Hydrogen Turbine 1 (HT1)

Final Project Report

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Contents

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1 GLOSSARY

1.1 Abbreviations

The following abbreviations have been used throughout this document:

Abbreviation	Description
AC	Alternating Current
AEM	Anion Exchange Membrane
ALK	Alkaline
AOWF	Aberdeen Offshore Wind Farm
DC	Direct Current
DESNZ	Department for Energy Security and Net Zero
EIA	Environmental Impact Assessment
EOWDC	European Offshore Wind Deployment Centre
FOAK	First of a Kind
HPPC	Hybrid Power Park Controller
HSE	Health and Safety Executive (UK)
HT1	Hydrogen Turbine 1
LP	Line Packing
MD-LOT	Marine Directorate Licencing and Operations Team
NSTA	North Sea Transition Authority
PEM	Proton Exchange Membrane
PPC	Power Park Controller
PPC	Pollution, Prevention and Control
PSV	Pressure Safety Valve
PWA	Pipeline Works Authorisation
SEPA	Scottish Environmental Protection Agency
SOEC	Solid Oxide Electrolyser Cell
TRL	Technology Readiness Level
UV	Ultra Violet
UXO	Unexploded Ordnance
WTG	Wind Turbine Generator

1.2 Definitions

Term	Definition
Balance of Plant	The supportive component systems to the electrolyser e.g. safety systems, cooling systems, lighting etc.
Deionisation	The removal of ions, reducing the conductivity of the substance (in this case water)

Term	Definition
Desalination	The process of removing salt from a liquid
Electrolysis	The process by which a current is passed through an electrolyte to split water into hydrogen and oxygen
Electrolyte	A substance that separates in water into charged particles called ions
Flaring	The process by which a gas, in this case hydrogen, is burned.
Fuel Cell	A system that uses the chemical energy of hydrogen to produce electricity and water.
Ion	An atom or a molecule with an electrical charge (either positive or negative) through gaining or losing electrons.
Island Mode	The ability for an asset to operate independently of an electrical grid connection
Line Packing	The process of filling a pipeline with fluid at pressure to act as a storage vessel.
Offtake	The end user of hydrogen
Topside	Plant located on top of the jacket foundation.
Venting	The process by which a gas, in this case hydrogen, is released to the atmosphere.

2 EXECUTIVE SUMMARY

Hydrogen Turbine 1 (HT1) project has concluded after making significant contributions to the advancement of hydrogen production from offshore wind. The project, based at the Aberdeen Offshore Wind Farm, sought to convert one of the existing wind turbines to produce hydrogen through installation of an electrolyser on the turbine. At the outset, it was envisaged that produced hydrogen would be exported to shore where it would be compressed and stored before delivery to a local offtaker. Due to the lack of a suitable local offtaker and increasing costs, Vattenfall proposed to re-frame the project, reducing the capacity of the electrolyser and opting to re-electrify produced hydrogen through a new hydrogen fuel cell, and power exported through the existing grid connection, as shown in Figure 1. This reduced project costs and risk, while maintaining the desired learnings from the project.

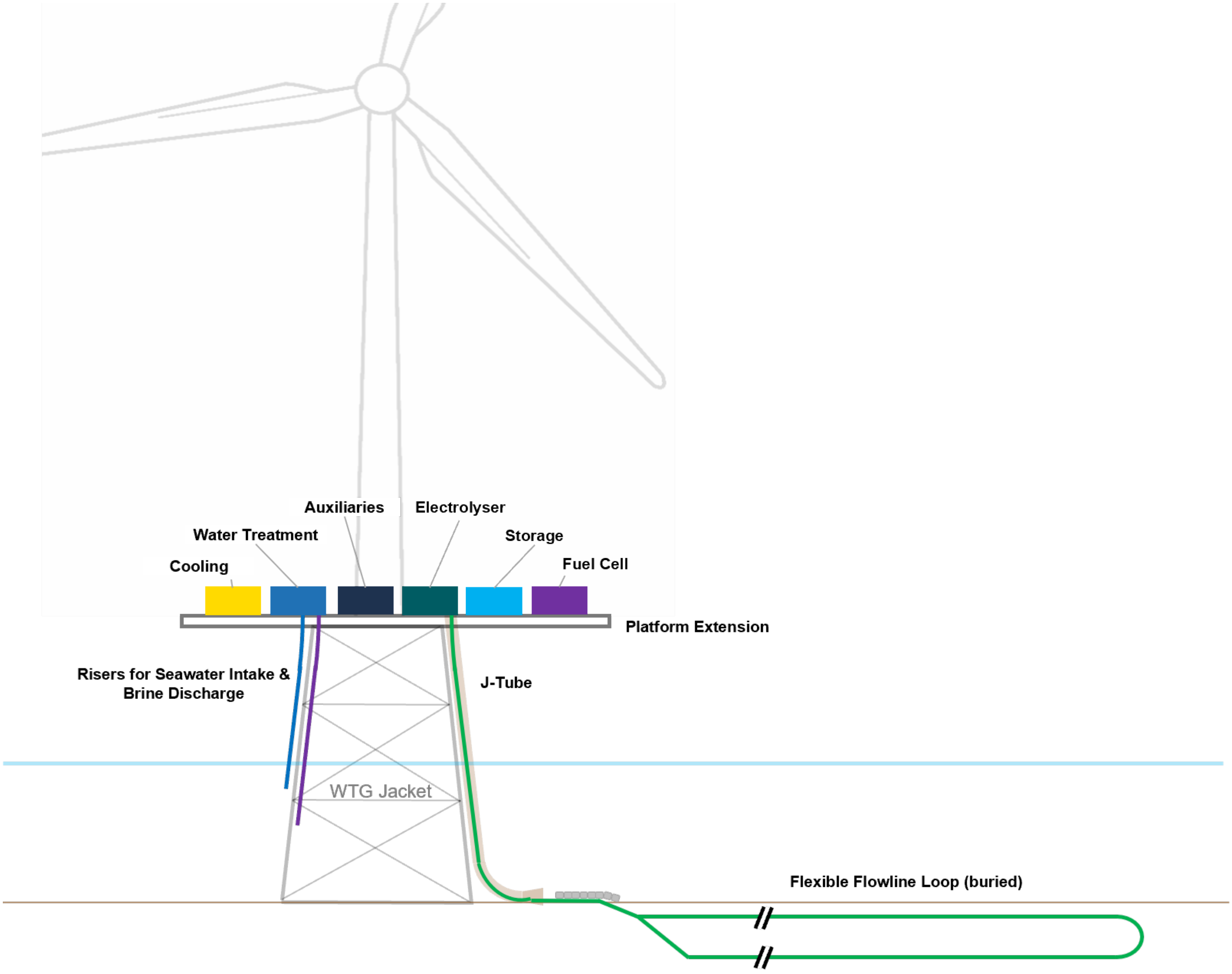

Figure 1: Hydrogen Turbine 1

The project design envisaged seawater, extracted through a new riser retrofit to the jacket, desalinated through thermal desalination technology, selected to utilize waste heat from electrolyser as part of a cooling loop. The desalinated water is then ultra purified for use in electrolysis. A (1MW) PEM electrolyser was selected due to its ability to react fast to changes in power input, as is expected from wind generated energy. PEM technology was selected due to the fast response time and small footprint. The electrolyser splits water into oxygen, which is vented to the atmosphere, and hydrogen which is processed for export via a small diameter flexible flowline loop. Hydrogen is stored, through line packing in the flowline and permanent storage on the platform before being re-electrified through a (200kW) fuel cell.

The concept, is a small-scale demonstration of decentralised hydrogen production, proving the ability to produce hydrogen offshore on a turbine which can be scaled to commercial-scale wind farm developments. In addition, it demonstrates how hydrogen could be used to smooth the intermittency of wind energy through energy storage, and through re-electrification of hydrogen, wind farms may be able to operate without reliance on a grid connection or back-up diesel generators.

As a “first of a kind” project, HT1 encountered various barriers to delivery. There was no blueprint of how a project such as this should be completed, particularly regarding Health & Safety and Consenting. Engagement with regulators has advanced guidance on how offshore hydrogen projects should be designed and operated, providing a steppingstone for future similar projects in the UK. The project also helped to identify gaps within legislation that would prevent an offshore hydrogen project such as HT1 gaining consent in the UK. Through engagement with the Department for Energy Security and Net Zero, Vattenfall are proud to have contributed to secondary legislation changes paving the way for future offshore hydrogen projects in the UK.

The lack of a local hydrogen offtake was one of the project's biggest obstacles to success and highlights the need for support across the entire value chain for hydrogen, from production, to transportation and storage, and ultimately use by the end customer. HT1 was re-framed to overcome this issue by re-electrification, demonstrating the ability to store wind energy in the form of hydrogen for use when demand is high.

The advancement of the hydrogen industry was another factor that led the project to close as learnings to be gained from the re-framed small scale decentralised demonstrator project were narrowing. This is a positive sign for the industry as it grows at an exponential rate. Low carbon hydrogen production has a use in a variety of different industries, including steel production and aviation, with the potential to decarbonize the existing high carbon hydrogen supply and hard to abate industries reliant on fossil fuels.

The project was concluded during the development phase, prior to Final Investment Decision. The project did not progress into execution and demonstration.

3 INTRODUCTION

3.1 Project Overview

The Hydrogen Turbine 1 (HT1) project sought to convert an existing offshore wind turbine, located at the Aberdeen Offshore Wind Farm (AOWF), to produce hydrogen through electrolysis and subsequently use the produced hydrogen to power a fuel cell to export electricity through the existing grid connection.

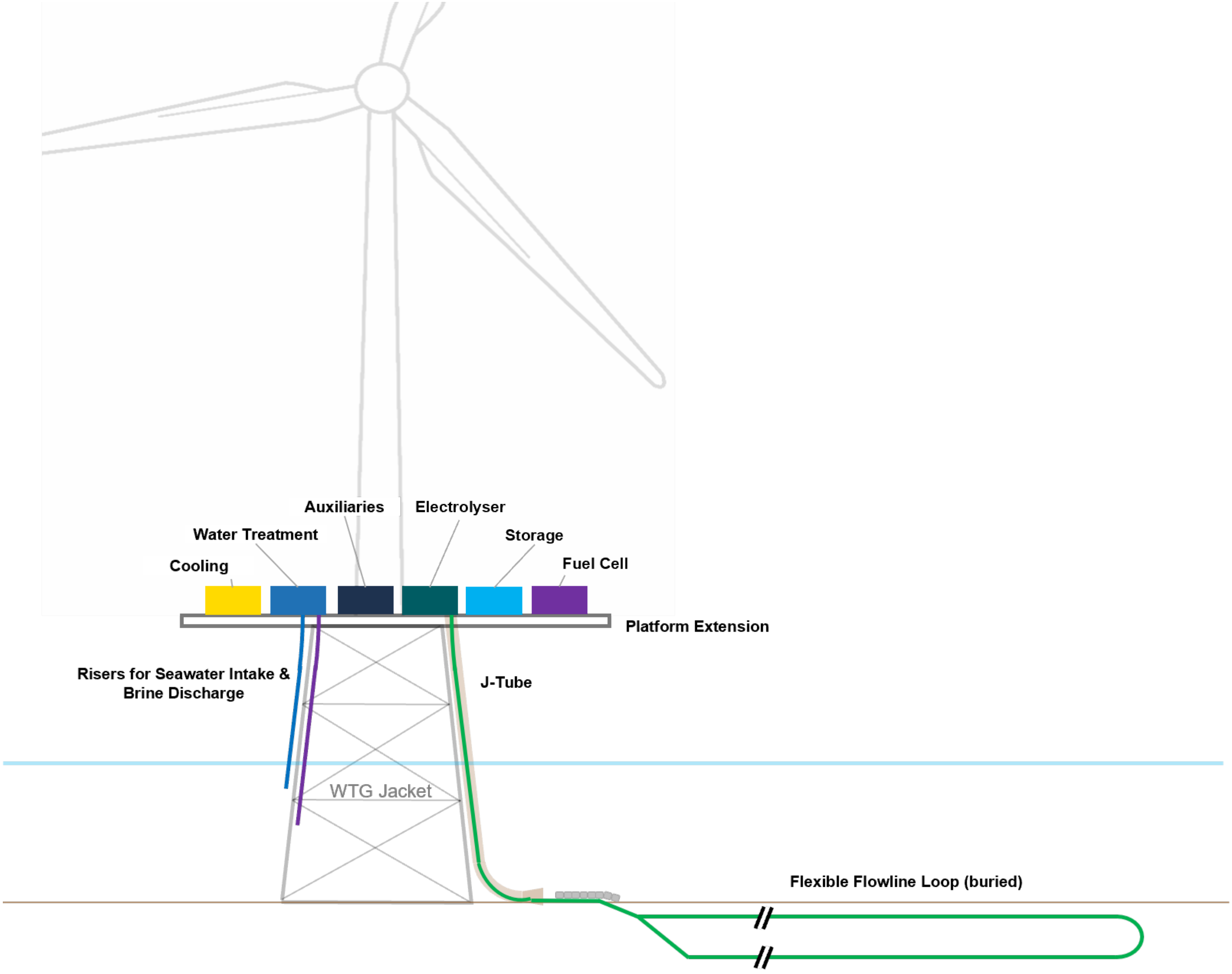

Figure 2: Project Overview

The existing turbine, a Vestas 8.8MW model, was to be fitted with a Hybrid Power Park Controller (HPPC) that directs power to hydrogen production and the balance of plant, with the remaining power exported to the grid.

In this configuration, seawater is extracted through a new riser, retrofit to the jacket foundation, then desalinated and ultra-purified to use as a feedstock for hydrogen production as well as providing a cooling medium for the system. A 1MW Proton Exchange Membrane (PEM) electrolyser splits the ultra-purified water into oxygen, which is vented to the environment, and hydrogen which is dried and processed, ready for use. Wastewater is treated and then released back to the sea.

Following production, hydrogen is exported through a short flowline loop, which also acts as a storage vessel, back to fixed storage topside before powering a fuel cell, where electricity generated is exported through the existing grid connection. Water produced by the fuel cell is released back to the sea, alongside wastewater.

Additional balance of plant is also installed, such as a nitrogen purging system, to allow the safe operation of the asset.
To provide sufficient space and support for the additional infrastructure, a platform extension is installed around the existing jacket foundation taking advantage of existing pad eye connection points. The new structure will provide support to two new risers for sea water intake and wastewater discharge, and two new J-tubes for the flowline loop.

3.2 Project Location

The Aberdeen Offshore Wind Farm, also known as the European Offshore Wind Deployment Centre (EOWDC), is located just off the coast of Aberdeen in Scotland and is a designated hub of offshore wind innovation. The wind farm uses next-generation technology, including 11 x 8.8 MW turbines paired with suction bucket jacket foundations, which were a first for the industry at the time of construction. The wind farm began generating power in July 2018, and its operations and maintenance team is stationed at Aberdeen Harbour.

Figure 3: Aberdeen Offshore Wind Farm

Aberdeen was selected for a number of reasons, including:

- AOWF is 100% owned by Vattenfall, therefore the site is already secured for the project.
- The site is a designated innovation centre and Vattenfall is obliged to bring innovations to the site each year.
- As an existing wind farm, consent and permits for additional hydrogen infrastructure are significantly simplified in comparison to a greenfield site and development can focus on the new innovative elements of the project, rather than the conventional wind farm components.
- The site is the closest to shore of all Vattenfall's offshore assets in operation and close to port infrastructure convenient for construction, installation, operation and maintenance of the asset.
- Aberdeen as a region has a wealth of experience in the offshore energy industry, including the oil and gas sector which is expected to be a key enabler to the advancement of the hydrogen industry.
- The region also has ambitions to be a centre of excellence for the emerging renewable and low-carbon hydrogen industry – the local city council is supportive and pro-active for future development of a low carbon hydrogen economy, as evidenced by creation of "Aberdeen Hydrogen Hub" initiative, which aims to stimulate demand and coordinate linking of supply and demand.
- Subsidies and funding schemes, such as HySupply2, were available from the UK and Scottish Governments to enable the project.
- UK and Scottish Governments support hydrogen development, with the UK targeting 10GW low carbon hydrogen production by 2030 [Ref. 6].

The project aimed to convert a single turbine to hydrogen production, whilst the remainder of the wind farm operates as normal. Turbine B-06, highlighted in Figure 3, was selected for the following reasons:

- B-06 is located at the Normally Open Point in the cable loop, allowing the turbine to be isolated from the remaining turbines on the farm without impacting normal operation of the site.
- B-06 is located furthest from shore minimising any visual impact and potential noise from the operation of the site.

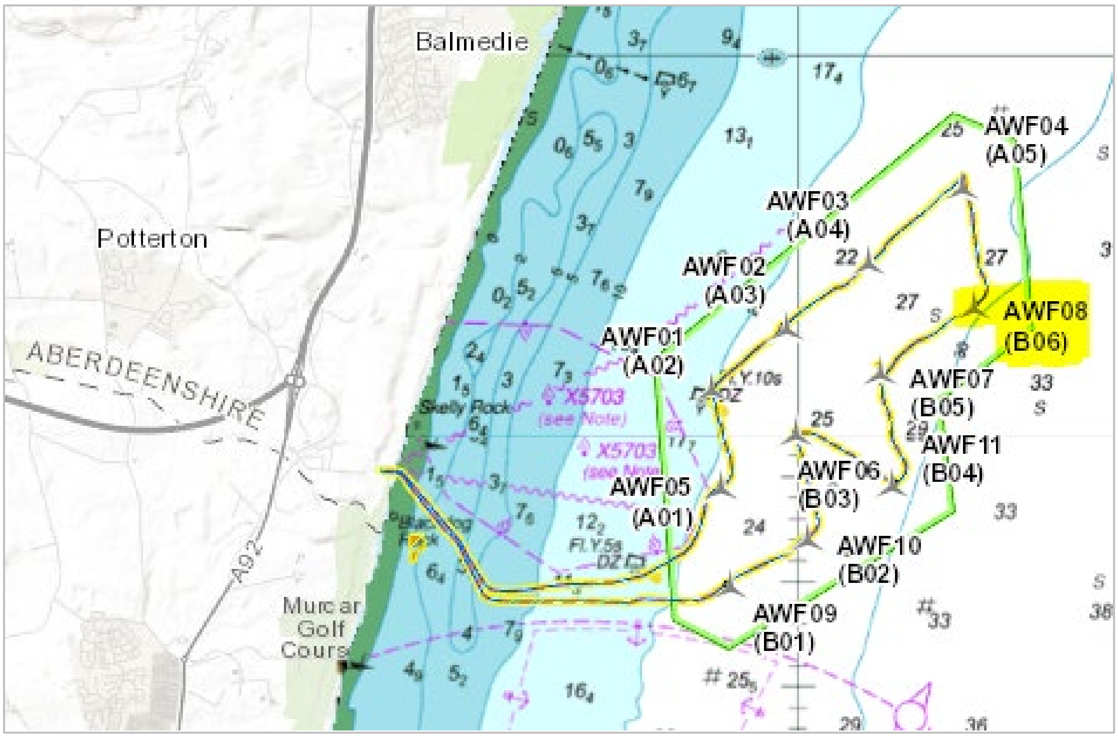

Figure 4: AOWF Layout with Turbine B-06 Highlighted

3.3 Background

The HT1 project originated within Vattenfall’s Offshore Development team, through a project stream called “Hydrogen Solutions”, initiated in June 2020. Hydrogen Solutions aimed to build on early investigations into offshore hydrogen production to understand the potential evolution of the industry. These investigations took into account the expected future evolution of the broader energy system, technology developments, infrastructure needs, end-use applications, geographical constraints, economic and regulatory aspects, scalability, and strategic fit with Vattenfall’s existing pipeline of offshore wind opportunities, as well as new opportunities that may be enabled.

The technical direction that emerged from this analysis as offering the best long-term success was offshore wind farms fully dedicated to hydrogen production, with export to shore via pipeline. This direction was chosen as early analysis indicated it had the potential to achieve the lowest cost hydrogen and the best overall business case outcomes for Vattenfall.[1]

These qualities were key, both in driving internal support for further development of the solution, as well as in driving external support for its realisation by end-users of hydrogen and other relevant stakeholders such as government bodies, infrastructure operators etc.

This direction was selected based on the following:

- Required scale needed for market relevance, sector leadership, and cost competitiveness
- Alignment with capacity targets in national and EU level hydrogen strategies

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[1] While Vattenfall remain positive about the future of offshore hydrogen production, further work has demonstrated that the optimal solution varies from project to project, depending on local constraints. Vattenfall will select the most appropriate solution, agnostic of where hydrogen is produced, onshore or offshore.

- Accounting for current Technical Readiness Level (TRL) and technical maturation requirements / time

A “back-casting” approach was used to work backwards from this end-goal to identify the steps needed to mature the solution towards large scale deployment. This resulted in a multi-step approach, summarised as:

1. Onshore component and systems testing
2. First offshore pilot(s)
3. Offshore clusters as part of larger wind farms
4. Entire offshore wind farms dedicated to hydrogen production.

Even though each of the individual technical elements already exist, system integration of the technical solution was still to be proven Therefore, these steps aim to gradually increase scale and technical complexity, whilst managing risk, decreasing uncertainty and preparing the solution for the offshore environment. This approach would systematically qualify the technical solution for large scale deployment, whilst maintaining investment and efficiency enabling rapid progression towards the level of cost-competitiveness required for profitability.

Project HT1 fits into this larger plan as step 2: a first full-scale demonstration of a turbine dedicated to producing hydrogen offshore.

3.4 Aim and Objectives

The aim of Project HT1 was to build experience and learnings in the design, installation, operation and maintenance of an offshore hydrogen production system to de-risk large scale projects. Vattenfall planned to use HT1 to demonstrate key equipment and systems required:

- Seawater extraction, filtration, desalination and purification
- Hydrogen production
- Hydrogen transport through pipeline (offshore)
- Hydrogen storage
- Re-electrification of produced H_2
- System integration

The project objectives were to be satisfied by demonstrating:

- Safe, reliable and integrated operation of the above listed equipment and systems in an offshore environment.

- The development and documentation of procedures, safety systems, processes and tools supporting the engineering, procurement, construction, manufacturing, installation and operation phases of a hydrogen project.

3.5 Project Evolution

Project HT1 evolved over time since its inception in early 2021, as is typical for a pilot project of this nature.

Initially, Vattenfall intended to model the entire value chain on Project HT1 “from turbine to truck” and the turbine would operate in “island mode” i.e. without an electrical connection, to simulate, as close as possible, a decentralised hydrogen production scenario.

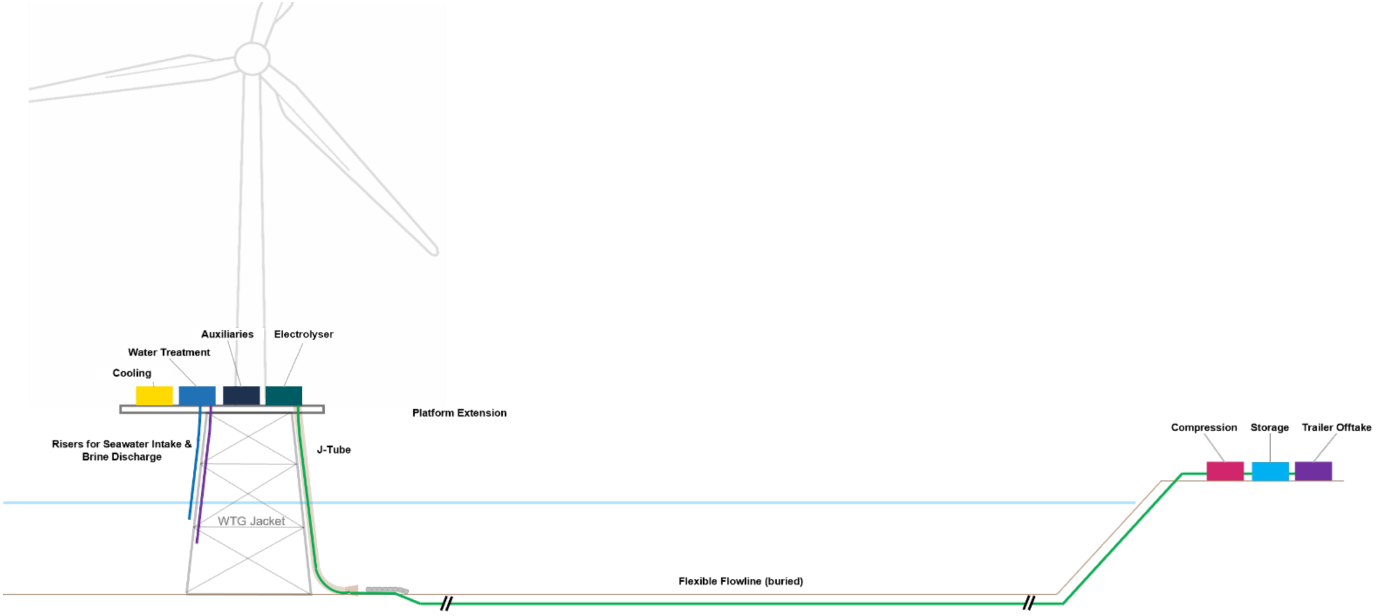

Figure 5: Initial Concept

The hydrogen production system would be sized to meet the output of the WTG (8.8MW) and hydrogen exported to shore via a new pipeline where it would be compressed and stored for trailer offtake at a new onshore facility. A fibre optic cable would be installed alongside the pipeline to provide communication between the onshore facility and the turbine.

In November 2022, the project was put on hold while a re-framing exercise was completed due to sustained increases in project costs, prolonged timeline and the lack of secured suitable local offtaker for the hydrogen. The aim of the re-framing exercise was to revise the concept to improve costs and reduce the potential onshore impact, whilst maintaining key technical and operational learnings.

This exercise culminated in Vattenfall's approval for the project to reform and proceed with the re-framed concept described in Section 3.1 with the following impacts:

- **Re-electrification of hydrogen** removed the need for an offtake by providing a revenue stream for the produced hydrogen through the existing grid connection. However, due to efficiency losses, it was recognised that this would be less than if exporting power directly from the WTG. It did however provide the opportunity to test the use of hydrogen as a storage medium to mitigate the intermittency of wind power generation.

- The **diminution in electrolytic capacity** reduced the power used to run the hydrogen production system, limiting the efficiency losses. 1MW was deemed to be the minimum capacity that would allow the same learnings to be gained from the system as a 10MW electrolyser.

- **Reducing the pipeline length,** rather than eliminating it, maintained the learnings of designing, installing and operating a pipeline for hydrogen service and provided a storage medium for hydrogen.

- **Eliminating the onshore scope** removed a major and non-innovative source of increasing costs on the project. It did however remove the ability to model the entire value chain envisaged for the offshore hydrogen industry.

3.6 Project Close and Timeline

Following a review of the project, HT1 was brought to a close. The project was envisaged to be a “first of a kind” project and has provided a significant amount of learnings to Vattenfall and our collaborators. However, a number of factors emerged which changed the trajectory of the progress of this project, including rising costs. Additionally, the industry overall has made progress in offshore hydrogen production and similar technology has already been demonstrated at this scale. This meant that learnings from the project would no longer be as significant as planned and not material enough to justify the expected significant costs.

3.7 Purpose of Document

The purpose of this document is to present a summary of the project and to discuss and disseminate lessons learned as the project comes to a close.

3.8 Funding from DESNZ

Part of the overall HT1 project was awarded funding of £9.3m as a discrete project under the Low Carbon Hydrogen Supply Competition, part of DESNZ’s £1bn Net Zero Innovation Portfolio. Complementary elements of the HT1 project were funded by Vattenfall. Overall, £2.4m has been spent on the DESNZ funded project activities under the Low Carbon Hydrogen Supply 2 competition for the HT1 project.

4 PROJECT DEVELOPMENT

The project has been developed in work packages depending on the complexity of interfaces between systems, expertise required and set up of the supply chain. The work packages are:

- Hydrogen Infrastructure
- Electrical Infrastructure
- Control Systems
- Platform Extension and Risers

4.1 Hydrogen Infrastructure

The hydrogen infrastructure package consisted of all new infrastructure required for the production, transport, storage and re-electrification of hydrogen, primarily:

- Water Treatment System
- Electrolyser
- Subsea Pipeline Loop
- Storage Vessel
- Fuel Cell
- Auxiliaries

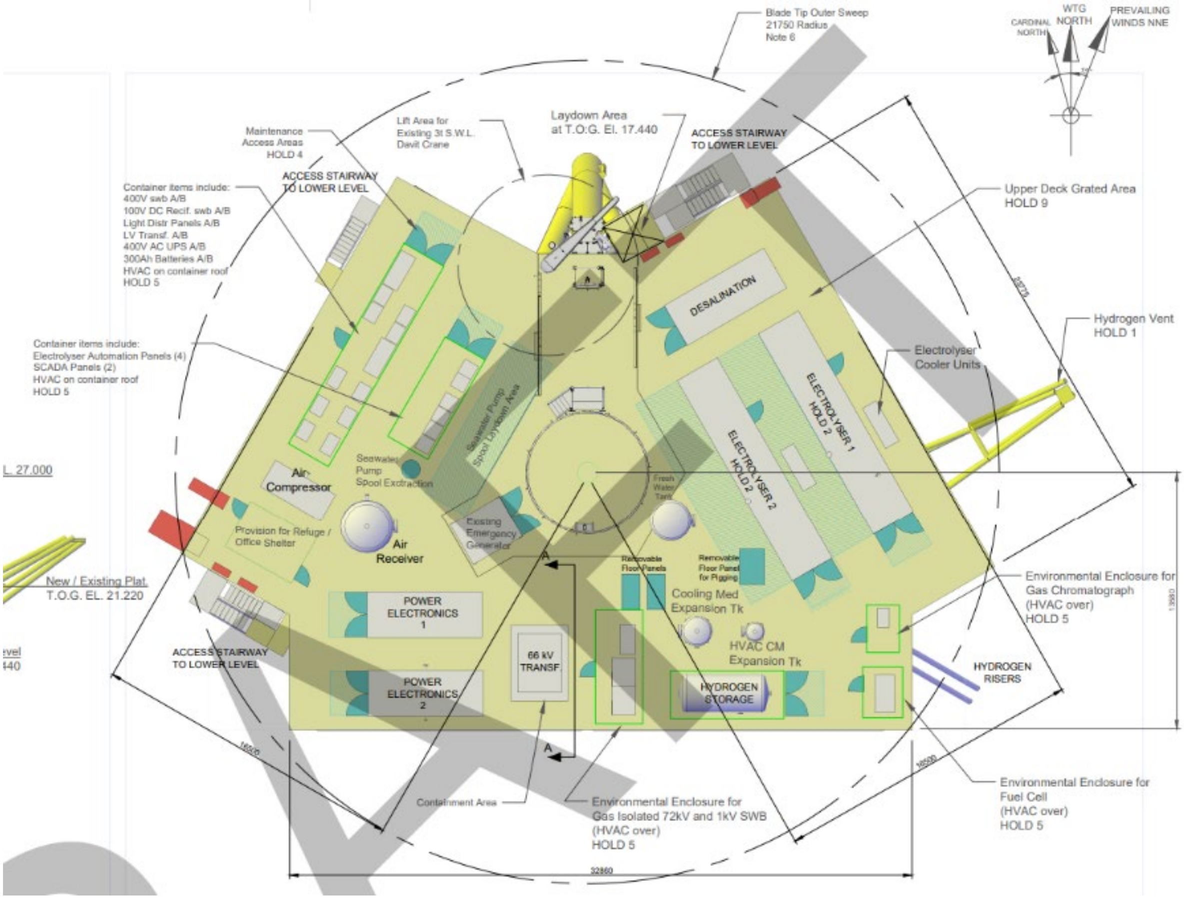

Figure 6: Draft Layout of Hydrogen Infrastructure

4.1.1 Water Treatment System

Water is the primary raw material required for electrolysis and one of the primary benefits of locating hydrogen production offshore is access to seawater. Electrolysis requires ultra-purified water to avoid accelerated degradation of the system and release of pollutants, therefore seawater must be treated to a suitable quality prior to use.

Seawater is extracted through a new riser retrofit to the jacket foundation (see Section 4.4). The riser is fitted with a coarse filter to avoid debris and marine life entering the riser. A pump is required to extract water through the riser. Both submersible and surface mounted pumps were considered, however a submersible pump was selected as it required less space on the platform and required less maintenance than surface mounted options. The downside of this option was the requirement for a larger riser to accommodate the pump and the potential for sand ingress, however the risk of this occurring was low due to the water depth on site and the risk could be further reduced by including spares in the system. The design proceeded using 2-off submersible pumps to provide redundancy in the event of failure of one system.

Prior to desalination, seawater is pre-treated to remove microorganisms, bacteria, protozoan and other impurities that can cause biofouling. Pre-treatment may be completed through chlorination or UV treatment. It was envisaged that UV pre-treatment would be used on HT1, however this is dependent on the quality of water required prior to desalination which varies from supplier to supplier some chemical treatment may be required. Replenishment of chemicals would have taken place during routine maintenance.

There are two available technologies for desalination: reverse osmosis and thermal evaporation.

Reverse osmosis uses a series of partially permeable membranes to remove salt ions from the water leaving purified water, while the salt ions are discharged to sea as brine.

Thermal evaporation technology heats the water and evaporates the seawater in several stages producing purified water and leaving behind any salt and contaminants. An anti-scalant is used to prevent precipitation of the salt.

Reverse osmosis technology is more common for offshore applications. However, in the case of hydrogen production, thermal evaporation may benefit from waste heat from the electrolysers to reduce the energy consumption of the plant and act as a cooling medium for the system. In addition, thermal evaporation uses a smaller footprint, reduced maintenance, is suitable for intermittent production and produces a purer distillate reducing further polishing. For these reasons, thermal evaporation technology was selected.

Further ultra purification, or polishing, of desalinated water is completed within the electrolyser system to ensure the correct quality of water is achieved prior to electrolysis. This deionisation process, reduces the conductivity of water to the level required for the electrolyser, usually through a mixed bed filter or an electro-deionisation unit.

4.1.2 Electrolyser

The electrolyser unit utilises renewable power from the turbine to split ultra-purified water into hydrogen and oxygen in a process known as electrolysis. There are various types of electrolysers which function in different ways, however there are two primary technologies available in the market that were considered[2]

- Proton Exchange Membrane (PEM) electrolysis uses a solid electrolyte. Water reacts at the anode forming oxygen and positively charged hydrogen atoms (protons). The protons move across the membrane following the circuit and combine with electrons at the cathode to form hydrogen gas.
- Alkaline (ALK) electrolysis uses an alkaline solution as the electrolyte. Hydrogen is formed at the cathode alongside negatively charged hydroxide ions which pass through the electrolyte to the anode forming oxygen and water.

Electrolysis occurs in individual cells, and these cells are stacked together to share common balance of plant providing a modular solution that can be scaled depending on the capacity required.

PEM electrolysis was selected for the following reasons:

- PEM has a fast response time allowing for more effective production as the input power fluctuates due to the intermittent nature of wind generated power
- PEM electrolysers are light and compact, reducing the required footprint of the platform extension and loading on the existing jacket.

4.1.3 Subsea Pipeline Loop

The subsea pipeline loop was included within the revised scope to maintain similar learnings of designing, installing, operating and maintaining a subsea pipeline for hydrogen service as was sought in the original concept which envisaged export to shore. In addition, it allowed use as a potential storage vessel through line packing. With the exception of making landfall, which is not a novel concept, the same learnings were anticipated.

Only a short pipeline loop (less than 500m) was envisaged to fulfil the objectives of the project. A routing study was conducted around the vicinity of the turbine taking into account a number of factors including: availability of survey data, soil conditions, boulders and debris, potential UXO, operations around the platform, potential for dropped objects, crossings, topside infrastructure layout, health and safety, environmental impact, installability and cost. The resultant preselected route was ~350m long with potential to adapt during detailed design and contractor appointment.

The required inner diameter of the pipe was calculated to be ~3-4-inch, which would be confirmed during detailed design as this may be optimised depending on the pipeline technology selected.

Subsea pipeline technology is relatively advanced, having been used in the oil and gas industry for decades. However, use of subsea pipelines for hydrogen service is novel and must be qualified for use, alongside other transport infrastructure such as connectors and valves.

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[2] Solid oxide (SOEC) and anion exchange membrane (AEM) technologies were initially considered as options, but ruled out due to the low TRL for offshore application and unavailability on the market within the project timeline.

Subsea pipelines can generally be split into two categories:

- rigid pipelines: typically manufactured using steel line pipe stalks, welded together to form a pipeline
- flexible pipelines, which could be:
  - bonded: consisting of layers or polymers and glass fibres bonded together
  - unbonded: consisting of layers of polymers and steel which are not bonded together.

Various technology qualification programmes are ongoing by the supply chain to qualify pipelines for hydrogen service with little, if any, variation required from products already field proven in the oil and gas industry.

Flexible pipeline technology was selected for HT1, however remained agnostic on whether this would be unbonded or bonded. This was for a number of reasons:

- Flexible pipeline technology is more suitable at small diameters and lengths as required on HT1.
- Flexible pipelines are, as the name suggests, more flexible and can be installed with a lower installation radius than rigid pipelines.
- Multiple qualification programmes are ongoing for both bonded and unbonded flexible flowlines, de-risking project deliverability
- Rigid pipelines are prone to hydrogen embrittlement, however this is not expected to be an issue on HT1 due to the low operating pressure of the system (< 40barg).

4.1.4 Storage Vessel

Storage is required to provide a buffer vessel between the electrolyser producing the hydrogen and the fuel cell consuming the hydrogen. This is to allow for safe operation of the system, allowing the fuel cell to respond and safely turn down, following shut down of the electrolyser, and vice versa

Use of a storage vessel also provides an opportunity to store energy in the form of hydrogen which could be used in periods of low wind and high demand, smoothing the intermittency of wind generated power.

Various storage options were assessed to determine the quantity of storage required. While novel options such as solid storage were considered, these were ruled out due to the added complexity and risk using new technology that was not core to the aims and objectives of the project. Only storage in the form of hydrogen gas without added compression was assessed. Additional compression was not considered due to the limited volume required, the need for additional energy intensive compressors and the safety implications of hydrogen stored at higher pressures.

The storage options assessed were:

- Line packing (LP) only
- 1m^3 vessel + LP
- 20ft or 40ft container
- Steel cylinder

It was found that line packing only would provide sufficient storage to operate the system safely for a fast response fuel cell. However that if the flowline were to be bypassed, this would provide very limited time for the fuel cell to respond which would not allow stable operation of the system. Including an additional 1m^3 vessel would provide sufficient time for a fast response fuel cell in both scenarios using the pipeline and bypass of the pipeline. Neither option would provide sufficient storage to allow the fuel cell to run independently from the electrolyser for a sustained period of time i.e. provide power when there isn't sufficient wind to generate power directly from the turbine, only proving the ability to do so with larger quantities of storage.

The other storage options would provide the ability to run the fuel cell for a period of time independent of the electrolyser.

As a 1m^3 vessel with line packing would provide sufficient storage to operate the fuel cell safely and would prove the ability for independent operation of the fuel cell, this option was selected.

4.1.5 Fuel Cell

A fuel cell is used to convert hydrogen into power for export to the grid. In simple terms, it operates like an electrolyser in reverse, through an electrochemical reaction with oxygen in the air producing power and pure freshwater as a by-product.

Due to efficiency losses in converting power to hydrogen, and hydrogen back into power, the fuel cell is rated to 200kW i.e. 1MW (peak) power in, 200kW (peak) power out. This is primarily due to energy loss as heat in the chemical reactions. Some of the waste heat is captured for use in thermal desalination (see Section 4.1.1) but for larger systems this may be an additional revenue stream.

4.1.6 Other Considerations

4.1.6.1 *Cooling Systems*

Both air-cooling and water-cooling systems were considered. Both were comparable in terms of performance, however water cooling was selected for two primary reasons:

- it dove-tails well with thermal desalination water treatment (see Section 4.1.1) and
- it is more compact than air cooling which may present issues due to blade tip clearance on the platform.

4.1.6.2 *Flaring vs Venting*

The controlled release of hydrogen was expected in several planned and / or un-planned (i.e. emergency) events during operation of the offshore hydrogen production system. There are various methods to release high-pressure hydrogen into the atmosphere in a safe manner, such as double block and bleed valve vents, Pressure Safety Valve (PSV) relieves, rupture discs, etc. via a venting or flaring system.

In the unlikely event of an un-planned depressurization of the full storage of the hydrogen, the limited production of hydrogen and low level of storage envisioned, the quantity of hydrogen to be flared or vented would be limited (up to 4kg, including flowline). This is a worst case scenario and the actual quantity of hydrogen stored will likely be less.

No venting is expected during the normal operation of the system in a steady state mode, however as the system will be working dynamically coupled to the generated power from the wind turbine, it could experience safe releases during events such as ramp down and up, start up, hot standby, cold standby, shut down, etc. These events are more likely to happen, compared to the release of stored hydrogen, however the quantity released is much lower.

Hydrogen is a secondary greenhouse gas, and therefore venting of such gas should be minimised as far as reasonable practicable. Cold venting is the most cost-effective means of disposing of waste hydrogen and hot flaring has negative social impacts due to association with oil and gas production, as well as light pollution. Furthermore, flaring of hydrogen requires a continuous gas flow to maintain the pilot light, estimated at a significant additional volume to that required to be released.

For these reasons, cold venting was selected as the most appropriate choice for HT1, however further work should be completed to find other ways of disposing of waste hydrogen to minimise the potential greenhouse gas impacts of hydrogen release.

4.1.6.3 *Nitrogen Purging Systems*

Nitrogen is an inert gas used to flush systems and pipework of hydrogen to make the system safe in the event of human intervention, or a safety critical event (e.g. fire). Consideration was given to two options:

1. Nitrogen cylinders
2. Nitrogen regeneration system

The former is a simple, cost effective system using a set of nitrogen cylinders connected to system and suitable for small scale plants. The bottles are replaced after use. The latter, a nitrogen generation system produces nitrogen on-site by extracting and purifying nitrogen from air. Nitrogen generation systems have a high up-front cost, but can be more cost effecting in the long run in applications with a consistent or high demand of nitrogen.

Due to the small scale of the project, and the unlikely requirement to use nitrogen, nitrogen cylinders were selected for this project.

4.2 Electrical Infrastructure

Power generated by the wind turbine is currently exported to the grid via a 66kV (AC) electrical connection. The balance of plant requires power in AC form, however the electrolyser, utilising the majority of power, requires a DC connection.

The wind turbine generates power in DC form, however this is converted to AC form for transport to shore.

Two primary options were considered:

1. Modify turbine to provide direct DC connection to system.
2. Connect to existing 66kV electrical connection and install additional transformer and rectifier to provide DC power.

Option 1 was discussed with the original equipment manufacturer of the wind turbine, however this would require significant modification of the turbine which would not be feasible within the project timeline. The second, although requiring more infrastructure was deemed to be the only feasible option with which to progress the project.

4.3 Control Systems

Incorporating hydrogen production into a wind farm adds complexity in control of systems, due to the additional balance of plant and safety systems required for the production, transport, storage and re-electrification of hydrogen. Control on HT1 was to be provided via a new Hybrid Power Park Controller (HPPC).

Selection of the HPPC took into account multiple factors, such as the effectiveness of the controller, integration with the various systems on the turbine, operation of the controller, and in retrofit cases, upgrade of the existing control system versus installation of a new control system.

4.4 Platform Extension & Risers

An extension to the current platform is required to provide additional footprint for new infrastructure required to convert the wind turbine for hydrogen production. In addition, four new risers are required for 1) extraction of sea water; 2) discharge of wastewater; 3) & 4) J-tubes to house the inlet and outlet of the subsea flowline loop.

The foundation structure is a suction bucket jacket foundation with a transition piece prepared for mounting of the wind turbine tower and providing access to the turbine, shown in Figure 5.

An iterative design approach was taken for the design of the platform extension and risers as the design of the topside infrastructure progressed, however the primary design philosophy was determined at the outset:

- Platform extension will wrap around the transition piece, minimising the cantilever from the centre of the tower;
- Design should minimise requirement for welding, where possible using mechanical connections and utlising the strongest points of the jacket e.g. existing lift / tow points.
- Design should remain within utilisation limits of existing jacket.
- Installation should be considered during design, minimising the number of offshore lifts.
- Riser location should consider both subsea constraints and location of topsides infrastructure to minimise pipework.

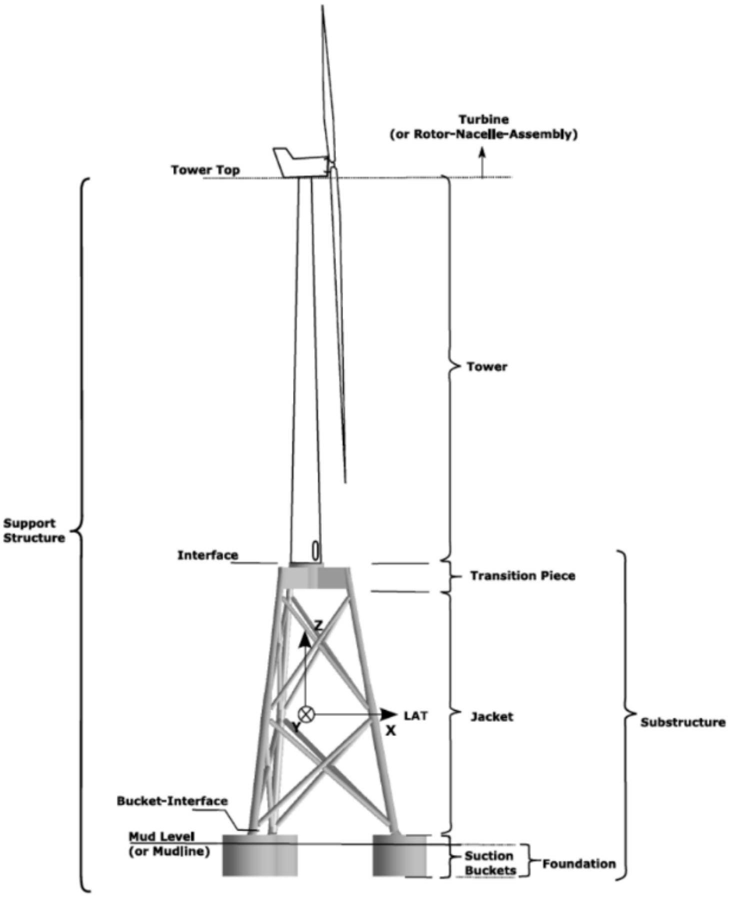

Figure 7: Overview of Wind Turbine

The resultant design involved the removal of the existing transition piece to ease installation. The existing transition piece is re-used and fabricated into the new platform extension allowing installation in two sections, using predominantly mechanical connections.

The platform is a two-tier design, utilizing the truss structure to extend the footprint of the foundation. Pipework and cabling is in-built to the platform minimizing construction and installation in-situ.

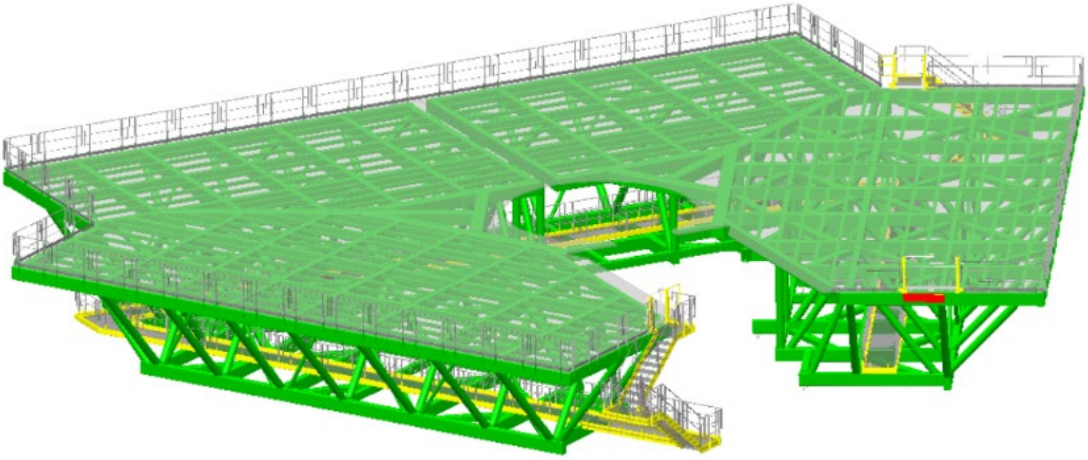

Figure 8: Platform Extension

Risers and J-tubes are installed following installation of the platform extension using a series of clamps attached to the existing jacket. These provide the necessary structural support and are located within the footprint of the platform extension eliminating the need for a marine protection structure. Riser clamps require diver installation due to the shallow water depth, however on new turbines, risers would be pre-fabricated to the foundation, eliminating this requirement.

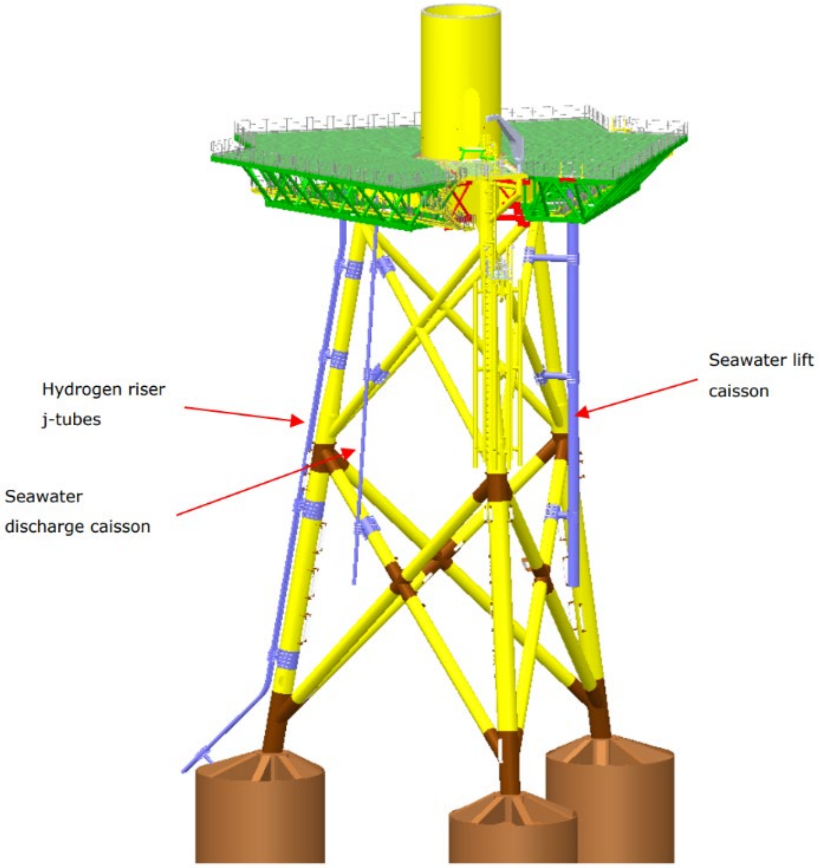

Figure 9: Risers and J-tubes

5 HEALTH & SAFETY

5.1 General

Hydrogen is a highly flammable gas that requires careful handling and storage to ensure safety. When handling hydrogen, it is important to be aware of its properties, such as its lighter-than-air nature and its ability to ignite easily. Ignition of hydrogen can result in jet fires and gas cloud explosions, which need to be considered seriously as the burning velocity of hydrogen can reach detonation speed. Beside the high risk related to the flammability, hydrogen is an odourless, colourless, and non-toxic gas. It will however - as other gasses - deplete oxygen if leaking into a confined space.

Hydrogen has a very large range of concentration (from 4% to 74%) where it can ignite when mixed with air. In comparison, the same range is from 5% to 17% for e.g. natural gas.

To minimize the risk of hydrogen leaks, it is important to use appropriate fittings, valves, and hoses in the design. Detection of hydrogen leak is needed to plan appropriate safety measures. Further it is necessary to avoid any ignition sources in areas where hydrogen leaks could occur.

It is important to define the safety measures to be taken if leaks are detected. This will typically be:

- Automatically bringing the plant to a safe state – depressurize relevant sections, and purge.
- Enhance ventilation to dilute the hydrogen concentration
- Remove power from non-Ex-rated equipment
- Alarm people in the area and evacuate the area immediately

When hydrogen is leaked or released into the atmosphere, it is considered to be a secondary greenhouse gas, contributing to the climate change. When released, hydrogen alters a chemical balance in the upper atmosphere which slows the depletion time of greenhouse gases like methane. Consequently – from an environmental point of view, leaks and releases of hydrogen should be minimized. Due care should be paid to the design of the safety measures – so a depressurization of the plant happens in a way which has the lowest impact on the environment.

Because the production, storage and use of hydrogen has both safety and environmental concerns, it is important that design choices and practices are well documented and accurately assessed, when designing a hydrogen related product.

5.2 Safety Approach

During project execution Vattenfall generated learnings about hydrogen safety, and how it can be effectively integrated into the company project execution model.

The process / technical safety part plays a key role in the design phase and during the concept development of a hydrogen plant and differs from offshore wind safety.

Safety engineering has to start early in the project and to be carried out in parallel of design and engineering of the process plant.

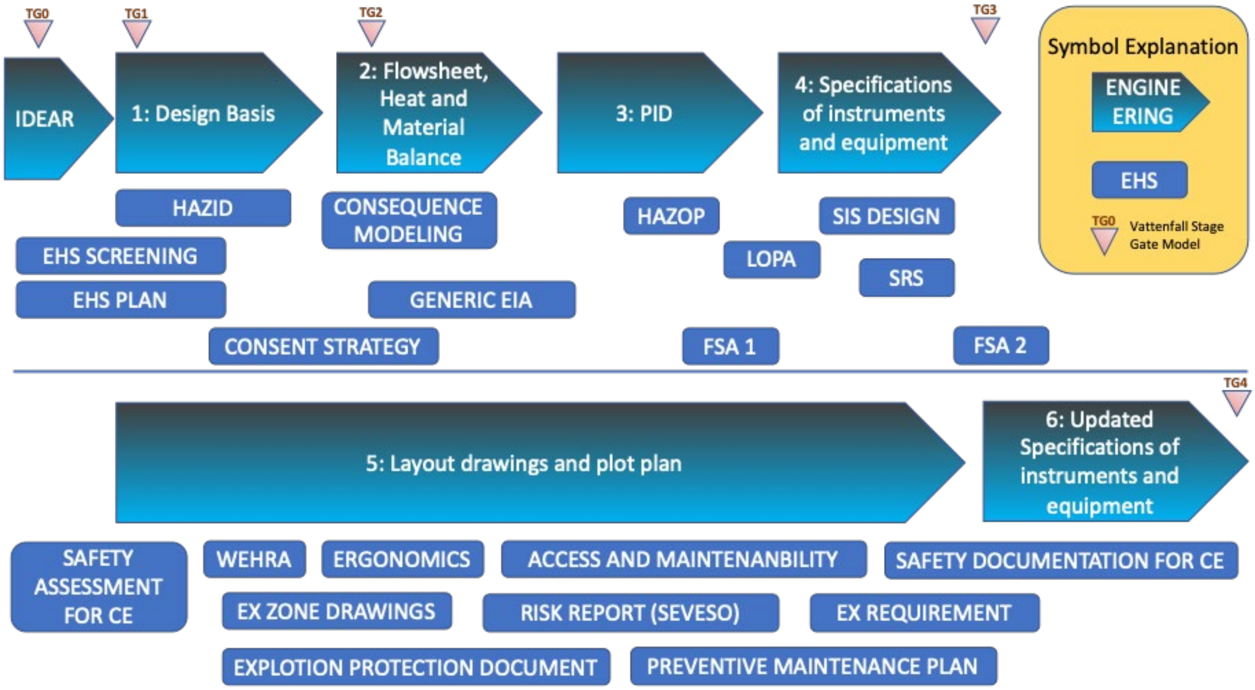

Figure 10: Safety Approach

5.3 Safety Case

At an early stage in the project, in lieu of specific guidance on offshore hydrogen production, the project decided to take a thorough approach by treating it as oil and gas facility and preparing a safety case. During dialogue with the UK Health and Safety Executive (HSE), it was decided that preparation of a safety case was one of the best ways to demonstrate that:

- The plant and facility were safe to operate, and;
- Vattenfall has a suitable management system in place to operate and maintain such a facility.

Both of which would be a requirement to obtain a “licence to operate” and permission to start up the facility.

In simple terms, the safety case consists of three elements:

1) A description of the plant and facility, and an explanation of its safe operation, detailed in engineering drawings and documented risk analysis.

2) A description of the organisation, intended to operate and maintain the plant and facility, and a demonstration of the capability to handle this type of technical chemical factory (hydrogen production), including handling of emergency situations, and major accidents.

3) A description of the management system, in place for the plant and facility, and a demonstration of how the system will assure that the safety of plant is maintained during its lifetime. This will include operational procedures and a clear responsibility for the different elements of the system.

5.4 Risk Assessment

Risk assessment workshops were held throughout the project life cycle to identify hazards and address these as the design matured.

The primary risks identified were as follows:

- Mixing of hydrogen and oxygen gas inside the plant creating an explosive environment with potential to cause major damage to equipment and severe injury to personnel in close proximity of the plant. Workshops identified the possible scenarios that this could occur and subsequently allowed the design of the plant to be modified to mitigate such events occurring (e.g. additional safety valves, monitoring systems etc.) and putting in safeguards (e.g. blast walls, procedures etc.) to protect personnel in the event of an incident.
- Release of hydrogen to the surroundings forming an explosive atmosphere e.g. through leaks or permeation. Designs were modified to control the release of hydrogen and include grating and vents to prevent build-up of hydrogen in enclosed spaces.
- Backflow of the inventory of the pipeline to the offshore facility leaking and creating a gas cloud ignition and explosion. Designs were modified to prevent backflow and allow controlled release of hydrogen.
- Marine impact on the riser causing uncontrolled release of hydrogen. Risers were housed within J-tubes and under the platform overhang to protect from damage.
- Seawater contamination of purified water damaging the electrolyser and potential release of harmful chemicals associated with electrolysis of seawater. Monitoring equipment was anticipated to prevent this occurring.
- Leak in onshore installation causing uncontrolled release of the inventory of the offshore pipeline. Commissioning plans include leak testing prior to operation and monitoring of the internal pressure of the pipeline to detect any leaks. Isolation valves included to shut off production from the pipeline in the event of a leak.

6 CONSENTING & STAKEHOLDER ENGAGEMENT

6.1 Consents and Permits Required for HT1

Throughout the determination of the consenting regime for the hydrogen flowline and storage aspect of HT1, Vattenfall were continually engaged with various regulatory bodies, and established an understanding[3] of the consents and licences that would be required for an offshore electrolysis-based Hydrogen generation project in Scottish Waters. The key consent requirements are as follows:

Table 1 Consents and Licenses Required for HT1[4]

Consent	Regulatory Authority	Regulated Activity
Marine Licence	MD-LOT	Offshore construction works
Section 36 Consent Variation	MD-LOT	Change in Electricity Generating Station[5]
Crown Estate Scotland Lease Variation	Crown Estate Scotland	Change to activity permitted under current lease
Registration under Controlled Activities Regulations (CAR)	SEPA	Water abstraction at WTG
Pollution Prevention and Control (PPC) Permit	SEPA	Hydrogen production and discharge to water and air
Pipeline Works Authorisation (PWA)	NSTA	Offshore Hydrogen pipeline
Hydrogen Storage Licence and Permit	NSTA	Hydrogen storage

Over the lifetime of the project, Vattenfall have worked to study the potential environmental impacts of the proposed offshore hydrogen facility to ensure a firm understanding of the environmental and consenting implications of the proposal.

Vattenfall identified the following studies to perform:

- EIA Screening Opinion Request to MD-LOT
- Pipeline routing assessment and landfall study

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[3] At the time of writing

[4] Excludes Health and Safety Requirements

[5] Assumes electrolyser is to be installed on an existing generation station

- Non Statutory Environmental Assessment
- Habitat Regulation Assessment (HRA) Screening
- Marine Protected Area (MPA) Assessment
- Water Framework Directive Assessment
- PPC Site Condition Assessment
- Screening Direction Assessment on Hydrogen Storage

6.2 Lessons Learned

Initially there wasn’t a clear regulatory framework in place for consenting the offshore hydrogen pipelines and storage part of the project, and it resulted difficult to progress the project from both an environmental assessment and an engineering and design perspective. However, this was addressed with new legislation in September 2023, and early engagement and analysis of applicable regulatory frameworks for future hydrogen projects is recognised as being crucial, which we learnt from this process.

As part of the PPC Permit, there is a requirement to follow environmental quality standards and standards for discharges to surface waters guidance as set out by SEPA, which details maximum discharges permitted into marine waters.

As with any FOAK project crossing multiple legislative regimes, there was a lack of clarity on the definitive pathways to consent. To overcome this, and ultimately achieve a timely secondary legislation change, it was imperative to work collaboratively and transparently with all potential regulator bodies and primary advisors. Vattenfall took an active role in engaging with all potential regulators and primary advisors. As offshore Hydrogen projects continue to develop in UK waters, it is highly recommended that regulatory round table events continue to agree a collaborative and streamlined working approach between all regulators and primary advisors to ensure an effective and efficient consenting process.

7 BENEFITS & BARRIERS

The HT1 project has had a positive impact on the advancement of the offshore hydrogen industry, realising various benefits and identifying barriers to success. These may be used to aid and improve future similar projects.

7.1 Benefits

The following benefits have been identified:

- The primary benefit of HT1 has been to demonstrate how hydrogen can be produced offshore from wind energy, providing a means of producing low carbon hydrogen at scale to meet demand and reduce reliance on fossil fuels.
- At the outset of the project, there was no clearly defined regulatory pathway to consent for a project such as HT1, particularly for offshore hydrogen transport and storage. As a result of engagement with DESNZ and various regulatory bodies on this project, secondary legislation changes were made to the Petroleum Act 1998 (Specified Pipelines) Order 2011 to provide a route to consent. Without HT1, UK legislation may have developed at a slower pace for regulating and consenting of hydrogen pipeline and storage offshore. This benefit means that from now any future offshore hydrogen projects in UK have a clear pathway to consent, allowing developers to accelerate the timeline and reduce the risk of the project not achieving final investment decision. Although continued coordination and collaboration between the various regulators and primary advisors is strongly recommended.
- The project has relied upon the expertise from the oil and gas industry to support the development of this project, demonstrating how the industry can transition towards other forms of renewable energy. Advancement of the industry could lead to a variety of skilled green jobs and create economic growth.
- Vattenfall have engaged with the supply chain throughout the project. This has highlighted some of the constraints, disseminated knowledge and incentivised private investment in diversification of technology for hydrogen user.
- Production on the turbine demonstrates that hydrogen production can be localised which may be of particular benefit to remote areas where access to energy infrastructure is limited or expensive to connect to.
- Vattenfall have presented the project at various events in the local community to disseminate the learnings of the project and improve knowledge of the benefits of hydrogen production and how it can be used.

7.2 Barriers

The following barriers to deliverability have been identified:

- The lack of local offtakers has been the primary barrier to success on the project.
- The lack of hydrogen transportation infrastructure prevented the project from securing offtake in other locations.

- Inflation and other economic factors led to large increases in the capital costs required to develop the project.
- Engagement with the supply chain demonstrated that the industry was growing fast and was extremely constrained. Equipment identified during early stages of the design was no longer available as suppliers moved to larger models. In addition, the increasing demand for onshore hydrogen production and small market meant suppliers were not interested in investing in offshore hydrogen production.

8 ECONOMIC ANALYSIS

8.1 Scalability

Project HT1 is a small-scale demonstration of decentralised hydrogen production that has potential to extend into a number of scenarios at a commercial scale:

1. Wind farms dedicated to hydrogen production;
2. Smoothing the effects of intermittency of conventional power producing wind farms;
3. Reducing (or eliminating) reliance on wind farms consuming power from grid.

8.1.1 Wind Farms dedicated to Hydrogen Production

Wind farms dedicated to hydrogen production could take a number of forms:

1. **Centralised onshore hydrogen production** connects conventional power producing wind farms to an onshore hydrogen production facility.
2. **Centralised offshore hydrogen production**, is a similar concept, however hydrogen production is completed offshore, at a centralised location prior to export to shore.
3. **Decentralised offshore hydrogen production** places hydrogen production directly on each individual wind turbine.

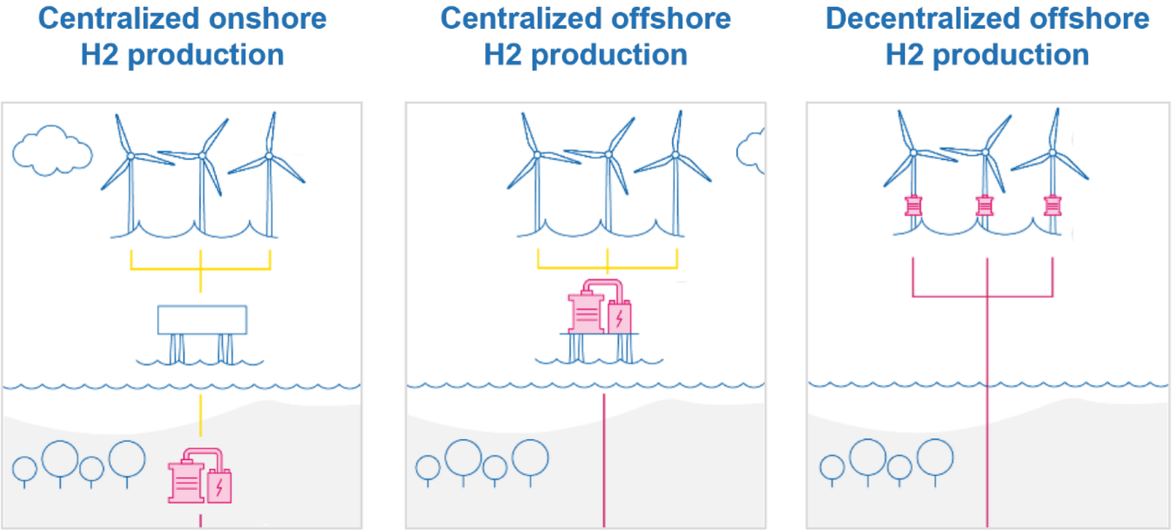

Figure 11: Concepts for Hydrogen Production from Offshore Wind

8.1.2 Smoothing Intermittency

To smooth the impact of intermittency, a form of energy storage is required, which could be hydrogen. Here, when supply exceeds demand, wind power would be used to generate hydrogen which is stored and then re-electrified when demand exceeds supply.

8.1.3 Reducing Reliance on Electrical Grid

Currently, wind farms consume power from the grid during start-up and in periods of low wind to provide base power to the system for safety and control. Diesel generators are also located on each turbine in the event of a grid outage. Hydrogen could be used as a means to generate power on site, without the need for a grid connection, or reliance on diesel generators.

8.2 Route to Market

The route to market must consider the full value chain in order to create commercially viable projects. This can be simplified into three core areas:

- hydrogen production (“make it”);
- transportation and storage (“move it”) and
- offtake of hydrogen (“use it”).

All three areas need to be progressed to ensure commercial development.

8.3 Rollout Potential

UK is a market leader in offshore wind power generation and, as an island nation, has enormous future potential for hydrogen both in the domestic and export market. Demand for low carbon hydrogen is also growing, to decarbonise hydrogen supply to current consumers, and to provide a low carbon alternative to “hard to abate” industries currently reliant on fossil fuels.

Demand is expected across various industries, including, but not limited to:

- Iron & Steel
- Chemicals
- Industrial Heat
- Refining
- Ammonia
- Transport
- Aviation
- Marine
- District Heating
- Power Generation

In addition, the EU is projected to be a net importer of low carbon hydrogen, hence the potential for wind energy in the UK to be used to create hydrogen for this market.

9 DISSEMINATION

Vattenfall has engaged with stakeholders and other interested parties throughout the project to disseminate knowledge and learnings gained, both directly and through events and conferences as listed in Table 2.

Table 2: Dissemination Events

Date	Event	Location
14/11/2022	**Pre-Application Public Consultation Event** Open event showcasing HT1 project and receiving feedback from local stakeholders	Aberdeen Science Centre Aberdeen, UK
15/11/2022	**Aberdeen Renewable Energy Group (AREG) Energy Futures Conference & Exhibition** Exhibition and stand on AOWF and HT1 Project	P&J Live Aberdeen, UK
16/11/2022	**Subsea Underwater Technology / Aberdeen Association of Civil Engineers Presentation Evening** Presentation of project to SUT and AACE members	Holiday Inn Express Westhill, UK
23/08/2023	**ETZ Hydrogen Masterclass** Presentation of project and panel discussion	Marcliffe Hotel & Spa Aberdeen, UK

10 CONCLUSION

Hydrogen Turbine 1 (HT1) project has concluded after making significant contributions to the advancement of hydrogen production from offshore wind. The project, based at the Aberdeen Offshore Wind Farm, sought to convert one of the existing wind turbines to produce hydrogen through installation of an electrolyser on the turbine. The project was brought to a close after other advancements in the industry meant that the learnings from the project would no longer be as significant as planned and not material enough to justify the expected costs.

The primary conclusions that can be taken from the development of HT1 to date are as follows:

- Offshore hydrogen production is a technically feasible concept, capable of producing low carbon hydrogen at scale to meet demand and reduce reliance on fossil fuels.

- A wide variety of different applications exist for offshore hydrogen production, including: wind farms dedicated to hydrogen production; storage and re-electrification of hydrogen as a means of smoothing the intermittent nature of offshore wind; and reduced reliance on the electrical grid network.

- PEM electrolysis is well suited to offshore wind as it has a fast response time, able to meet the challenge of fluctuating power input and it’s lightweight, compact design reduces the required footprint for the system and loading on the jacket structure.

- Thermal desalination technology paired with water cooling realises synergies in the system resulting in a lower energy consumption of the balance of plant. In addition, the system requires a smaller footprint and produces a purer distillate, reducing the need for further treatment.

- The UK now has an established pathway to consent for similar projects involving offshore hydrogen production, aided by the development of HT1

- Connecting supply and demand is a key barrier to projects of this nature.

11 REFERENCES

[Ref. 1] Explanatory Memorandum to The Petroleum Act 1998, UK Government [Link]

[Ref. 2] Environmental Quality Standards and Standards for Discharges to Surface Waters, SEPA, [Link]

[Ref. 3] European Commission [Link]

[Ref. 4] British Energy Security Strategy, UK Government, 2022 [Link]