Low Carbon Hydrogen Supply 2 Project

Project Report Submitted to BEIS
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Public Report

Project:
System Design and Integration for the Offshore Production of Green Hydrogen (H_2) Using Offshore Wind Farms (OWFs)

Funding Competition:
Low Carbon Hydrogen Supply 2 Competition

Department for Business, Energy & Industrial Strategy

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Glossary

ASTM - American Society for Testing and Materials
BEIS – Department for Business, Energy and Industrial Strategy
BPP – BPP-Technical Services Limited
CDS - Climate Data Store
CAPEX – Capital Expenditure
DECEX – Decommissioning Expenditure
DID – Deliverable Identification
EDI - Electro-Deionisation
FEED – Front-End Engineering and Design
FWF – Floating Wind Farm
FWG – Fresh Water Generator
GHG - Green House Gas
GHPS – Green Hydrogen Production System
HVAC - High Voltage Alternating Current
HVDC – High Voltage Direct Current
INTOG - Innovation and Targeted Oil and Gas Decarbonisation
IRR – Internal Rate of Return
LCOH – Levelized Cost of Hydrogen
MEP distillation - Multi-Effect Plate distillation
NAS Battery – Sodium Sulphur Battery
NPV – Net Present Value
O&G – Oil and Gas
OPEX – Operational Expenditure
OSS – Offshore Sub-station
OWF – Offshore Wind Farm
OWF–H2 – Offshore Wind Farm used for Offshore Hydrogen Production
PEME – Polymer Electrolyte Membrane Electrolyser
SWRO – Sea Water Reverse Osmosis
TRL – Technology Readiness Level
WACC - Weight Average Cost of Capital
WP – Work Packages

1 Executive Summary

This project has developed a system for Green Hydrogen (H2) production that can operate with intermittent power inputs; typically from renewable energy sources. These can include offshore or onshore wind turbines through to land-based systems powered by solar arrays, tidal turbines and off-peak electrical power. The work has been carried out by developing a detailed design and integration engineering tool that can carry out representative feasibility and FEED studies of such systems including economic analyses to yield the consequential Levelised Cost of Hydrogen (LCOH) produced.

This engineering tool has the following capabilities:

a) It takes input from the configuration of the power producer (wind, solar, tidal, off-peak power) and enables permutations of system configurations to be conceived, sized and evaluated for performance.

b) The system has, built within it, accurate and representative models of components such as electrolysers, battery packs, water treatment, thermal management and control system. Thus, the output of the engineering tool gives ‘real world’ estimates of system performance and cost.

c) The integration tool simulates Green Hydrogen production performance and enables the effects of climate (wind frequency, variations in solar array output etc) to be assessed. The simulation can model variations in input power and Hydrogen off-take rates to assess overall system up-time and efficiency.

d) The integrated tool incorporates a detailed techno-economic assessment of such a Green Hydrogen production system. This includes determining the LCOH and in more detail the profile of Green Hydrogen production for given climate variations.

A case study was developed to determine the LCOH given by the optimum configuration of an OWF-H2 system. Hydrogen delivered to shore through a dedicated Hydrogen pipeline and a thermal-based desalination system were found to be the most suitable solutions compared to transporting Hydrogen with pressurised vessels and seawater reverse osmosis respectively.

The project work has tested and verified the architecture, design and operation of the Green Hydrogen production system and was also able to demonstrate its potential commercial viability. Typical LCOH values obtained were ~£2.91/kg (US$3.2/kg); these are within a competitive price range.

A demonstrator case study for Phase 2 was then developed for a much smaller land-based plant running on off-peak grid electricity. It is intended as the basis of a physical demonstrator that could also be used to scale up to commercial sized plants.

2 Overview of the Project

Climate change and the need for sustainability are all driving a growing opportunity and requirement for Green Hydrogen production. Technological improvements are reducing the cost of production and transport of H2, making it increasingly commercially attractive. Moreover, political intent, driven by the public, is driving policy changes to limit climate change. 33 countries (including the UK) have declared a climate emergency. The UK Government's target to cut 78% of carbon emissions by 2035 is ambitious.

H2 production integrated into OWFs can contribute significantly to this requirement. However, whilst the system components (e.g. electrolysers, wind turbines and platforms) are commercially available (TRL 7 to 9), the overall system design and integration is not at this TRL level but only at TRL 3 to 4. An OWF is a significant investment of time and money, and OWF developers need confidence in their return on investment which depends on identifying reliable designs with predictable performance.

Currently, 95% of H2 is produced by using steam reforming natural gas and coal cracking processes; these release significant greenhouse gases [4th Generation, 2020]. The UK government has invested £240 million to develop the UK’s H2 capacity using low carbon technologies, aiming to produce 10GW of low carbon H2 production capacity by 2030 [GOVUK,2022].

Offshore wind farms require substantial subsea export cables using HVAC. The cost of the electrical infrastructure (offshore substation, export cable and onshore substation) for distances greater than 100 miles significantly impacts CAPEX, possibly making some projects commercially uneconomical. An alternative solution is to produce H2 by electrolysis close to the point of electricity generation, removing the requirement for an export cable.

Producing H2 offshore using OWF power offers a commercial solution to store and deliver energy onshore. This will result in diversifying available energy sources whilst decreasing the industry’s carbon footprint.

This project is aimed at developing a system definition along with the integration tools needed to combine high available TRL components and assess the design feasibility and the economics of a novel large-scale green hydrogen supply solution: producing H2 from the output of OWFs.

The project is part of a Phase 1 programme funded through the UK Government BEIS Low Carbon Hydrogen Supply 2 competition.

A detailed description of BPP’s expertise and that of the companies that collaborated and shared sensitive information with BPP can be found in **Appendix A**: Project Team & Industrial Partners**.**

2.1 Aims and Objectives

This was a 9-month project, started on 10th of January 2022 and delivered to the BEIS monitoring officer on the 11th of September 2022.

The project consists of 8 WPs, which are briefly summarised in **Table 1.** All WPs were coordinated and managed by BPP.

Work Packages	Objectives
Project Management	Manage, coordinate and communicate the project activities and deliver the final project report
Subcontractor Engagement	Verification of design parameters of the selected technologies through close interaction with relevant suppliers
Equipment Modelling	Implementation of design parameters, set up mathematical models and test
System Modelling	Integration of equipment modelling into system model, assess power flow parameters, test model
Site Data Assessment	Site identification and assessment of key environmental conditions
Wind Farm Optimisation Layout	Optimise wind farm field and cable layouts, integrate sub-station, test available options
Techno-Economic Assessment of the Integrated System	Implement & integrate options, assess technical and cost performances of each option
Final Report	Preparation of final report

Table 1: Work Packages & Associated Objectives

The key objectives achieved through this project are:

1. Stimulate cooperation between the offshore energy and H2 sectors and integrate current technologies for Green H2 production from OWF;
2. Accurate sizing and modelling of the offshore H2 production system;
3. Optimise layout and configuration of inter-array cables, OWFs and Green H2 substations;
4. Design and cost assessment of viable economic and transportation solutions of gaseous H2 from the offshore wind farm to shore.

2.2 High TRL Equipment Selection and Modelling

This stage was carried out to identify the most cost-effective technologies comprising the offshore hydrogen production system, which can ensure safe and reliable operations of the system even during low-wind periods.

BPP has developed comprehensive mathematical models to represent the dynamic behaviour of the various components comprising the Green H2 system when supplied by the fluctuating, intermittent energy produced by an OWF. This modelling has been carried out in close collaboration with leading manufacturers of the relevant equipment, listed in **Appendix A**: Project Team & Industrial Partners, and enables these components to be readily deployed within future system assemblies. The model is flexible enough to accommodate any future adaptations and upgrades incorporate emerging technologies and implementing different power flow optimisation techniques.

2.2.1 Boundary Conditions & Description of the System

The OWF-H2 system being modelled is shown in **Figure 1**.

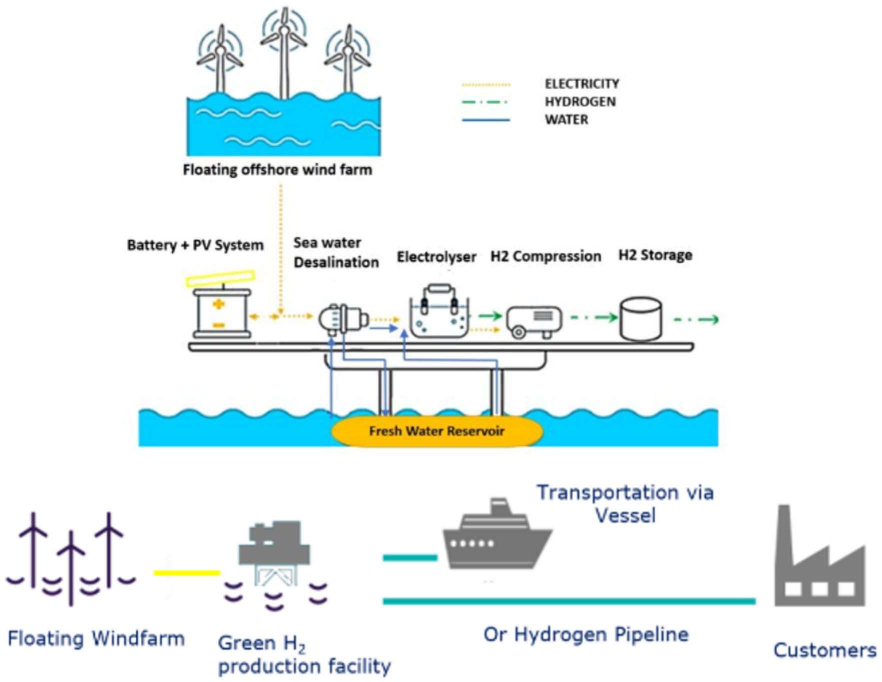


Figure 1: Schematic representation of FWF-H2 system

The system comprises an offshore Green H2 substation with remote OWF turbines powering seawater purification that feeds PEM electrolysers, producing H2 and O2. The project has compared SWRO with heat-based distillation system, by assessing the technical feasibility, complexity, performance and cost of the overall system in both cases.

A battery system was used to optimise energy consumption, to smooth out power fluctuations and permit around-the-clock operation of critical systems. The produced O2 will be commercialised in a manner yet to be defined whilst the H2 will be shipped in canisters or in a H2 dedicated pipeline, allowing considerable cost reductions when compared to current OWF solutions transporting energy ashore by HVDC subsea power cables.

To assess the technical and commercial viability of the offshore Hydrogen generation system described above, an initial case study of a wind farm of size 240MW was considered as representative of future utility-scale wind farms where this system would be applied. Therefore, the case study consisted of 16 turbines rated at 15MW each, placed in water deeper than 80m and at a distance of 160km from the coast of North-East Scotland in the North Sea. More details on the selected location are provided in **Section 2.4**. The input data of the Case Study are summarised in **Table 2**.

Variable	Value	Unit
Turbine capacity	15	MW
Wind farm capacity	240	MW
Number of turbines	16	-
Distance from the shore	160	km
Water depth	89	m
Wind Turbine technology	Floating	-
Offshore substation design	Fixed	-
Project design life	30	years

Table 2: Input data of the Case Study

No integrated technologies are available at a high TRL for such a large power system. However, some technologies are more capable of being scaled up to such large proportions while considering the harsh conditions of the surrounding environment. Other key drivers in the selection of the components were their weight and size as space is limited on an OSS.

2.2.2 Electrolyser - Nel Hydrogen & BPP

After a thorough Literature Review and discussions with industry leaders, PEM electrolysers were selected as the most suitable technology in part due to them being 10 times smaller and lighter than the next best solution which is considered to be Alkaline electrolysers.

2.2.3 Transformer System – Scotech & BPP

To step-down the voltages to an acceptable level, BPP's work explored possible solutions. A two-stage process was established to be the most economically viable to keep the secondary current within industry standards while minimising the number of transformers required. The model also considers the conversion efficiency for the active power passing through the transformers, and the cost for auxiliary power components.

Furthermore, the selected transformers are flooded with a polymeric solution rather than oil, which is more efficient and better economically sourced and less toxic in the event of leaks.

2.2.4 Heat Exchanger System – Alfa Laval & BPP

Within the technical specifications of the electrolyser is the cooling required to maintain the electrolysers at their optimal temperature. A significant proportion of the power consumed by the electrolyser is expelled as heat energy which makes an air-cooling system unsustainable. A heat exchanger is required with a high specific heat capacity medium to efficiently extract the heat energy. Typically, a solution primarily composed of fresh water is used; however, this would significantly oversize the desalination system.

Depending on the considered sea-water desalination system (SWRO vs thermal-based) the following solutions were considered and modelled to increase the energy efficiency of the system by using the dissipated heat from the electrolysis process:

- SWRO desalination: Some of the heated water is recycled into the desalination system to ensure the incoming water to the SWRO desalination system, provided by Veolia is at an optimal temperature.
- Thermal-based desalination: Dissipated heat from the electrolysis process is used to drive a desalination unit, provided by Alfa Laval.

2.2.5 SWRO Desalination System - Veolia & BPP

The PEM electrolysers manufactured by NEL Hydrogen use fresh water to produce very pure hydrogen typically >99.99%. However, to maintain this efficiency, it is advised that at least a water quality of ASTM Type II is guaranteed, however, ASTM Type I is recommended. Hence, water with a conductivity less than 0.056 μS/cm is required, while sea water in the North Sea has a conductivity of 53,000 μS/cm.

Together Veolia and BPP devised a three-stage SWRO desalination system. The system consists of a sand filter and two SWRO units, the latter of which includes an EDI unit.

2.2.6 Thermal-based Desalination System – Alfa Laval & BPP

Thermal-based desalination systems are typically not considered for offshore applications as they require large amounts of heat energy to desalinate water. While permeate water generation efficiency for SWRO is ~6.5kWh/m^3, thermal-based solutions can require up to 385kWh/m^3 of heat energy but only as little as 1.3kWh/m^3 electrical energy to power the pumps. This technology provides an opportunity to recycle the exhausted heat energy from the electrolyser with the added effect of making the heat exchanger half the size required in an SWRO configuration to keep the electrolyser cool as some of the heat would have been harvested already by the desalination system.

BPP designed a two-stage desalination system which harnesses Multi-Effect Plate (MEP) distillation, and an electro-deionisation unit that could achieve the same water quality as the SWRO system described above.

2.2.7 Battery System - Revi & BPP

NAS batteries were selected as the primary energy storage technology due to their high energy density, low self-discharge and relative safety. The selected batteries are available in stacks of 1.45MWh and require a specific Power Control Unit (PCU) container. In particular, the rate of charge is decreased in a stepwise process known as supplementary charging and the ramp rate is limited when battery capacity is greater than 80%. Degradation is also a key issue and after consulting with Revi it was determined to model degradation by reducing the battery's capacity by 5% per 1000 equivalent cycles.

2.2.8 Modelling of Hydrogen Compression System

The Hydrogen compression was modelled assuming an adiabatic process with a suitable isentropic efficiency value. Constraints on discharge temperature were imposed on the model which allowed for the selection of the number of required stages within the compression train, which depends on the system inputs and the assumed intercooled temperature. Following this, the required compression work (or compressor power) to achieve the desired pressure was calculated; thus, sizing the compressor.

The discharge pressures were chosen based on reasonable standard values within the industry at 100bar for the pipeline transport option, and 350bar for transportation via cannisters. Representative costs for the compressors were determined from the literature for reciprocating piston-type compressors, which were deemed most suitable for H2 compression due to their large throughput capacity, oil-free operation, and suitability for intermittent operation.

2.2.9 Modelling of Hydrogen Transportation System

Compressed hydrogen transport is, at present, the only feasible method of transporting H2 from an OSS. Liquified transportation is currently too complex with energy and space requirements that are too large operate on an offshore platform. Other technologies such as using metal hydride storage are also theoretically possible, but not advanced enough to be a feasible option.

Two methods of the transportation of compressed H2 were modelled and applied to the case study of a utility sized wind farm: Transportation by pipeline, and by ship in pressurised cannisters. The pipeline modelling was built using widely used and understood equations.

The capital and infrastructure costs were estimated from regression analyses of known industry pipeline costs and was expressed as a polynomial function of the pipeline diameter. The operational costs was taken from the UK Oil and & Gas authority's reports on UKCS operating costs. This covers all aspects of pipe operation and maintenance such as inspection, cleaning, and pigging. The pipeline cost function was implemented within a stochastic optimisation scheme to determine the lowest NPV cost for a given pipeline which still meets the material and safety requirements.

For the cannister model, the most practical option was identified in the form of 20’ ISO standard containers, specially designed to transport large, pressurised hydrogen cylinders.

2.3 System Modelling

The next stage was to define the best strategy to integrate all the different analyses performed in the previous WPs in a unique software tool, which was developed in MATLAB & SIMULINK. This comprehensive mathematical model was then used to assess the techno-economic feasibility and the performance of the whole system, as described in **Section 2.6**.

The architecture of the software combines stochastic and metaheuristic analysis to optimise windfarm layout, cable length and displacement, wind farm efficiency, cost and performances of the green hydrogen system, whilst minimising technical risk to generate a reliable cost for developers.

2.3.1 Offshore Substation Modelling

Following the execution of the above algorithms, the software performs a parametric analysis of the Green H2 substation cost as a function of the weight and size of the Green H2 production system. The software determines the dimensions of the topside, the amount of structural steel needed for topside structures and subsea jackets, the size and cost of pile foundations and scour protection as these were found to have the greatest influence on the CAPEX.

2.4 Site Identification & Assessment of Environmental Conditions

The objective here was to identify a suitable geographical location within the UK for the development of a case-study for the offshore production of Green H2 using OWFs and use real environmental data to develop a case study for the OWF-H2 system.

2.4.1 Criteria for Site Identification

The most important factors considered for the selection of the offshore wind site are:

1. Offshore wind power density;
2. Existing H2 projects & port infrastructures for Green H2 importation;
3. Available offshore wind farm locations.

The project boundaries for the site selection are summarised in **Table 2**.

2.4.2 Description of Target Sites

The geographical location selected for the development of a case study of the OWF-H2 system, shown in **Figure 2**, meets all the requirements described in the previous section. The area selected was within the Innovation and Targeted Oil and Gas Decarbonisation (INTOG), Northeast Scotland, which states: “Up to 500MW of innovation or test and demonstration projects, which must be <100MW in size, will be awarded”

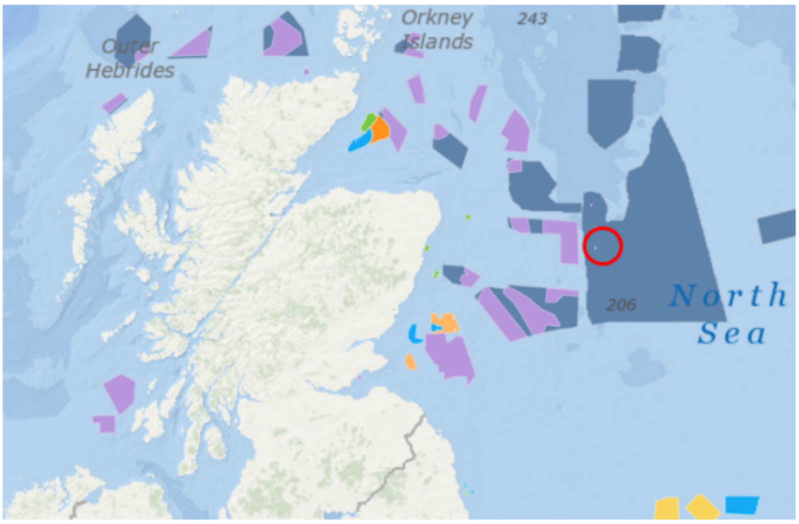


Figure 2: Geographical location selected for the case study

2.4.3 Environmental Conditions and Data

The co-ordinates of the chosen location have been used in combination with the Climate Data Store (CDS) global hindcast dataset to produce an estimate for the weather conditions at the site and, therefore, the expected power production of the array.

2.5 Wind Farm Optimisation Layout

The objective of this tool is to optimise the layout of turbines and inter-array cables for a wind farm of specified capacity and location. The optimisation was performed in two stages. Firstly, the turbine positioning was optimised to minimise wake effects and maximise power output from the wind farm. The inter-array cable layout was then optimised for minimum cabling costs. This was a very computationally intensive problem - for a 16-turbine wind farm there are 20 million trillion possible layouts which was further complicated when considering the placement of the offshore substation(s) and its associated export cable or pipeline.

2.5.1 Parameters and Methodology of Wind Farm Optimisation

The turbines are assumed to be arranged in a grid layout, parameterised by orientation (alpha), shear angle (beta) and aspect ratio. These parameters are adjusted to maximise total power output from the turbines. Wind speed reduction due to turbine wakes was calculated using the Jensen model. The optimal grid will be different for each location as it depends on the prevailing wind direction among other factors. The full parameter search used to obtain the optimised layout is computationally expensive, so the software uses a more advanced search algorithm for the actual optimisation.

The second stage was optimisation of the inter-array cable layout. There is a complex cost function used to analyse each candidate layout, which aims to evaluate the cables' contribution to the overall levelized cost of energy (LCOE). Some key variables that drive the LCOE contribution over the wind farm lifetime are: Power fed to the offshore substation, Inter-Array Cable Cost; Failure Rates of Inter-Array Cables. Using a combination of BPP expertise and available literature, inter-array cable failure rate, Downtime and Cost of Cable Failures can be estimated.

As previously mentioned, there was an extremely large number of possible layouts even for relatively small wind farms; so evaluating the cost of every layout was impossible. Therefore, a customised version of a Particle Swarm optimisation algorithm was used to find the layout with minimum cost. This is a stochastic process, hence the convergence time was unknown. The convergence was verified by running identical optimisations on several computer cores and asserting that they all find the same layout. The software can even optimise layouts with one or multiple offshore substations. The software's functionality was verified by conducting a case study using an existing wind farm.

2.6 Methodology of Cost Model Building

The following approach was used to estimate the overall cost of producing Green Hydrogen (H2) using an OWF.

The differences between the infrastructure of OWF-H2 system in respect to a traditional OWF exporting energy to shore are:

1. Subsea export power cable replaced by H2 export pipeline;
2. Size of the offshore substation and the components installed into it.

The cost of the OWF-H2 system was determined by considering the impact of four main subcomponents of the overall system: Floating offshore wind farm, Fixed offshore substations, Green Hydrogen production system, Hydrogen pipeline.

The cost model was based on the estimation of key financial parameters of the system, which consists of the CAPEX, OPEX and DECEX for the installation, commissioning maintenance and decommissioning of the FWF-H2 system.

The advantage provided by BPP's cost model lies in its analytical approach that enables the estimation of the overall investment for an OWF-H2 as a function of: Windfarm location, Size of the OWF, Efficiency of OWF-H2 facility i.e., overall Hydrogen produced and wind power curtailed.

The wind farm is not grid connected, and all the energy generated is used for Hydrogen production and balance of the system. The electrolysers are located offshore, and the Hydrogen is transported to an onshore facility using a subsea pipeline. In this project it was assumed that the Hydrogen produced is fed directly into the gas grid or used onsite, and no cost for the onshore infrastructure was included in the economic model.

Table *3* outlines the assumptions for the economic model developed for the case study, assuming the OWF-H2 system to be built in 2025.

Variable	Value	Unit
Turbine capacity	15	MW
Wind farm capacity	240	MW

Variable	Value	Unit
Number of turbines	16	
Distance from the shore	160	km
Water depth	89	m
Wind Turbine technology	Floating	
Offshore substation design	Fixed	
End of construction year	2025	
Project design life	30	years
Fresh water supply	Thermal-based	
Transport type	Pipeline	
Onshore hydrogen delivery	No delivery	
Discount rate	5%	

Table 3: The assumptions for the economic model developed for the case study

2.7 Model Assumptions

A comprehensive Literature Review was carried out to estimate the development and installation costs of a FWF in function of its geographical coordinates, which directly relate to distance to shore and water depth of the selected installation site.

The CAPEX of the components comprising the Green H2 system was provided by different industrial partners. OPEX costs for balance of plant are taken as a percentage of the equipment CAPEX. Hydrogen transport costs considers Hydrogen offtake to occur via a subsea Hydrogen pipeline to an onshore location, from where further delivery via gaseous trucking or direct use can be selected.

The levelised cost of the hydrogen production facility was estimated as the ratio of the total costs of a generic/illustrative plant to the total amount of hydrogen expected to be produced over the plant's lifetime. Both are expressed in net present value terms [BEIS_Hydrogen Production Cost].

3 Modelling Results and Conclusion

The wind farm optimisation software was run for the project case study, to obtain the optimal layout, inter array cable length and cable cost. The optimal layout is depicted in **Figure *3*** below. The layout uses 33.0 km of inter-array cable totalling £4.77m.

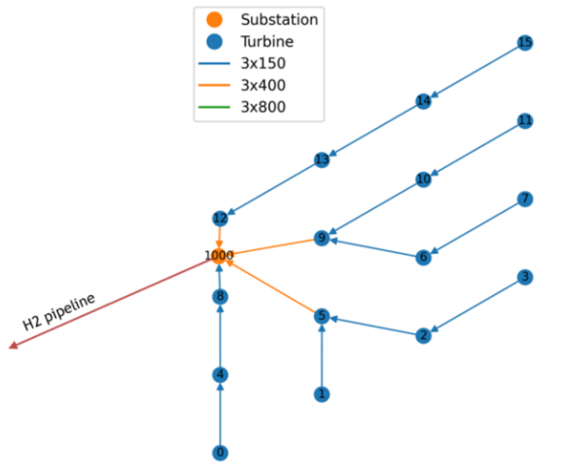


Figure 3: Optimal cable layout for 240 MW case study

The Floating Offshore Wind Farm Optimization tool was used to estimate the power production profile of the optimised FWF layout. **Figure 4** shows the power distribution of a 240MW offshore wind farm over a 30-year lifetime. This wind data was then fed into BPP's comprehensive engineering tool in MATLAB-SIMULINK, which integrates cost, size and layout optimisation techniques for the offshore wind farm, green hydrogen production system and hydrogen pipeline.

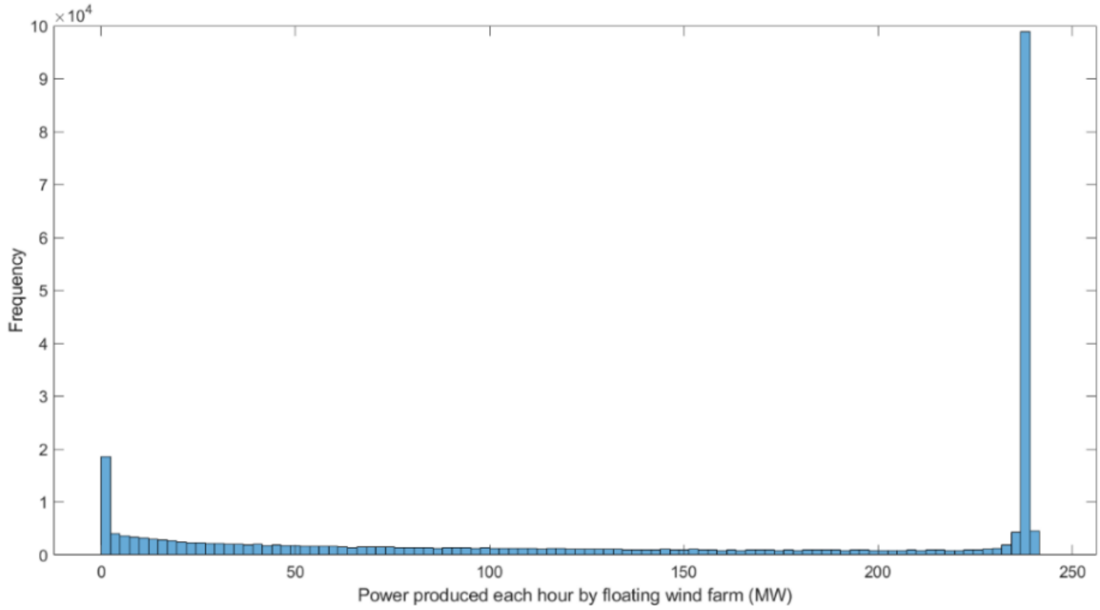


Figure 4: Histogram for the distribution of power produced by the floating wind farm

It emerged that the Green Hydrogen system using a thermal-based desalination system (dotted red line) has a 0.1% lower LCOH than an SWRO desalination. Although this difference might seem negligible over 30 years lifetime, the OWF-H2 system with FWG generates more than 183 ton of H2 than the SWRO- based system.

Table 4 summarises the results obtained for the optimal configuration of the OWF-H2 system, assumed to be operational by 2025.

Result in 2025	Unit	Value
Wind farm power	MW	240
PEME system	MW	237.5
NAS battery system	MWh	14.5
LCOH	£/kg	2.459
Total CAPEX	£M	700.0
Total lifetime OPEX	£M	781.0
Overall hydrogen production	tonnes/day	60.914

Table 4: Values of the optimum configuration of the FWF-H2 system installed in 2025

A sensitivity analysis was then performed on the LCOH assuming a cost reduction on the following components to account for technological improvement and WACC: PEME electrolyser, NAS battery system, installation cost of H2 pipeline, and the turbine cost, foundation cost and OPEX of the Floating offshore wind turbines. A cost reduction of 1% was assumed for each year for the other technologies.

The forecasted LCOH of the OWF-H2 system considering a time range between 2023 and 2050 is shown in **Figure 5**.

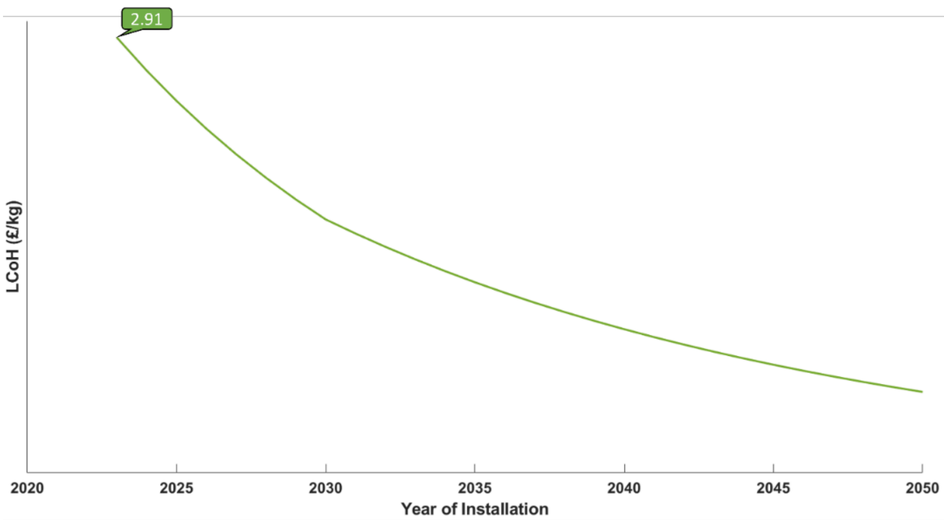


Figure 5: LCOH in function of the assumed year of installation

The results shown in **Figure 5** depict a better economic scenario than what was found in previous studies investigating the cost of producing Hydrogen directly offshore from an offshore wind farm.

The LCOH of £2.91/kg (US$3.2/kg) shown above is competitive against present day estimates by others. See for example **Figure 6** below that shows the cost ranges for Green Hydrogen defined by 2020 KPMG paper on The Hydrogen Trajectory. (https://home.kpmg/ky/en/home/insights_new/2020/11/the-hydrogen-trajectory.html)

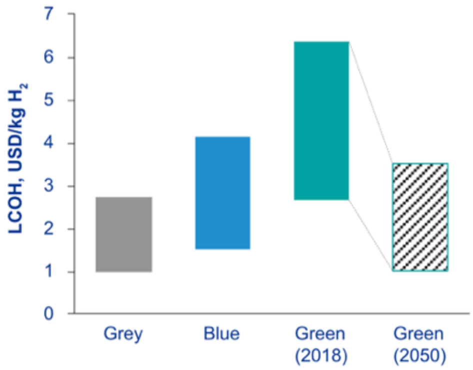


Figure 6: Present Day Estimates for LCOH

Overall, BPP has developed and integrated multiple optimisation techniques to get a more accurate and realistic estimation of the LCOH. A more accurate estimate of the LCOH from the OWF-H2 system will be possible once FWFs are installed on a large scale.

The cost of the Hydrogen pipeline is found to be 56.5% lower compared to the HVDC export cable. An additional advantage of exporting Hydrogen to shore rather than electrical energy is the increased energy density of the offshore wind farm, as power losses due to the Joule effect are reduced because wind energy is used closer to the point of generation. If retrofitting of existing O&G pipelines is also considered, then the cost can drop even lower.

The design developed by BPP is flexible enough to accommodate any future adaptations and upgrades to incorporate different sites, emerging technologies and cost reduction curves for each component.

In natural gas-based hydrogen production, steam methane reforming (SMR), CO2 direct emissions are estimated to be around 9 kg CO2/kg H2, while upstream methane emissions from natural gas production and transport can add as an average 2.7 kg CO2eq/kg H2 [Global Hydrogen Review 2021]. While capturing CO2 from the concentrated process stream can reduce overall emissions by 60%, producing hydrogen from OWF will certainly represent a cleaner solution.

The future implementation of the OFW-H2 facility would enable a drastic reduction of the overall GHG emissions produced by the energy and industrial sectors that will use the produced green hydrogen to replace carbon-intensive processes. The 240 MW floating offshore wind farm used to produce hydrogen directly offshore would lead to avoiding 4.5 MtonCO2 of emissions over 30 years.

4 Description of the Demonstrator Project

BPP has developed a small-scale pilot system design as a demonstrator. It incorporates the technologies described above as well as BPP's proprietary algorithm for optimum power flow management to minimise the LCOH and to maximise the IRR and NPV. This pilot demonstrator system will provide a foundation upon which further hydrogen production facilities could be built using intermittent renewable energy sources.

The scope of the Demonstrator project is to test at a reasonably large scale, the design of the Green Hydrogen System developed by BPP during Phase 1; and verify the system architecture and the design tools for Green Hydrogen production performance. Hence, this project is intended to demonstrate the potential for using intermittent power sources for Green Hydrogen production.

The facility is environmentally friendly, sustainable and efficient. Its immediate application would be aimed at re-fuelling cars and heavy-duty vehicles.

The primary unique feature of the system is that it continuously produces Green Hydrogen and Oxygen using intermittent sources such as off-peak power from the grid, the outputs of wind turbines, solar arrays and tidal turbines. The secondary benefit is that this energy can be stored and utilised on demand. The stored Hydrogen and its sale with 'spot' pricing and using energy trading opportunities holds considerable revenue potential.

The operational principles of the Demonstrator Project are summarised below:

1. Freshwater will be made available at the selected location using local water resources, if available.
2. The input freshwater will then be treated by dedicated water purification units to lower the conductivity of the water supplied to the electrolyser system. Any excess fresh water produced by the water purification system will be stored in a fresh water tank and supplied to the electrolyser or made available to the facility.
3. As an intermittent, fluctuating power supply will be expected to supply the GHPS, the PEM electrolyser system will include its own dedicated power supply to cope with such drops and surges of power.
4. Backup power will be supplied to the overall system via a NAS battery.
5. The produced hydrogen is ultimately stored in dedicated pressurised canisters.

The produced Hydrogen will be made available at no cost to local public service or private transportation needs. This will replicate a complete Hydrogen production to utilisation chain.

5 Design of the Demonstrator Project

While coordinating with the sub-contractors to create techno-economic models of their respective products, preliminary work was carried out to determine the optimal configuration for a demonstrator system.

The Green H2 Pilot system was designed to be:

a) Efficient and to operate using automation for most of its operational processes. Automation is vital to minimise labour costs, maximise reliability and safety of the system. Process control measures are embedded in the facility production equipment – these would include control of power flow, Hydrogen, Oxygen and temperature.
b) Competitive with regards to the green hydrogen production cost by integrating cost-effective and environmentally friendly technology in a “first of its kind” system.

In designing the Demonstrator Project, eight key objectives have been set – listed below:

1. Rapidly profitable with as early income and positive cash flow as possible;
2. Easily scalable and modular;
3. Applicable to any geographical location;
4. Inherently robust and resilient due to effective control strategies and automation level;
5. Significant de-risking of the investment in comparison to other approaches;
6. Highly automated and controlled for increasing reliability and minimising down time;
7. Selection of a strategic geographical location for testing and future expansion of the facility within an accessible Hydrogen business chain;
8. Providing an excellent test bed for a company or organisation that wants to enter the emerging hydrogen market, growth of which is considered vital by governmental policies for the national economy and supported by multiple public funding streams

6 Benefits and Barriers

BPP’s objective is to support and then develop credible innovative hydrogen supply technologies and corresponding enabling technologies to bring about a step change in the potential for distributed hydrogen production. This will achieve the following aims:

- **Reduce costs of hydrogen supply** – the Demonstrator Project will support advances in hydrogen supply solutions (both incumbent and challenger solutions) that will reduce the cost of hydrogen relative to current best available options.
- **Increase Carbon saving potential** – the Demonstrator Project will support the development of technologies which will improve resource efficiency through improvements in energy efficiency or greater use of a constrained renewable source, poorer quality water use and higher capture rates.
- **Develop novel technologies to increase market competition** – the project will have a focus on enabling diversification in hydrogen supply solutions.
- **Knowledge building to inform policy development** – BPP and its partners will produce a number of reports which will provide market insight on the support required to enable rollout and costs of a range of hydrogen supply solutions.

- **Develop the knowledge and skills required to meet net zero** – the project will enable the development of the skills and experience required across the supply chain

The expected benefits in producing green hydrogen directly offshore using offshore wind farm are described in **Section 3.** The estimated LCOH achievable are given in **Figure 5**.

The key barriers to achieve future commercialisation of this novel Green H2 supply solution are listed below:

- **CAPEX & OPEX reduction**: Simplifying system design to reduce labour cost, increase automation, reliability and safety of the entire process.
- **Improve system efficiency**: Integrate cost-effective and efficient technologies and implement an efficient power flow algorithm to improve the performance of Green H2 system and decrease the LCOH;
- **Increase electrolyser manufacturability**: Electrolysers are currently not manufactured in scale. Manufacturing equipment will be required for a wider commercialisation of the proposed solution allowing the use of larger structures at low cost.

The Demonstrator project will promote its work to industrial partners involved in the production, transmission and distribution of energy, infrastructure financing and climate change services. Major stakeholders will include:

- Wind Farm Operators;
- Oil & Gas Companies;
- Electrical and Energy Companies;
- Electrolyser and Fuel Cell Industries;
- Investment Funds.

Technical support from subcontractors and specialised companies will allow for a rapid implementation of the project in the identified timeframe, increasing the likelihood of first-mover advantage and maximizing business opportunities, whilst economic support from investors will decrease the financial risk of the project.

7 Costed development plan

An initial design of a Green Hydrogen Demonstrator System has been developed consisting of an electrolyser that can produce from 23 to 100 tons of Hydrogen per year, a battery capable of singularly powering the electrolyser, and a water desalination system.

The ranges of estimated costs are as follows:

- All the equipment required, including the auxiliary components, are predicted to cost in the range of from £1.9M to £3.6M depending on the power levels available and production rates required;
- Labour costs in the range of £1.4M to £2M;
- Site costs are likely to be £0.17M to £0.65M depending on location;

- Other management and support costs being £0.7M to £1.0M over the first 3 years;
- Annual operating costs are estimated to be in the range of from £0.6M to £1.0M;

8 Rollout potential

Hydrogen can accelerate the energy transition by allowing clean energy to be stored and large volumes to be transported over long distances via pipelines and ships. It can foster greater resilience, cost-efficiency, and optimization at a system level. Hydrogen is a versatile clean molecule that plays multiple roles across end-uses and goes hand-in-hand with other decarbonization levers such as direct electrification, carbon capture and storage, biofuels, and energy efficiency measures. Hydrogen applications includes:

- Fuel directly usable in fuel cells used in mobility or stationary power;
- High-grade heat needed for cement production;
- Grid power generation;
- Feedstock to produce ammonia or synthetic fuels;
- For use in the maritime and aviation sectors;
- Reductant for processing iron ore for clean steelmaking.

Beyond its importance in decarbonization, Hydrogen is gaining traction as a way to increase energy security. Countries are increasingly pursuing energy independence and diversification of energy supplies, particularly considering the current war in Europe and uncertainties in global politics. In the EU, the war in Ukraine has led to bolder ambitions for clean hydrogen to strengthen energy security

Stakeholders have accelerated plans to develop hydrogen pipeline transmissions and for many countries hydrogen is about monetizing decentralized energy resources like renewables or ensuring energy security and self-sufficiency.

A key requirement to achieve these ambitions is to build a domestic industry around technology for seaborne hydrogen trade and use in the power and automotive sectors. There is, therefore, a requirement to develop credible innovative hydrogen supply solutions.

This Phase 2 work will be carried out by forming a consortium of equipment suppliers, investors and key system designers including BPP. The aim is to enable future development directions for Green H2 production, providing a basis for future implementation of the designed Green H2 production system and its integration within emerging and cost-effective renewable energy sources.
A Business Case has been developed for this roll out potential.

9 Route to market assessment

As the demand for a net zero sustainable transport fuel increases, the market for Hydrogen is set to expand substantially. Globally, there are over 60 million tons of hydrogen produced annually, worth almost US$100 Bn. This annual demand is forecast to increase tenfold by 2050 – from 8 EJ in 2015 to almost 80 EJ in 2050.

This project fits within the scope of the new UK Energy Security Strategy and could represent a valuable asset for the UK as global leader in the future hydrogen economy.

The pipeline of hydrogen projects is continuing to grow, but actual deployment is lagging. In 2022 some 680 large-scale hydrogen project proposals, equivalent to USD 240 billion in direct investment through 2030, have been put forward – an investment increase of 50% since November 2021. Yet, only about 10% (USD 22 billion) have reached final investment decision. Europe is home to over 30% of proposed hydrogen investment globally.

The urgency to invest in mature hydrogen projects today is greater than ever. The rebound of carbon emissions to above pre-COVID levels, the invasion of Ukraine, and the growing concerns around energy security resulting from the war in Europe make one thing clear: our economies need clean hydrogen, and action is needed to convert proposals into actual deployment and reach final investment decision (FID).

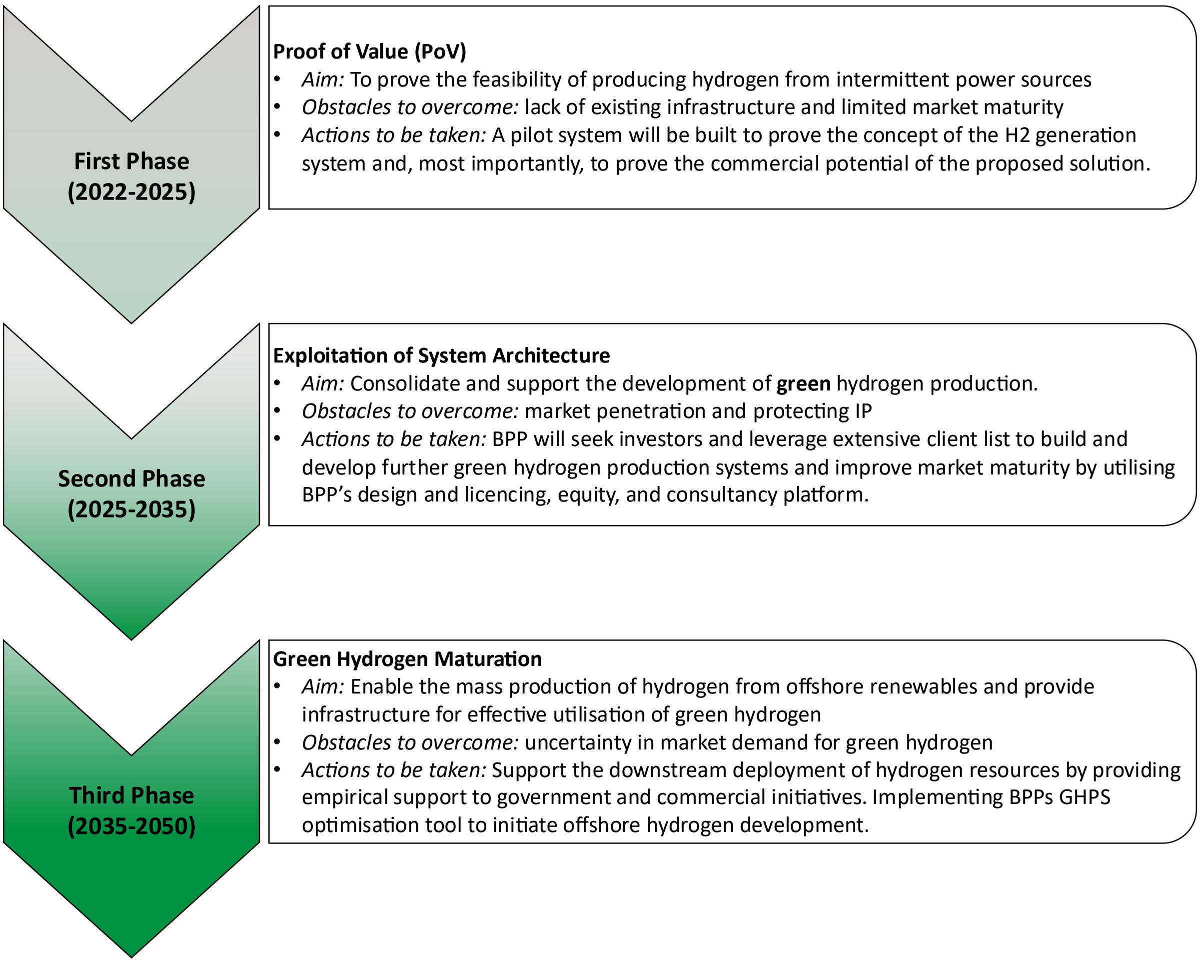
Taking into account these considerations, the major challenge for the future commercialisation BPP's Green Hydrogen Production system remain:

1. Establishment a clean hydrogen economy
2. Transition from carbon-intensive to low-carbon hydrogen production
3. Development of optimised Hydrogen value chain;
4. Need for international standards on hydrogen for safety aspects related to hydrogen production, storage, and transportation in multi-sectors.
5. Government support of a multi-sector global hydrogen economy, both for production and end-users to gradually stimulate this energy transition.

The availability of this Hydrogen Production demonstrator is expected to accelerate this maturity and to provide the industry with a cost-efficient solution.

The successful completion of the Hydrogen Production demonstrator will enable BPP and its partners to provide Green Hydrogen in the current and future energy landscape, leveraging on BPP's extensive Hydrogen and offshore expertise, seamless project execution capabilities and established presence in the Hydrogen market.

It is suggested that BPP will enter into Green Hydrogen market in three phases, as shown below:



The most attractive production markets for Green Hydrogen are those with abundant and low-cost renewable resources, where the following parameters play a pivotal role for the implementation of Green Hydrogen technologies:

- Continuously falling renewable energy production costs
- Economies of scale
- Establishment of efficient Green Hydrogen production technologies

BPP will target the following sectors and will support these in achieving net-zero carbon dioxide by developing cost-efficient and tailored solutions for Green Hydrogen production:

- **Islands & remote locations -** Many islands and remote locations have a less than ideal solution for their future energy infrastructure, relying on the mainland and low-capacity energy infrastructure to meet their energy needs. This limits their economic and industrial potential.
- **Remote Onshore Renewables -** The system can be placed near remote renewables, including onshore wind turbines, and provide an alternate robust and highly autonomous source of storing and transporting energy for facilities isolated from the grid while allowing greater flexibility for sources such as hydropower.

- **Transport Sector -** The produced Hydrogen can be used to supply a dedicated H2 refuelling station close to the GHPS for light and heavy-duty vehicles. The successful implementation of this solution will support the development of an H2 supply chain and the establishment of decentralised Hydrogen Hubs
- **Industrial sites -** BPP will target industrial sites characterised by carbon-intensive energy processes and/or inefficient energy sources management, for which Hydrogen can represent a sustainable and cost-efficient solution.
- **Offshore sector -** BPP has a number of established commercial relationships in these sectors, including firms such as Shell, SSE, Scottish Power, Xidao Wind Power, Copenhagen Infrastructure Partners and Keppel. These companies are highly likely to drive the Green H2 market in the near to medium term and BPP intends to exploit these existing relationships. BPP will target the offshore wind sector, with secondary markets including:
- **Wind Farm Developers -** By optimising wind farm placement and minimising power losses. Can also provide quantified cost-benefit analysis for FWF development in different territories.
- **Oil & Gas Companies expanding to clean energy -** BPP-HYPRO will provide quantified benefits/profit predicted for any proposed FWF-H2 system.
- **Insulation Contractors -** Clear and thorough data on sea conditions and their effect on wind farms will be valuable to firms insulating H2 systems from the weather.
- **Banks/loan providers assessing risk -** Can access clear projections of expected returns and compare cost and benefits when considering a loan.
- **UK and other Governments -** Support in meeting green energy targets.

10 Dissemination

Over the past 9 months BPP has carried out several marketing activities, to promote this project and increase its visibility in a highly dynamic market.

The company has adopted a new trading name **"BPP Renewables**" to give more emphasis and relevance to its new capability and services around Green H2. In conjunction with this BPP has launched a new website: https://www.bpp-renewables.com/ which provides a detailed description of this new study.

BPP has developed several brochures, an example is shown in Appendix B: Dissemination, to engage with potential clients and explore new opportunities. Thanks to this material BPP has entered in conversation with a variety of stakeholders and companies interested in BPP's initiatives focused on Green Hydrogen.

BPP, as a member of the UN Green Hydrogen Energy Compact Catalogue, is regularly sharing its knowledge and exploitation plans with the UN through updated reports.

BPP will attend major international events organized to connect industry leaders in offshore, hydrogen and renewable sectors. In October 2022 BPP attended the FOWF22 event in Aberdeen, and presented this project to the audience. This was the ideal place to engage with relevant companies for future natural developments of this project.

11 Conclusion

Five principal innovations have been developed within this Phase 1 project:

1. The system design and integration engineering tool enables the continuous production of Green Hydrogen from intermittent sources of power. These could be the outputs of onshore and offshore wind turbines, the outputs of solar arrays, tidal turbines and even off-peak power from the grid. All of these energy sources are intermittent and dependent on meteorological and demand related effects.

2. The secondary but crucial impact of the above capability is to enable energy from intermittent (usually renewable) sources to be stored and utilised on demand. This component of the innovation enables the power factor of the renewable energy source to be improved. It also introduces a commercial component that improves the income and economics of the Hydrogen economy by generating greater economic opportunities for 'spot' pricing and energy trading.

3. A key innovation underpinning the above is a proprietary power flow algorithm and control system that can utilise intermittent sources of power to enable reliable long-term production of Green Hydrogen.

4. A further innovation is the fact that the system design and integration engineering tool accurately models the electrolyser, battery power, water treatment and thermal management systems that make up the production train. This modelling has been carried out using data provided by leading manufacturers of the relevant equipment and enables these components to be more accurately simulated within future system assemblies.

5. The fifth and final innovation is case studies of full-size and pilot systems for implementing the Green Hydrogen production system. The full-size system is an offshore system powered by wind turbines located off the North-East coast of Scotland. The pilot system is a small demonstrator unit capable of being housed in a 7.5m x 11m x 3m space. This unit can be used to demonstrate performance but also forms the basis for small scale commercial systems.

Appendix A: Project Team & Industrial Partners

BPP has provided professional services, consulting and product development services to the hydrocarbon, renewable energy, and clean-tech sector since 1982, with trusted engineers working across the energy, insurance utilities and transport sectors. It specialises in design, engineering and product development for emerging industrial sectors with on-going work, for example, in subsea power cables for offshore wind farms. This requires an internal innovation-based culture that runs through the company and provides clients with consistent, knowledge-based long-term services.

BPP is an independent, privately owned company with a minority (20%) shareholding owned by Shell Technology Ventures Fund 1. This shareholding brings in the oil major Shell and is in recognition by them of BPP-TECH's long-term track record of innovations in the hydrocarbon and renewable energy sector. BPP employs a total of 22 staff qualified to BEng, MSc and PhD levels across various disciplines, and has offices in London, Newcastle and Aberdeen. The team members working on this project are qualified engineers with substantial experience in their respective fields.

BPP has used data from the principal manufacturers of equipment to develop a software tool for modelling, integrating and analysing the proposed system's technologies. The following is a summary of the key product suppliers that BPP have engaged with:

1. **Nel Hydrogen (Nel)**: Nel is a global company providing solutions for the production, storage and distribution of hydrogen. Nel provided technical specifications of their PEME;
2. **Veolia**: Veolia is a French multi-national company specialising in water treatment processes. Veolia provided technical specification of the SWRO desalination system;
3. **Revi S.A.S**: Revi provides products, services, and integrated solutions in the energy sector, working across electricity generation, transmission, and distribution market and provided BPP with the technical specifications of the NAS battery system;
4. **Alfa Laval**: Alfa Laval produces products in the areas of heat transfer, separation and fluid handling. Alfa Laval provided the technical specifications of seawater heat exchangers and thermal-based desalination units;
5. **Jiangshan Scotech Electrical Co., Ltd (Scotech)**: SCOTECH is a subsidiary of Zhejiang Longxiang Electricity Co., Ltd which is a large transformer manufacturer offering a full range of transformers. SCOTECH provided the technical specifications of the most-appropriate transformers to be considered in this project.

Each of these companies have signed a Collaboration Agreement and NDA for the Phase 1 and Phase 2 of the project and have leveraged their expertise in their respective fields to support BPP in selecting the technologies stated above.

Appendix B: Dissemination

BPP-TECH

GREEN HYDROGEN FROM OFFSHORE AND ONSHORE WIND FARMS

BPP-TECH has developed a solution and design tools of a scalable system for large-scale production of Green H2 utilising technologies at High Technology Readiness Levels (TRLs) commercially available in the open market.

A key feature of offshore H2 production facilities is that they will not need high cost subsea export cables going to shore.

The scalable system enables use of intermittent power from offshore or onshore wind turbines combined with a battery system for continuous operation of H2 electrolysers. Key benefits of this solution are:

- Eliminate wind farm export cables to shore
- Increase wind farm efficiency and store renewable energy
- Develop commercially viable green H2 supply chain

Optimised system design and integration

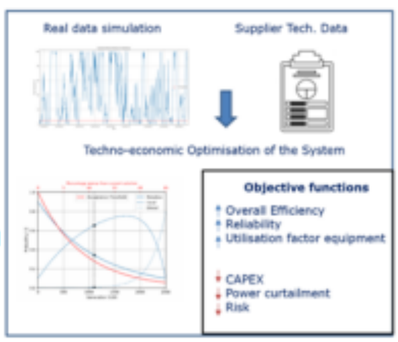
BPP-TECH's solution is based on the combination of multiple systems into one simulation which outputs an optimised process for the system design, including:

- Optimum layout of the Floating Wind Farm H2 system
- Real-life simulation of green H2 production system
- Evaluation of solutions for H2 storage and transportation
- Detailed modelling of offshore Green H2 system comprising proven high TRL technologies

Real-life simulation of Green H2 production system

Comprehensive system design and integration software tool to predict performance, CAPEX and OPEX of high TRL technologies. Operational characteristics of high TRL technologies implemented into a complete techno-economic design tool and modular simulation for the offshore production of Green H2, scalable by farm size and geographical location.

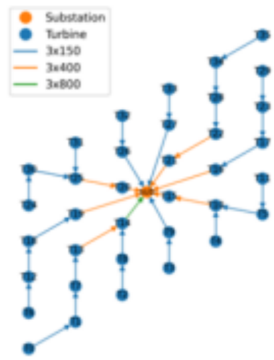
BPP's Integrated Engineering Approach



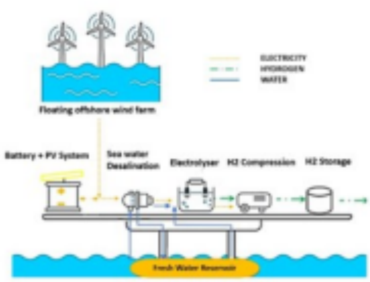
Optimum layout of the FWF-H2 system

Robust optimisation schemes to enable power loss, cable cost and risk reduction from different turbine layouts. The optimisation includes all key factors including cable size, turbine positions, conductor material, burial depth, junction boxes, sub-stations, wind and wave conditions and ambient sea temperature.

Cable and Junction Material CAPEX -:- £10,988,226
Power Loss due to Joule effect -:- £7,234,159
Power Loss due to Cable failure -:- £1,432,793



Example of System Schematic



For further details, contact:

Minoo Patel
+44 2074489550
m.patel@bpp-tech.com

Giuseppe Sercia
+44 20 7448 9526
g.sercia@bpp-tech.com

bpp-tech.com