptake. A floor price for carbon dioxide and, ideally, a specific incentive per kilogram of hydrogen would encourage decarbonisation of these processes using this renewable energy source.

- For segments where hydrogen would be used for industrial heat, it is likely that the lower energy value of heat (versus the chemical value of hydrogen) will mean a slower uptake. Incentives will need to be accordingly larger to enable a switch to renewable hydrogen. This analysis suggests a requirement for a subsidy of the order of £200/$tCO_{2,e}$ which represents a relatively high abatement cost.

For **transport**, a variety of vehicle types were explored including: cars, vans, buses, trucks, trains and boats. To assess the validity of supplying different segments of the transport market, the cost of hydrogen was compared with the price of diesel on a per kilometre basis for a range of demand scenarios.

This analysis suggested that the economies of scale delivered by Gigastack can enable an affordable supply of hydrogen for many areas of the transport sector.

- Small incentives, such as through the RTFO, for light duty vehicles, such as cars and vans, are only required for the initial uptake of vehicles in the region. For higher demands (100s of vehicles in the region), the cost under all three scenarios is lower than the price of diesel when comparing fuel consumption on a per kilometre basis.

- For heavy duty vehicles, such as buses and trucks, incentives are required for a greater range of demand. However, as demand increases, i.e. past 50 buses at a depot, the requirement for these incentives tends to zero as, for all three scenarios, fuel parity with diesel is reached on a per kilometre basis.

- For those vehicles that can access untaxed diesel, i.e. trains and boats, significant support is required. This would either come in the form of significant incentives for the hydrogen or the removal of the rebate for diesel for these industries. With no tax rebate, both Scenario 2 and 3 become attractive to these end users at high volumes.

For **hydrogen for heat**, the cost of producing and distributing the hydrogen to the pipeline was assessed. Two separate scenarios were considered where there is and is not existing infrastructure that enables injection of the gas into the distribution network. As a significant capital cost component, the analysis showed that the distributive costs in this case are significant enough to influence the siting of the electrolyser in improving the business case, i.e. locating close to existing gas injection infrastructure is optimal.

The business case for hydrogen for heat is highly dependent on the regulatory and policy environment. Blending hydrogen into gas networks at up to 20% by volume will require some form of incentive, such as the Renewable Heat Incentive that is currently used to support the injection of biomethane. Renewable hydrogen inclusion in these blends should be encouraged to further decarbonise the gas network.

However, where there are dedicated hydrogen grids, as proposed by H21 NoE[12], there could be an entirely new policy landscape. This is likely to lead to a higher value for hydrogen on the gas networks than the methane which is in use today. This policy framework could be tweaked to favour renewable hydrogen injection

[12] H21, Northern Gas Networks, Equinor, & Cadent. (2018). *H21 North of England*.

/ blends to ensure a fully net zero gas distribution network. It is unlikely, however, that these measures will be in place before the end of the 2020s.

For the roll-out strategy, Element Energy made forecasts for the hydrogen demand from chemical processes in industry, transport and heat out to 2030 in the UK. Forecasts were also made for the total hydrogen demand from Europe and the Rest of the World (RoW). Three different uptake scenarios were considered: “Low Ambition”, “Central Growth” and “High Ambition”, to ensure complete coverage of the possible hydrogen futures in these three markets.

To assess the market size that ITM Power can access through their new Gigastack technology, Element Energy defined the expected market share in the UK’s industry, transport and heat markets as well as the international markets. This was supported by establishing the total possible hydrogen production from ITM Power’s Gigastacks by assuming a two-year lead time on all installations and a variety of load factors.

As shown in Figure 14, ITM Power’s decision to invest in the Giga-factory is more than validated in each case.

- In the Low Ambition scenario, ITM Power is more dependent on the export of their electrolyser technology as the UK hydrogen market fails to grow significantly.
- In the Central Growth case, total hydrogen production in 2030 is nearly saturated by demand from the UK at a load factor of 50%. However, once again the international markets ensure that the remaining hydrogen production potential is saturated.
- In the High Ambition scenario, the UK demand for hydrogen is much more significant and satisfies the Giga-factory’s total production potential up to a load factor of 100%. Exports to foreign markets in this scenarios suggest that there could be further investment in another two Giga-factories.

This analysis demonstrates that, in addition to the UK demand, there is significant demand from the international community. There is therefore significant export potential for ITM Power and the UK; this could greatly contribute to making the UK the world’s centre for excellence on hydrogen production.

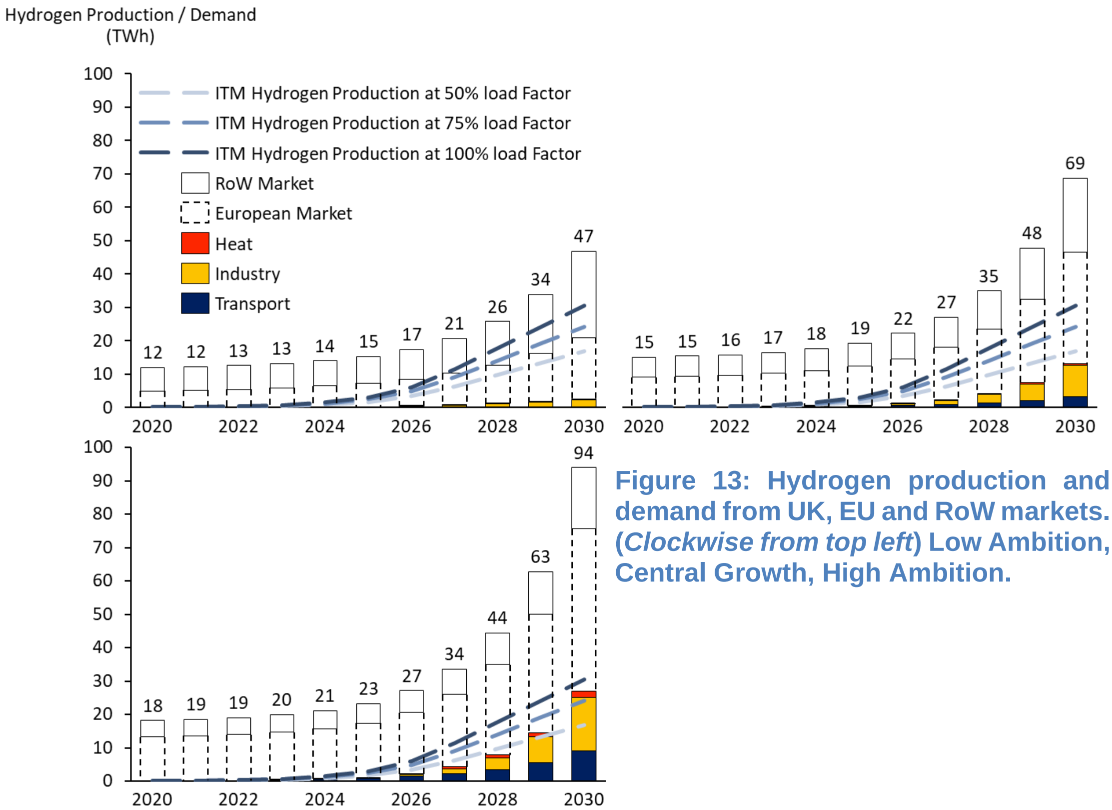

Figure 13: Hydrogen production and demand from UK, EU and RoW markets. (*Clockwise from top left*) Low Ambition, Central Growth, High Ambition.

4 Conclusions and Next Steps

As a result of this feasibility study, the consortium has made significant gains in readying the UK for a reliable bulk supply of affordable and renewable hydrogen from 100MW+ installations. Specifically;

- ITM Power has developed computational designs for their new stack which decreases the system cost to <£400/kW and increases stack capacity;
- ITM Power has also frozen the design of their Giga-factory and identified the necessary equipment and workforce to deliver the required increase in throughput;
- Windfarm-electrolyser configurations have been analysed which deliver bulk supplies of reliable, renewable and affordable hydrogen;
- And finally, business cases and a roll-out strategy for the Gigastack stacks have been assessed to ensure targeted deployments and an increased rate of commercialisation.

The consortium's new ambition is to work on Phase 2 of the Gigastack project, funded by BEIS' Hydrogen Supply Competition. In this new phase, the consortium will work with Phillips 66, as a commercial partner, to take part in the commercialisation of renewable hydrogen. The readiness of this hydrogen supply solution is currently too immature to warrant the involvement of a customer without public funding.

In Phase 2, ITM Power will build and test a representative system, based on its 4th generation stack design. This stack will be tested using conditions which are representative of the loading found at an offshore windfarm. These tests will validate the core KPI's of the stack which will then be ready for build and deployment at a 5MW scale. This practical work will demonstrate the achievement of the required technical performance and also the underlying bill of materials (BOM) cost which is required to achieve the Gigastack project's technical and economic aims.

For the factory, ITM Power will validate the selected machinery. This will include; the build of test rooms; installation and commissioning of manufacturing equipment required for this high throughput volume and test-lines; and demonstration of the manufacturing infrastructure itself. This will deliver manufacturing process documents & manuals as well as validating the work done in Phase 1 of the project, increasing the MRL to a level 6/7.

Finally, the consortium will aim to conduct a comprehensive Front-End Engineering Design (FEED) study on a 100MW electrolyser system using staged installations of 20MW electrolysers, including all aspects of dynamics and integration with the targeted customer. The study will bring forward commercial, technical and regulatory optimisation aspects when planning up to a 100MW scale implementation. The consortium has identified the Phillips 66 Humber Refinery as a first commercial customer for these large-scale systems. The overall business case here is created by the fact that refineries will need to use renewable hydrogen to meet their renewable fuel requirements under UK's Renewable Transportation Fuels Obligation (RTFO).

Within the RTFO, there is consideration for Renewable Fuels of Non-Biological Origin (RNFBO) which could include renewable hydrogen. These RFNBO products can qualify as "development" fuels, the next generation of low carbon fuels and a market which the government is aiming to develop over the next decade.

The specific advantage of the Phillips 66 location is that it is located next to the substation for Ørsted's massive Hornsea wind farms (1.32GW). This makes it the ideal location to test both the coupled wind farm-electrolyser scenario developed in Phase 1 and the sale of renewable hydrogen to a high-volume market with an existing business case. Furthermore, the long sales cycle of multi-MW plants and non-recurring engineering costs involved necessitate the participation of a large off taker; Phillips 66 fills this role.