Investigation into hydrogen production, storage and transport

From far offshore floating wind farms

MSc Thesis Sustainable Energy Technology

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Investigation into hydrogen production, storage and transport
From far offshore floating wind farms

by

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TU Delft

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Abstract

Offshore wind farms designed solely for hydrogen production are promising solutions for maximizing wind energy conversion, decarbonizing industries that cannot directly utilize electricity, and reducing the need for additional grid reinforcements. Furthermore, floating offshore wind turbines enable the capture of wind resources in deeper waters. This has created the possibility of locating wind farms far offshore.

This study looks into the technological and economic feasibility of in-turbine hydrogen production, storage, and transport via vessels from far offshore floating wind farms. Transport of hydrogen via pipelines and transport of hydrogen via a large vessel connected to the entire wind farm are also studied for comparison and bench marking purposes. To investigate the performance of various transport methods, a wind farm model is built that includes the components required for hydrogen production at the wind turbine as well as the components required for hydrogen transport. The model simulates wind farm operation, vessel operations with regard to onsite storage, and vessel operations when connected to the entire wind farm. Based on the levelized cost of hydrogen(LCOH), the performance of the three different farms has been compared. The study was conducted over distances ranging from 100 to 700 km.

Throughout the range of distances studied, on-site hydrogen storage and periodic removal via vessel proves to be the least cost effective solution. Weather conditions are seen to be a significant factor in the operation of the vessel fleet servicing the farm with on-site storage. When combined with a four-vessel fleet servicing the entire wind farm, the optimum storage size in the farm type with onsite storage is found to be equal to the wind turbine average weekly production. A key distinction is seen in the cost trends, a steady increase is seen in hydrogen transport via pipelines with increase in distance, while, the LCOH of hydrogen remains nearly identical for the transport of hydrogen via vessels over the range of distances studied. The farm produces the most hydrogen with pipeline transport of hydrogen followed by transport of hydrogen via a large vessel, and the least hydrogen with in platform hydrogen storage and periodic emptying of the storage by vessels.

The study indicates that the pipeline transport of hydrogen is the most cost effective transport option.

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Nomenclature

Abbreviations

Abbreviation	Definition
AEL	Alkaline electrolysis
APU	Auxiliary Power unit
ERD	Energy recovery device
FCFS	First come first serve
HDPE	High density polyethylene
HHV	Hydrogen Higher heating value
HPU	Hydrogen production unit
LCOH	Levelized cost of hydrogen
PEM	Polymer electrolytic membrane electrolysis
SAL	Single Anchor loading system
SOE	Solid oxide electrolysis
TDS	Total dissolved salts
SWRO	Salt water reverse osmosis
IEA	Internation Energy Agency

Symbols

Symbol	Definition	Unit
V	Velocity	[m/s]
ρ	Density	[kg/m^3]
H_s	Significant wave height	[m]
ppm	parts per million	-
V_{hub}	wind speed at hub height	[m/s]
V_{ref}	reference wind speed	[m/s]
h_{hub}	hub height of wind turbine	[m]
h_{ref}	reference height	[m]
α	shear coefficient	-
V_{cut-in}	wind turbine cut-in speed	[m/s]
$V_{cut-out}$	wind turbine cut out speed	[m/s]
V_{rated}	rated wind speed	[m/s]
A	swept area of wind turbine	[m/s]
η_{mech}	wind turbine mechanical efficiency	-
Q	mass flow rate	[kg/s]
R	Real gas constant	[J/KMol]
Z	Compressibility factor	-
M_h	Molar mass of hydrogen	[g]
N_γ	Number of compression stages	-
λ	friction coefficient	-
ϕ	pipe roughness	-

1
Introduction

The introductory chapter establishes the background for the research contained in this report and describes its scope and objectives. Section 1.1 provides an insight on the recent trends in the energy sector and the need for hydrogen. Following that, section 1.2 summarizes the offshore industry outlook and challenges in the near future.The concept of hydrogen production at sea is then introduced in section 1.3. A brief discussion follows on the existing research into hydrogen production offshore, following which the thesis objective and research questions are proposed in the research goals section. Finally, the thesis approach and the report layout are presented to conclude the introduction chapter.

1.1. Role of hydrogen in the energy transition

To achieve the Paris Agreement's targets, the energy sector must undergo significant changes.Wind and solar energy integration in the world energy supply is still modest.However due to continuously dropping costs and a need to change our energy systems, wind and solar energy deployment is expected to increase exponentially by 2050[1]. The variable nature of wind and solar energy brings along with it issues of grid congestion and balancing which vary due to the different environmental conditions at different locations [2]. In addition it may be difficult to completely decarbonize key sectors, such as transportation, industry, and uses that require high-grade heat, only by electrification. Hydrogen from renewables permits renewable energy made from the power sector into a useful product for end-use industries [3].The different sectors in which hydrogen is required can be seen in Figure 1.1.

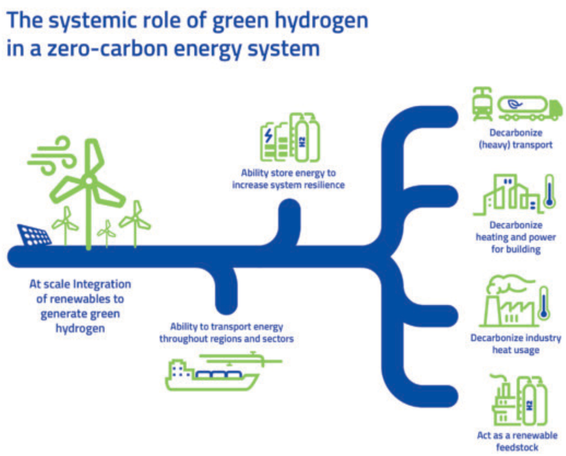

Figure 1.1: Role of Hydrogen in the energy sector [3]

The fuel promises to be an energy vector for sectors where electricity can not single handedly fulfill decarbonization goals. While hydrogen is not the only means for decarbonization it is likely to play a big part as hydrogen makes the large-scale integration of renewables possible because it enables energy players to convert and store energy as a renewable gas [3],[4].

1.2. Trends and challenges in the offshore wind sector

As of 2018 the offshore installed wind capacity was 23 GW. A substantial proportion of the installed wind farm capacities are located in the North sea in Europe. A 13% year on year increase in installed capacity is expected in offshore according to [1]. This growth in capacity is accompanied by a trend in increased wind turbine sizes which leads to larger capital expenses but lower operation and maintenance cost. Recent developments in the offshore wind industry have led to sites with good wind availability being exploited near the shore.

The artificial scarcity of potential offshore wind sites and the search for further more wind farm sites pushes the industry out to sea – far offshore [1],[5] as can be seen in Figure 1.2.

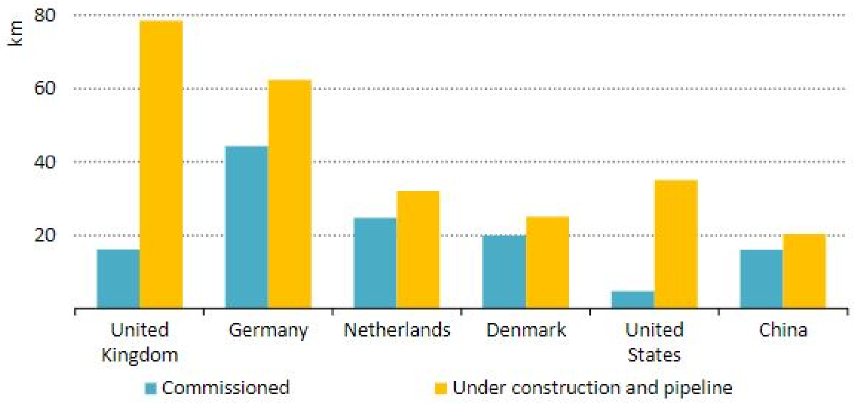

Figure 1.2: Average distance from shore for offshore wind projects [1]

Moving out to sea far offshore creates challenging installation conditions at higher depths. Floating wind turbines could potentially be a solution as they offer novel support structure foundations which can be used in deep waters up to 50 - 60 meters depth [6].Currently more than 50 MW floating wind power is installed with the goal to demonstrate the commercial and technical viability of floating wind[7]. In addition larger distances from shore lead to high costs of electrical infrastructure which impact the levelized cost of electricity [8], and hence poses questions on the economic viability of far offshore wind farms. To meet the long term goals in the capacity building of offshore wind, such challenges must be circumvented.

1.3. Hydrogen conversion at sea

As touched upon in the previous section, far offshore wind farms bring with it challenges with respect to construction and import of energy to shore through large electrical infrastructure. Hydrogen as an energy vector offers promise to solve some of these concerns. Even though the cost per unit length of a hydrogen pipeline is greater than electrical cables offshore, the energy capacity that can be transmitted via hydrogen is greater [9]. Such studies indicate that if the right method of transporting energy as hydrogen is selected it may build a strong business case for far offshore wind farms. In addition the storage and generation of hydrogen poses less risk far offshore and has a higher chance of societal acceptance in comparison to onshore production and storage [10]. Hydrogen as an energy vector could also help to remove roadblocks to offshore wind farm integration, such as grid connection facilities and substations, which are needed to carry power generated offshore to onshore. [11]. The cost-effectiveness of hydrogen production powered by offshore wind and the different transport options needs to be examined as there exists a potential to enable decarbonization at scale.

1.4. Existing research

Due to the current trends in the global energy market and the long term vision of sustainability, offshore power to hydrogen has been an important topic in Northern Europe. Extensive work has been done studying the technical and economic feasibility of dedicated and hybrid offshore hydrogen production systems[12]. The recently envisioned hub and spoke model also depends on the success of power to hydrogen and synthetic gases to bridge the gap between supply and demand [13]. The re-purposing of offshore oil and gas platforms has also been discussed by [12]. The predominant mode of transportation of hydrogen produced from electrolysis in the offshore platforms, is through sub-sea pipeline [14]. According to the study conducted by [11] into the different pathways of offloading hydrogen it is reaffirmed that pipelines are the best mode of transport at small distances. The use of vessels then to transport hydrogen only becomes competitive at distances of 150-250 km [11].Such studies are based on a dedicated hydrogen production platform for the entire wind farm.
Recently there has been an expanded interest in feasibility studies for in-turbine hydrogen production. Decentralized hydrogen production in the turbine is a flexible and modular system as the failure of an electrolyzer will not necessarily impact the overall hydrogen production of the farm, as in the case of centralized hydrogen production [15] . In-turbine hydrogen production eliminates the need for large electrical infrastructure and substation requirements further reducing capital expenditures[5]. As shown by [16] the decentralized hydrogen production offshore requires lower capex and provides flexibility in terms of hydrogen transport. In the case of floating wind turbines such as the ones selected in [5] the hydrogen produced can be stored on the platform and transported via vessels.

1.5. Research goals

In this section the thesis objective is described. Next the research questions arising from the the thesis objective are presented.

1.5.1. Objective of the thesis

As discussed in the previous sections, currently, the offshore wind industry is moving towards deeper waters to exploit better wind site conditions. Hydrogen promises to be an efficient vector to transport energy from far offshore sites. By coupling the knowledge of hydrogen production systems with the offshore wind industry, it is possible to build a strong business case for far offshore floating wind. Key to the use of floating platforms for far offshore hydrogen production, will be the mode or method of transporting hydrogen from the wind farm. This study looks into the feasibility of hydrogen production from a wind farm in decentralized manner. In a possible scenario, autonomous hydrogen production units may store compressed hydrogen gas at site in hydrogen storage units which may later emptied into hydrogen gas carriers or the hydrogen can be transported directly via pipeline. The primary objective is to investigate the different methods of hydrogen transport from far offshore wind farms, and to gain insight on the impact of storage capabilities on the transport methods used. The study scope is limited to compressed hydrogen gas transport. Three methods of transport are investigated, the transport of hydrogen via pipelines, the transport of hydrogen via vessel from a central collection point tied to the wind farm and the transport of hydrogen via vessels from hydrogen storage located at individual turbines. Furthermore, the transport of hydrogen via pipelines and vessel from a central collection point are used for comparison purposes to assess the feasibility of hydrogen transport via vessel from localized hydrogen storage at turbines.

1.5.2. Research Questions

As described before the study will propose and compare different wind farm configurations for far offshore hydrogen production. The main research question of the study is presented below and the sub research questions framed are used to help answer the main research question.

> **"What is the techno-economic feasibility of in-turbine hydrogen production, storage and transport via vessels from far offshore floating wind farms?"**

The following sub research questions are used to methodically answer the main research question :

1- What are the system components that are needed by the different wind farm types?
2 - What would be the variation of levelized cost of hydrogen for the different wind farm types with

respect to distance from shore?
3 - What is the economic sensitivity of the wind farm types subject to change in prices of the components required in the supply chain of hydrogen transport?
4 - At what distances does the transport of compressed hydrogen become competitive via vessel when compared to pipelines?
5 - What is the variation in the amount of hydrogen transported to shore by each wind farm type?

1.6. Approach

To answer the research questions of the study, a literature study is performed on the key components required for hydrogen production,storage and transport. Following which different wind farm types are proposed and subsequently modeled. The system model of each farm type is implemented in Python using Object Oriented Programming. The system model for a specific farm type includes sub models of all the different components that are required by it - namely the electrolyzer, compressor, storage and back up power system fall under the hydrogen production block, whereas, the storage, vessel and pipeline come under the transportation block. The system model also provides an interface between the different set of components.

A case study is then set up to investigate the different farm types with respect to the transportation method of hydrogen selected. To this extent the technical and economic input parameters common to all farm types, and specific to each farm type are implemented in the model. The levelized cost of hydrogen (LCOH) is used as a metric to compare the outcomes of the case study for different wind farm types. The operational behaviour of vessels and the impact on the farm types requiring vessels for transport are then further examined to identify key challenges to hydrogen transport via vessels. Lastly, a sensitivity analysis is performed by changing the input price parameters with respect to the components in the transportation block of each wind farm type and the results are discussed.

1.7. Report layout

The report structure is as follows. Chapter 2 presents an overview of the different wind farm types, and the components required at farm level for production and transport of hydrogen.Next, the system model set up for each farm type and the implementation of the components are discussed in chapter 3. Chapter 4 details the case study set up and results for each wind farm type are presented. Chapter 5, discusses and compares the results obtained for each farm type and the sensitivity study done on the different farm types. Further recommendations and shortcomings are discussed in chapter 6, followed by the conclusion in chapter 7.

2

Wind farm types and component overview

Before diving into the different wind farm types and the components used therein, this chapter first introduces the concept of in-turbine hydrogen production. Next an overview of the different farm types studied are presented. The key differences between farm types are discussed and further represented through schematics, and, to conclude a breakdown of the components by farm type are tabulated. Third, the different components necessary for hydrogen production and components required in the storage and distribution supply chain are detailed.

2.1. In-turbine hydrogen production

The main goal of the research is to assess different wind farm types far offshore to produce hydrogen in conjunction with storage and transportation methods available. As mentioned before, the scope of the study is limited to in-turbine hydrogen production in the wind farm. In addition to reduction of large scale offshore electrical infrastructure costs, the conversion of electricity to hydrogen at the wind turbine reduces the need for in-turbine transformers and rectifiers. Hence there are lower electric power conversion losses.
Another advantage of in-turbine hydrogen production is the lowered dependency on a single electrolysis platform when compared to centralized electrolysis. In the event a single production unit fails the farm may still continue operations. When compared to hydrogen liquefaction, the transport of hydrogen as compressed gas is a much simpler process. Hydrogen liquefaction and hydrogen transport in the form of ammonia require large amounts of energy and an elaborate system design on the the platform deck[17]. This study is limited to the transport of hydrogen in compressed gas state. The farm types selected look into the transport of hydrogen exclusively via vessels, pipelines and a combination of both. The end goal is to compare the different combinations which can be built for large scale hydrogen production.

In Figure 2.1 a schematic is presented of a hydrogen production unit,HPU, which encompasses the components required for in-turbine hydrogen production. The floating support structure provides a platform to place the components required for hydrogen production. The wind turbine produces the power that is fed into the electrolyzer and, a desalination unit is required for pre-treatment of water going into the elctrolyzer. Lastly, the auxiliary power system is required to supply back up power to the HPU. The components are further explained in the component overview section.

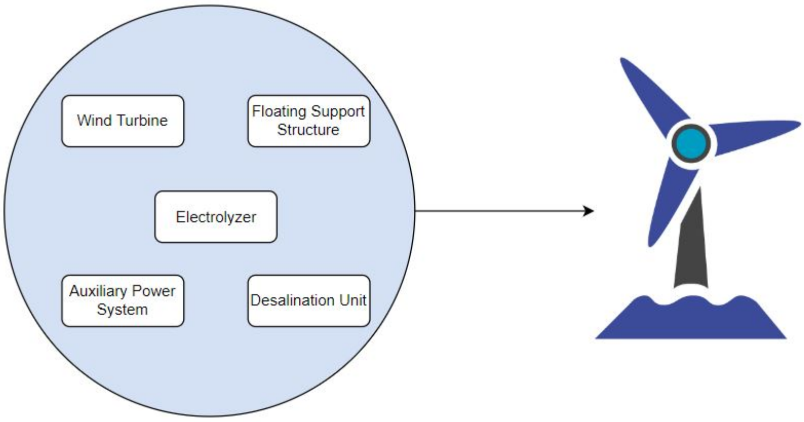

Figure 2.1: Component requirement of a hydrogen production unit

2.2. Farm types

This section provides an overview of the different farm types studied and outlines their key differences.

2.2.1. Farm type I : Hydrogen Transport via pipeline

In farm type I, each HPU is connected to an inter array pipeline grid that in turn connects to a main pipeline trunk as can be seen in the Figure 2.2. The hydrogen produced by an HPU is transported through the inter array grid, and then transported to shore via the main pipeline trunk. In such a configuration the extent of compression on site is dependent on the required pressure in the pipeline. Pressure drops in the pipeline downstream are taken care of, by installing re-compression stations offshore. This configuration combines the existing knowledge of pipeline for gas transport with localized in-turbine hydrogen production. Challenges in this configuration are limited to construction of the offshore hydrogen pipeline, and the rather large dependency of the entire farm output on the main trunk. Lastly, farm type I is modeled to provide a baseline for comparison to the farm type that requires localized hydrogen storage and periodic removal of hydrogen. To this extent, no further analysis or optimization is done for the components used and for the farm as a whole.

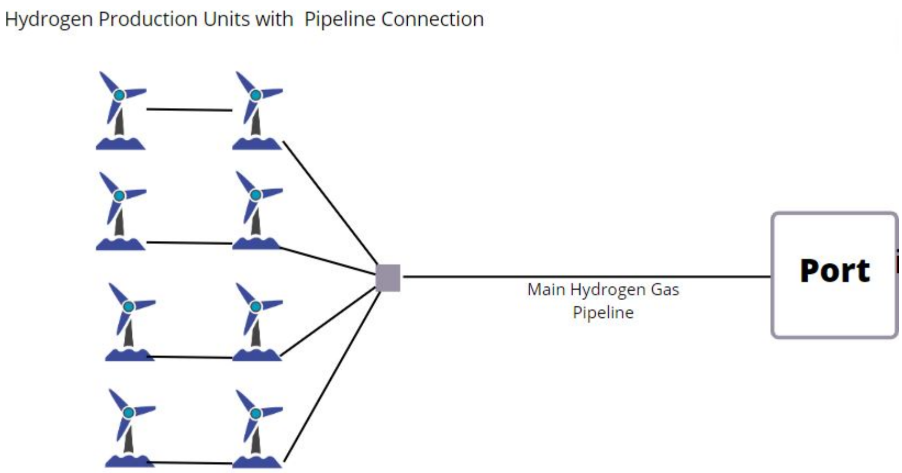

Figure 2.2: Hydrogen Transport Via Pipeline

2.2.2. Farm type II : Hydrogen transport via pipeline and large vessel

Similar to floating storage and production platform seen in the oil and gas sector, in farm type II a large storage vessel is connected to the entire wind farm through a common connection point depicted in Figure 2.3. This is done by building inter array pipelines which are connected to the large vessel through a single point mooring connection system. Hydrogen produced is stored in the vessel until it is filled to its maximum capacity. Once the vessel is filled to its maximum capacity it is assumed to be replaced by a vessel of equal size. This farm type is once again used as a baseline to compare it to localized hydrogen storage at wind turbines. Such a farm type eliminates the need for in-turbine localized compression and storage, as the hydrogen produced from the wind farm is directly compressed and stored in the large carrier vessel.

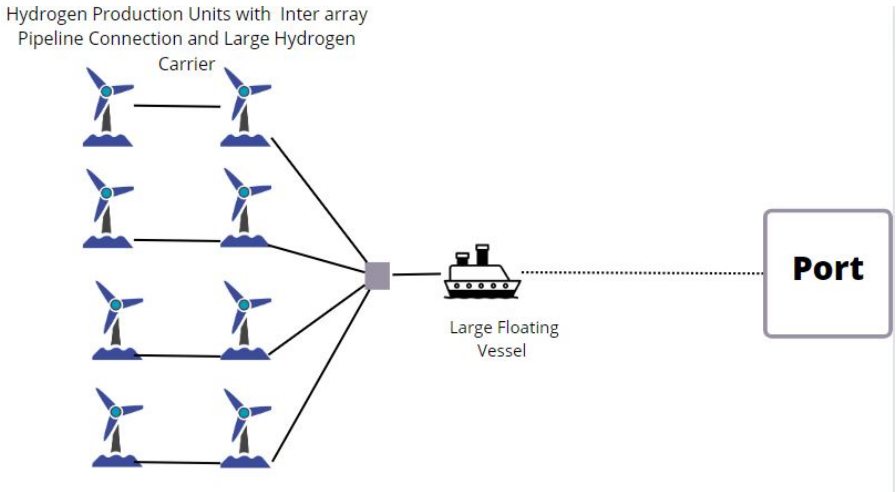

Figure 2.3: Hydrogen Transport Via large carrier vessel

2.2.3. Farm type III : In-turbine hydrogen storage and transport via vessel fleet

A schematic representation of farm type III is shown in Figure 2.4, the hydrogen is produced and stored on the floating platforms. The hydrogen is stored on the platform in hydrogen storage modules. It is then periodically transferred when the storage is full to a compressed hydrogen carrier vessel. This carrier vessel operates and services the entire wind farm. Once the hydrogen vessel reaches its maximum capacity it returns to shore to offload the hydrogen gas. Such a farm type might be advantageous if it is not possible to build pipelines for hydrogen transport or if the cost of hydrogen vessel carriers and storage on site offer a better business case. The storage at the site is dependent on the space available at the hydrogen production unit. In reality such a farm design may require less time for beginning operations, when compared to farm types that are dependent on pipelines to transmit hydrogen to the large vessel or to shore. This is because the components of the HPU maybe assembled at shore and then placed at sea to begin hydrogen production. Whereas for farm types depending on pipelines, it is required that the pipeline infrastructure is ready to transport hydrogen before the farm begins hydrogen production.

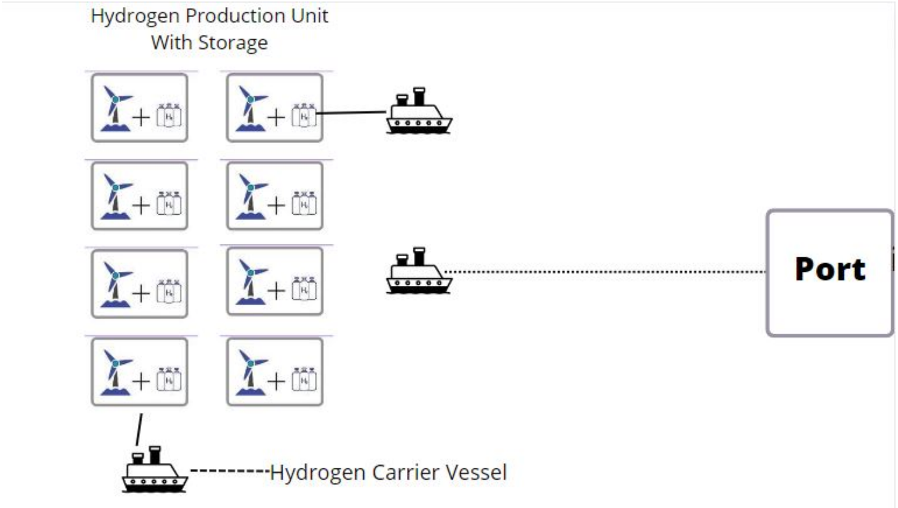

Figure 2.4: Hydrogen Transport Via Multiple Vessels

2.2.4. Breakdown of components by farm type :

A breakdown of the system components is provided in the Table 2.1. It is evident that the hydrogen production system remains unchanged for all topologies, however the transport and logistics of hydrogen impact the necessarry use of compression systems, storage and pipelines.

Component	Farm I	Farm II	Farm III
Floating wind power system	X	X	X
Electrolyzer	X	X	X
Desalination system	X	X	X
Auxiliary power system	X	X	X
Compressor	X	X	X
Storage	-	-	X
Pipeline	X	X	-
Vessel	-	X	X
Single point mooring system	-	X	-

Table 2.1: Component breakdown by farm type

2.3. Component descriptions

This section consists of a description of the components used in the studied farm types. A brief summary is provided of the component requirement, the type of component and the rational behind their selection if any.

2.3.1. Floating wind power system

The floating wind power system consists of two parts. The offshore wind turbine power generator and its floating support structure. Utility scale offshore floating wind is demonstrated in the Hywind and Windfloat projects [18]. The floating platform is a critical component to the success of far offshore wind farms.The development of floating platforms comes on the back of successful use of floating platforms in the oil and gas industry in the form of semi-submersibles, tension leg platforms and spar buoys.There exists a knowledge base for the operation and behaviour of the structures in deeper waters [19]. Any floating support structure can be modified to build wind turbines dedicated hydrogen production [15]. An overview of the types of floating structures can be seen in Figure 2.5.

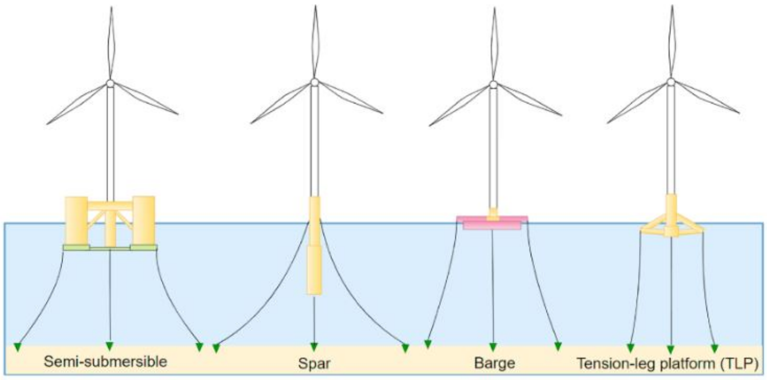

Figure 2.5: Types of offshore floating support structures
[15]

As the goal of the study is to examine decentralized hydrogen production and storage, it is necessary for the floating platform to have sufficient space for the required hardware components. Among the different types of floating support structures the semi-submersible floating platform is shaped as an equilateral triangle and it can house the components for hydrogen production and storage without much further modification. Other options such as spar buoy or the tension leg platform will require additional modification to be able to host the components required for hydrogen production. For this study the semi-submersible type is selected over the other design options as the semi submersible offers sufficient space for both storage and production of hydrogen, and due to the extensive data available on design and economics of semi submersibles[15]. In addition, such a concept is already producing power as demonstrated by the WindFloat project [18].

2.3.2. Electrolyzer

The electrolyzer converts the electrical energy into hydrogen. It is the most important component of the hydrogen production unit. The electrolyzer contributes a major proportion of the cost of the hydrogen production unit. The goal of the electrolyzer is to maximize hydrogen production from the power available. There are currently three methods of electrolysis, alkaline electrolysis method(AEL), Solid Oxide Electrolysis(SOE) and lastly Polymer electrolytic membrane method(PEM) to produce hydrogen[20].
Currently there is a lot of work being done to bring SOE to a commercial level, hydrogen production from SOE operates at extremely high temperatures when compared to PEM and AEL, and it requires steam input instead of water [21]. The problems associated with SOE are durability and the long term stability [22],[21]. The major advantage that SOE holds over PEM and AEL is the possible higher operating efficiency [23]. Due to the technology being in the developmental stage and the extreme operating conditions which could create safety hazards [15], it is not expected to be applicable for the commercial scale as discussed in this study. Hence, the SOE electrolyzer is discarded.
AEL and PEM are currently the two leading electrolysis technologies in the market. It is necessary to distinguish and evaluate a suitable electrolysis method for the purpose of the study. A qualitative assessment is made to narrow down to one electrolysis technology for localized hydrogen production.

AEL is the traditional and mature way to produce hydrogen and has a stronger commercial outreach than PEM electrolyzers [24]. Further improvement in technology is expected with the current emphasis on hydrogen production but this improvement will not be comparable to PEM electrolysis[25].This electrolyzer technology has been used in the most part connected to a constant power supply and an alkaline liquid electrolyte for electrolysis[20],[26].
PEM electrolysis on the other hand makes use of a solid electrolytic membrane made from expensive material such as Platinum and Iridium [27],[15]. This results in higher costs for PEM electrolysis. The use of solid membranes provides stronger durability and structural integrity. The use of solid membranes reduces gas permeability at lower loads of the electrolyzer [28]. Reduced gas permeability is an essential safety parameter and is also important to maintain purity of the produced hydrogen gas. PEM electrolysis yields hydrogen of higher purity levels than AEL [29]. This reduces the need for down-

stream purification of hydrogen before storage or transport via pipeline.

A breakdown of the electrolyzer characteristics is presented in Table 2.2. On further scrutiny of these characteristics a qualitative selection of electrolyzer technology is made.

Characteristic	Alkaline Electrolysis	PEM Electrolysis
Output Pressure range(Bar)	0	30
Power consumption at Nominal Power(Kwh/kg)	52	61
Ramp Up	0.2-20%/s	100%/s
Ramp Down	0.2-20 /s	100%/s
Start Up	1-10 minutes	1 sec - 5 minutes
Load Range	15-100% Nom. Load	15-160% Nom.Load

Table 2.2: Characteristics of PEM and Alkaline Electrolyzers [30]

As seen from Table 2.2 the cold start,ramp up and ramp down capabilities of the PEM electrolyzer are superior than AEL electrolyzer. Hence, it can be concluded that the load following characteristics of the PEM electrolyzer are superior. As the electrolyzer is connected to a single wind turbine it is expected to follow the load profile of the wind turbine. The ability to follow variable form of wind power is crucial to harnessing power and generating the maximum possible hydrogen at a given instant of time. PEM electrolyzers can also be kept in standby mode with minimum power requirements [30]. The PEM electrolysis also has a higher operating pressure than the AEL [8],[30]. The operation and build up of higher pressures in the PEM stacks reduces the need for compression post generation for storage or transmission via pipelines [30],[31]. Lastly the maintenance activities required for the PEM electrolyzers are lower when compared to AEL. This can be attributed to the solid nature of the electrolyte and complex handling requirements of Alkaline electrolyte for AEL [5]. In addition, PEM electrolyzer are more compact units and require a smaller footprint due to their functioning at higher current densities[29]. Due to the above mentioned attributes, PEM electrolysis is selected as the electrolyzer technology.

For this study it is assumed that PEM electrolyzer system includes the following sub components : gas conditioning unit, electrolyzer stacks, water management system, a lye system, power conditioning units and lastly a system control unit. These components are included within the system boundary as shown in Figure 2.6. The sub components are not modeled, however, it is important to note that the overall system efficiency of the electrolyzer depends on the individual efficiency of these components. In Figure 2.7 it can be seen that the system efficiency of the electrolyzer reaches peak efficiency at low part load. The overall system efficiency at nominal power is considered for hourly hydrogen calculations.

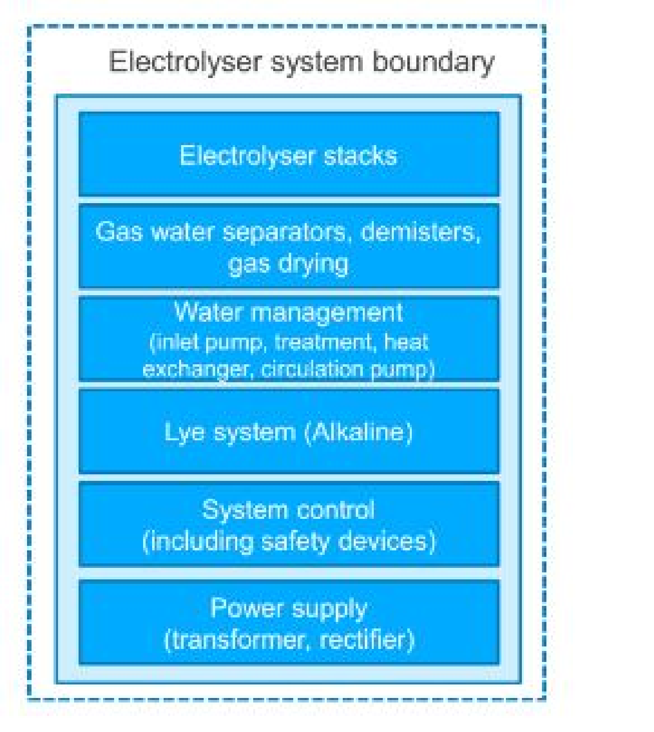

Figure 2.6: Electrolyzer system boundary [30]

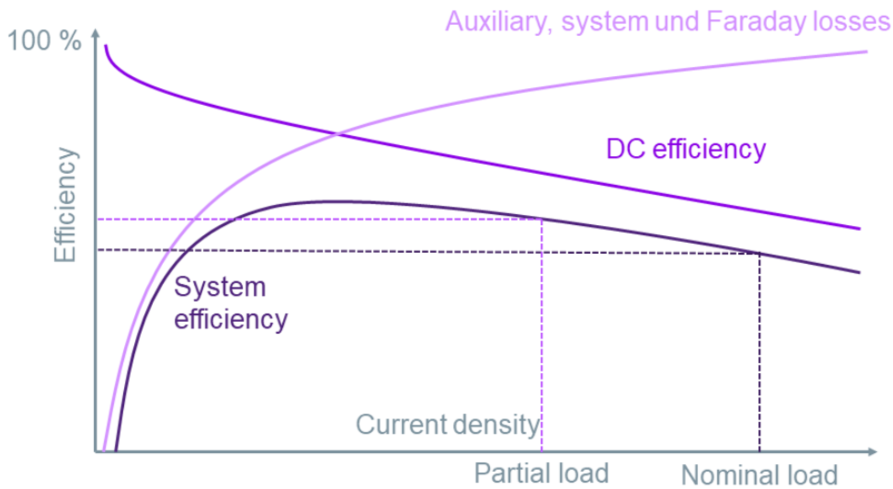

Figure 2.7: System efficiency [32]

Lastly the optimal sizing of the electrolyzer per wind turbine requires a more detailed approach as stated by [15]. For simplicity in this study the electrolyzer size is matched to the wind turbine size.

2.3.3. Desalination system

The water input to the electrolyzer for electrolysis must be demineralized [33]. The count of total dissolved solids (TDS) of the demineralized water needs to be between 1-10 ppm [33]. As mentioned earlier the water conditioning system is in the scope of the electrolyzer system. The supply water to the electrolyzer system must be that of tap water quality which has 350 ppm [15]. In offshore environments to achieve this purity level prior to input to the electrolyzer it is necessary to install a desalination system. Two mature desalination methods exist in the form of thermal desalination and reverse osmosis desalination [33]. With the advent of energy recovery devices, salt water reverse osmosis(SWRO) has become cost competitive with thermal desalination solutions [34]. For this study, SWRO method has been selected for desalination. Reverse osmosis is a compact purely electrically driven solution and it works sufficiently well when integrated with PEM electrolyzers [35]. The process of SWRO starts with filtration of the intake water to clear out any large particles, following which the seawater at high TDS levels is pushed through a semi permeable membrane by the use of a high pressure pump as seen in Figure 2.8. At this point the energy recovery device(ERD) retrieves the pressure stored in the concentrate and this pressure energy is used to force seawater through the membrane along with the high pressure pump, leading to improvement in the energy efficiency of the device. [28],[34].

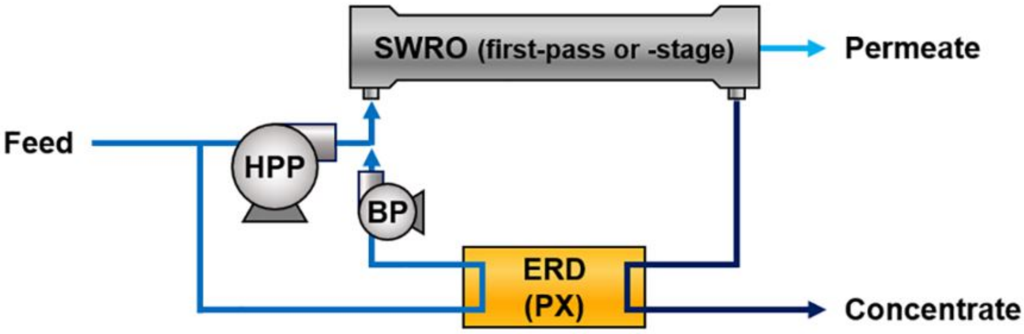

Figure 2.8: A schematic of a single pass Reverse Osmosis system with Energy Recovery Device[34]

The energy consumption per meter cube of water produced is around 2-4 Kwh. This power consumption scales with the requirement of pure water for the electrolyzer at a given instant of time. A single pass membrane is sufficient to generate tap water quality that is required for input to the electrolyzer system as seen in Figure 2.9 [34].

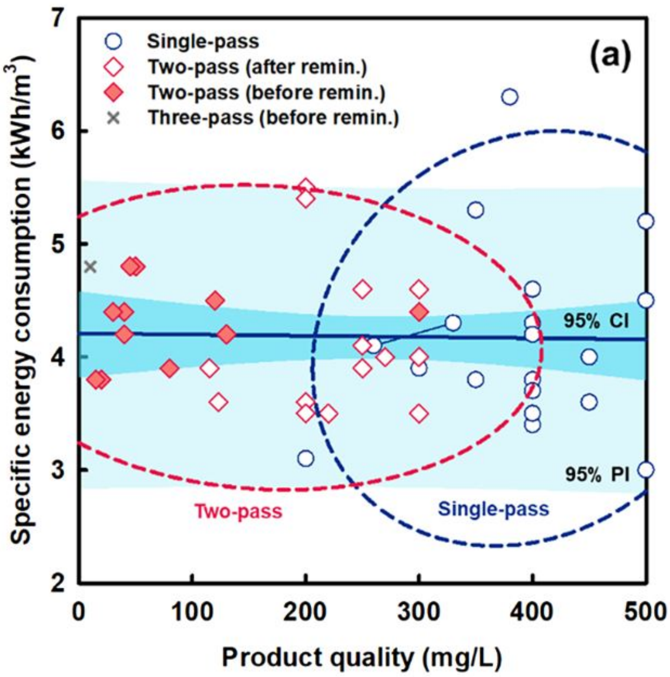

Figure 2.9: Water quality output with use of membranes[34]

From an environmental perspective it is important to make sure the brine produced is treated prior to discharge,the discharge of brine in all wind farm types discussed in this study are decentralized. Hence, there is a smaller chance of causing harm to the environment at large [36].

2.3.4. Auxiliary power system

The auxiliary power requirement in conventional wind farms is limited to meeting the wind turbine emergency loads [37]. In the case of hydrogen production units, it is necessary that the auxiliary power supply meets the back up power requirement of the wind turbine and the components that are required for hydrogen production. Namely the large loads that are essential are the wind turbine yaw load, the ventilation and heating loads of the electrolyzer and wind turbine. A back-up power source in the form of Lithium Phosphate battery is selected. Batteries of this type are available in standard containerized solutions for upto 1MW size [38]. The auxiliary power system is designed to provide a power back up for 10 hours and it is seen that the battery system also has its own power requirements to maintain suitable ambient conditions in the containerized battery storage [39].

2.3.5. Compressor

The role of the compressor is to raise the hydrogen pressure level from the existing output pressure levels from the electrolyzer. The extent of compression depends on the wind farm type and the system requirements. For instance the need for compression in the pipeline configuration is dependent on the allowable pressures in the pipeline and required mass flow rates that need to be sustained. In the case of pressure drops over long transmission lines, recompression of the gas might be required to maintain a suitable flow rate [40]. In wind farm type II, the farm is connected to a large floating vessel. A centralized compression system is placed on the vessel to raise the pressure levels to maximum storage pressures of the vessel and to maintain the mass flow at any given time. The size of the compression system depends on the maximum throughput per hour and correspondingly the work that needs to be done to raise the gas pressure. Lastly, in the farm type III there is a two fold requirement of compression, one to raise the pressure to the set storage pressure levels on the hydrogen production unit platform and a second to maintain the required mass flow rate during loading from platform storage to vessel.

Gas compressors are usually of two types centrifugal and rotary type compressors. Rotary type compressors are prone to higher hydrogen leakages due to the small size of hydrogen molecules. Reciprocating compressors can be used with lower modification at volume flow rates up-to 1700 meter cube per hour [40],[41]. An evolution of the reciprocating type is the diaphragm compressor which has a hydraulic fluid that enables reduction of hydrogen leakages as the hydraulic fluid provides a secure seal [42].A detailed analysis on the different types of compressors can be seen in [42]. In this study the compressor is sized based on the power required to compress hydrogen gas in a single stage compression as discussed by [43],[40]. Further explanation on the compressor losses and energy required are detailed in the compressor model section.

2.3.6. Storage

Hydrogen storage is a key component of farm type III. Before hydrogen can be shipped via vessel to the shore, it must be stored on the platform. The volumetric density of hydrogen at ambient pressure is very low, hence, it is necessary to compress it to higher pressures to store sizeable amounts of hydrogen produced. With increase in pressure there is an increase in the volumetric density of hydrogen as shown in Figure 2.10 [44].

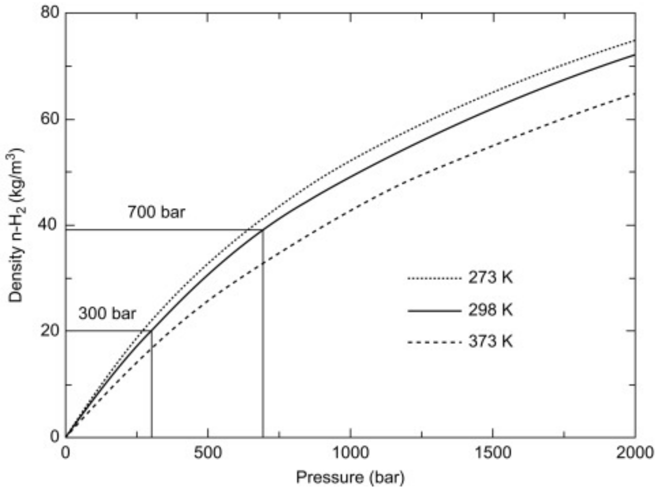

Figure 2.10: Increase in hydrogen volumetric density with pressure[34]

Hydrogen storage is generally done in fabricated tanks [8]. These tanks are reinforced with glass fibre composites or polymers such as high density polyethylene, HDPE, and are cylindrical in shape [45]. A linear correlation can be drawn between the cost of storage structures and the mass of the structure [46],[47]. Higher pressure storage tanks require excess material and result in greater costs[31].

The depth of discharge of storage modules is inversely related to the cycle life of the storage modules. Modules that have a high depth of discharge have a shortened lifetime compared to modules that have a low depth of discharge [48]. To enhance the longevity of the storage a safe depth of discharge must be selected. Lastly, hydrogen storage modules may be placed horizontally or vertically on the hydrogen production unit. To this extent a similar argumentation is followed as given by [31] to place hydrogen in twenty foot equivalent containers in a vertical orientation to avoid fire hazards due to hydrogen leaks. The vertical orientation of storage modules helps store more hydrogen per unit area.

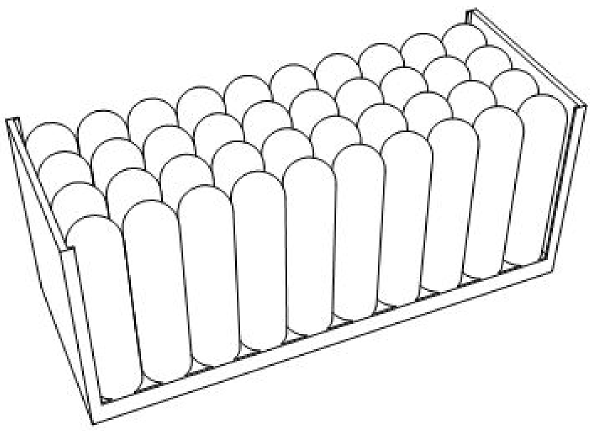

Figure 2.11: Storage Orientation in Twenty Foot Equivalent Containers[31]

2.3.7. Pipelines

The transport of hydrogen through pipelines is an established technology. Hydrogen pipelines exist around industrial clusters, majorly oil and gas industries. A large share of the existing pipelines can be found in USA [49]. According to manufacturers and industry experts, apart from the embrittlement issues arising from the light weight of hydrogen gas there is no other clear difference between transport of natural gas and hydrogen through pipes [50]. To overcome and minimize hydrogen diffusion in the pipe, high density polyethylene pipes and stainless steel pipes can be a suitable alternative as they have capacity to transport pure hydrogen gas [51],[9].

Hydrogen has a negative Joule Thompson effect, that is with pressure drop hydrogen gas tends to increase in temperature, however it is expected that pipelines will be designed to accommodate this effect [52]. According to [40],[52] the pressure in the pipeline will undergo drops upto 25-30 bar/100 Km. Hydrogen flow pressures can be limited to 50-60 bar due to embrittlement concerns [31]. In the case of distances longer than 100 km compression platforms will be required to raise the pressure of the gas to maintain the required mass flow rate.

Lastly, bottom fixed pipelines connecting the farm type I to shore or the farm output to the large vessel are rigid in nature. The pipelines from individual hydrogen production units connecting to the main pipeline however are expected to be flexible in nature, as they must accommodate for the waves and ocean currents in addition to the dynamic motion of the floater. For these reasons, a rigid piping system can not be used and flexible risers that provide higher bending tolerance must be used to connect the HPU to the bottom fixed rigid pipeline [50].

2.3.8. Vessel

Currently there exists no compressed hydrogen carriers in the market. However, there are conceptual designs for compressed hydrogen carriers [53]. In conversation with representatives of Provaris previously Global energy ventures, it is understood that the requirement for compressed hydrogen carriers are likely to be project specific in the near future. That is to say that the vessel will be custom built for project specific use. It is unlikely that in the near term there will be an abundance of charter vessels for compressed hydrogen transport like in the oil and gas industry for liquid fuel transport. There are two conceptual vessel designs proposed by [53] a large 2000 ton vessel and a 430 ton hydrogen carrier both storing hydrogen at 250 bars. The conceptual design can be seen in Figure 2.12.
The structural design of the vessel together with the hydrogen storage pressure on the platform dictates the extent of compression systems on the vessel. Cascading flow strategies such as the one discussed by [31] will depend on the extent of free flow that is possible before pressure equalization occurs between the vessel at any given point and the storage on the hydrogen production unit.

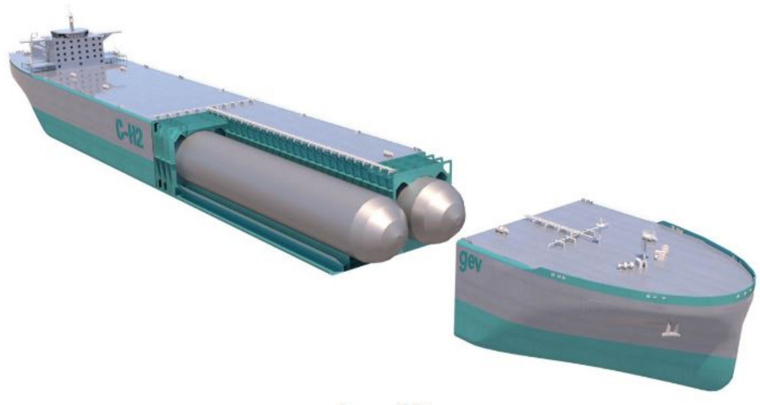

Figure 2.12: Conceptual design of Hydrogen Carrier Vessels [53]

For this study, as will be discussed later in the case study section the design of the vessels is taken as it is from the Provaris company catalogue without further scrutiny. Large hollow storage tanks in the vessel allow free flow until mass flow rates drop below a threshold rate at which point compression systems on board the vessel will be used to maintain the mass flow.

The cost of the vessel are expected to be the costs arising from their manufacture,the required compression systems and the operational costs over the lifetime of the project.

2.3.9. Single Point Mooring System

The single point mooring system is required in farm type II where a single large tanker vessel is required to be connected to the entire farm. This system is common in offshore oil and gas field industry for safe maneuvering and cargo loading [54],[55]. The single anchor loading system (SAL) is a type of single point mooring system that is connected to the ship with a single hawser. The SAL system is shown in Figure 2.13. The SAL is a sub-sea system and the anchor of such a system plays a dual role by also acting as a sub-sea manifold. The hydrogen gas is then transported to the vessel through a flexible pipe.

The SAL system is selected to connect the wind farm to the large vessel.

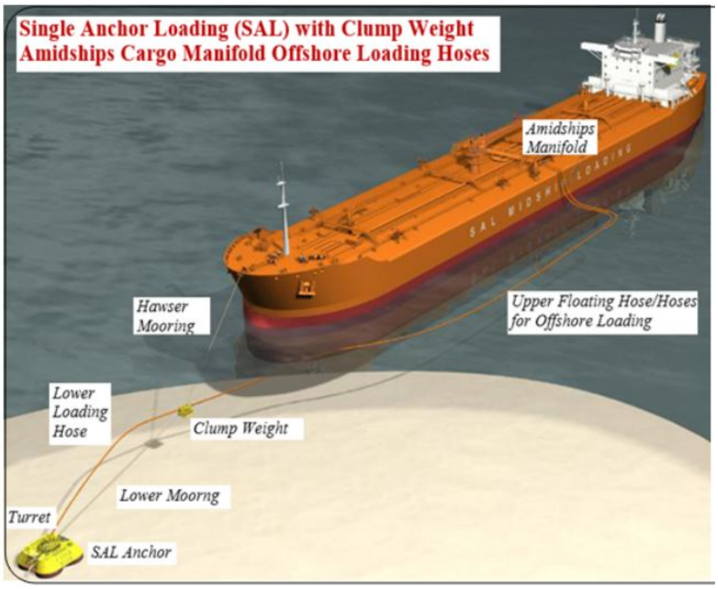

Figure 2.13: Single Anchor Loading system [55]

3
System Modeling

This chapter explains the system modeling and the model set up of individual components with respect to the different wind farm configurations discussed in chapter 2. This chapter is sub-divided into four sections.
The first section describes the system level framework of the different wind farm configurations with an explanation of the system model set-up at a broad level as an introduction and then describes the operation of the vessel controller and next the hydrogen production unit (HPU) at a localized level. Second, the modelling of the components required to produce hydrogen at each HPU and the components required in the supply chain are discussed in the component modeling section. The principle used for loading hydrogen in the vessel is detailed in section 3.
Lastly the vessel operation for farm type II and III are demonstrated in the vessel fleet working demonstration section.

3.1. System Set-up

This section details the system level working of the model. The economic metric and the model working are first explained in the model overview section. Next, the HPU operation for the different farm types is elaborated.

3.1.1. Model Overview

The operation of the different wind farm types as shown in Figure 3.1 is a combination of the operation of multiple hydrogen production units (HPUs) in the wind farm and the transportation method of the specific wind farm type. The HPU block primarily consists of the components required for hydrogen production. These components are controlled locally at the HPU level by the HPU controller. The wind farm is an intermediate interface between the controller and the multiple HPUs in the wind farm. The role of the wind farm is to transfer HPU specific information to the system controller, and also to transfer information from the system controller to the specific HPU when required. The transportation block consists of the components required for the transport of hydrogen to shore and process involved such as the loading process. The role of the system controller is to combine the interaction between the wind farm and the transport option of the farm type. The exchange of data takes place between the system controller and the wind farm, and the system controller and the selected transportation block. The two way exchange of data flow is key to operate the wind farm type III.

In the case of farm type I, the exchange of data is uni-directional and limited to wind speeds given to the wind farm by the system controller.
In wind farm type II there is still no data exchanged from an individual HPU to the system controller, however, in this farm type the system controller transfers weather data and information about the large vessel. The large vessel storage status is relayed at every instant to the wind farm and subsequently to the individual HPUs. This is important as the wind farm requires shutdown during moments of bad weather or when storage is full.
Requirement of two way exchange of data is prevalent in wind farm type III. The system controller plays

a more active role in the operation of this farm type. This is because the storage at individual HPUs needs to be emptied to when they are filled so that the HPU can restart production. In this farm type the system controller in addition to relaying weather data to the farm, also stores information regarding the storage status of all the HPUs at any given instant of time. When the HPU storage is filled the system controller is responsible for assigning vessels to empty the storage. A more detailed explanation of the transportation method used in farm type II and III are presented in the vessel operation section.

The levelized cost of hydrogen produced is calculated to examine the performance of the different wind farm types. The levelized cost of hydrogen is calculated by dividing the capital expense,Capex, plus the operational expense cost over the lifetime,$Opex_n$, by the hydrogen produced over the lifetime of the plant. To calculate the levelized cost of hydrogen LCOH(€/kg), the costing block takes two inputs : the cost parameters from all components of the wind farm inclusive of the supply chain and the hydrogen produced and transported by the farm. The formula used to calculate the LCOH is presented in Equation 3.1 The model overview is presented as a flowchart in Figure 3.1.

$$LCOH(€/kg) = \frac{NPVofTotalInvestment}{HydrogenProduced_{lifetime}} = \frac{Capex + Opex_n}{HydrogenProduced_{lifetime}} \quad (3.1)$$

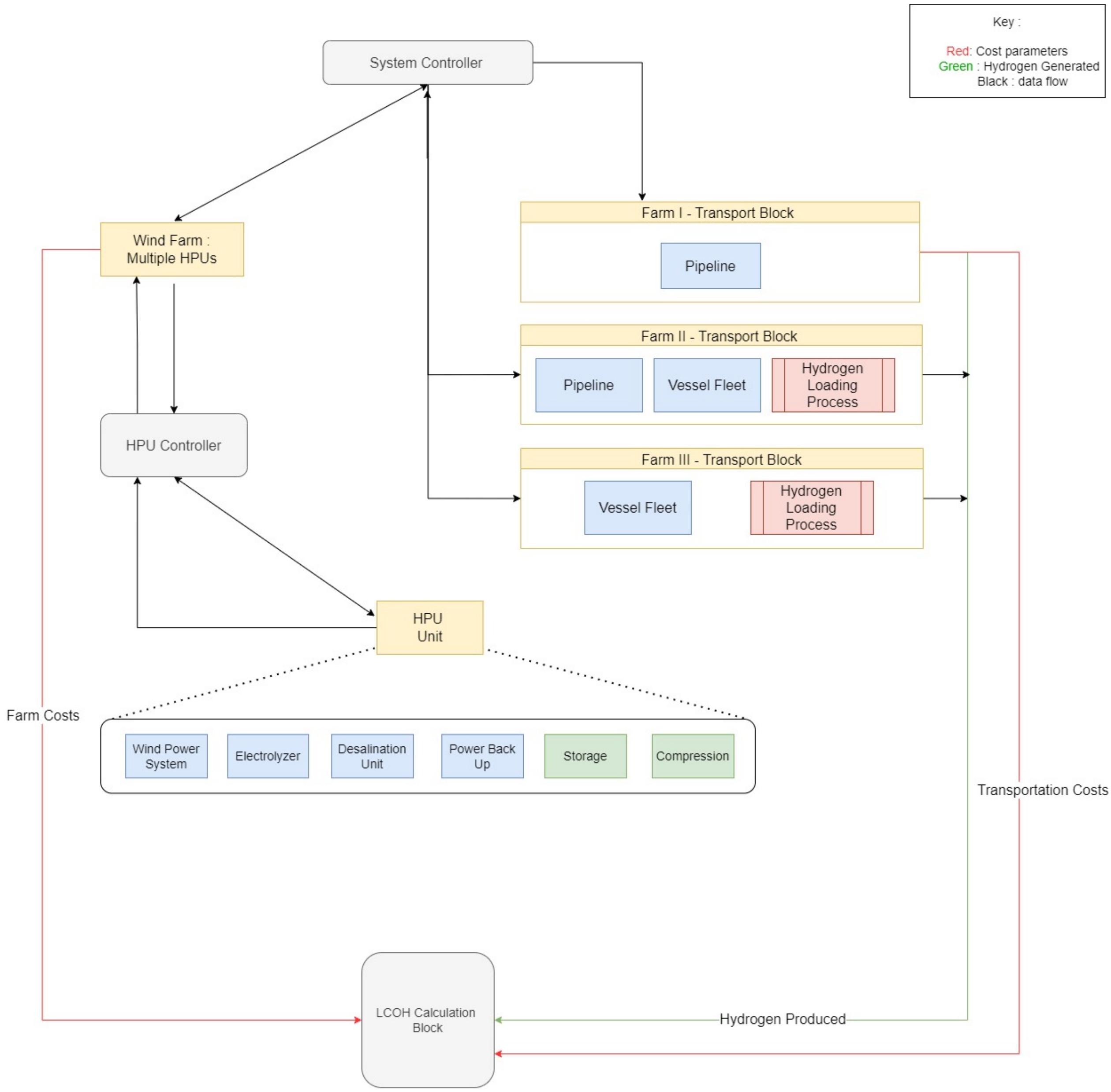

Figure 3.1: System model overview - the components in the HPU common to all farm types are presented in blue and components with changing requirements in green. Control blocks are grey in color and the process block is shown in red.

3.1.2. Vessel control

This section explains the vessel operation control logic for wind farm II and III. The vessel operation for farm type II poses lower complexity when compared to farm type III. Nevertheless it is briefly explained, as it provides a stepping stone to the vessel operational control in farm type III.
The vessel operations for both farms are dependent on the significant wave height, H_s. Two critical parameters affecting the vessel operations for both wind farm II and III are, the wave docking limit, that is the significant wave height for which a vessel is allowed to connect and begin hydrogen loading, and, the wave loading limit which is the significant wave height up to which hydrogen loading is allowed, if the wave height is greater than the stipulated limit the vessel must be undocked.

3.1.3. Farm type II

In farm type II the hydrogen produced by the farm is stored in the large vessel storage hulls at each times step. The vessel is the returned to port when it is completely filled. To this extent an assumption is made that the secondary vessel is ready and available when the first storage vessel is filled to maximum capacity. However, the vessel may be detached from the inter array grid restricting storage of hydrogen due to poor weather conditions. In such an instance the wind farm stops producing hydrogen and HPUs are shut down.

3.1.4. Farm Type III

Wind farm configuration type III consists of platform storage at each HPU and multiple hydrogen carrier vessels which load hydrogen from the HPU storage periodically. The system controller operates and controls the interaction between the wind farm consisting of multiple HPUs and the vessel fleet consisting of multiple hydrogen carrier vessels.

Figure 3.2 shows the scheduling strategy used to operate the wind farm. Each HPU in a wind farm set up has a specified amount of hydrogen storage, once the storage is filled the HPU shuts down into a state wherein no hydrogen is produced even in the availability of wind power. To resume operation the hydrogen storage must be emptied at the earliest possible time by hydrogen carrier vessels. The system controller assigns vessels to load hydrogen from the HPU when their storage is filled. This process of emptying platform storage from an HPU is a service provided by a vessel and from now it is referred to as an inter-farm trip.

The system controller operates the vessels to service HPUs based on a first come first serve (FCFS) scheduler. Two queues are used to operate and assign vessels to HPUs, one queue is maintained for the HPUs that need to be serviced in order of their requirement and the second queue lists the vessel in the order that they are free. In the event that multiple vessels are busy, the vessel which is free to service the HPU at the earliest, is assigned to it. Each inter-farm trip is given the same priority level. The queuing system operates in a non preemptive manner, which implies that a inter-farm trip that has been initiated is completed before a vessel is assigned to the next HPU for service.
The vessel status which is an attribute of the vessel is updated at each instant of time as its earliest free hour. The earliest free hour of a vessel, stands for the earliest time instant at which a vessel can begin a new inter-farm trip. The earliest free hour of a vessel is calculated when an inter-farm trip is assigned to it. This is done by calculating the number of hours required to service a HPU taking into account the loading rate and weather conditions at site. An inter-farm trip is assigned to a vessel if it has the earliest response time when called to service a HPU.
The model allows the vessel to dock for removal of hydrogen from an HPU only if the significant wave height is within docking limits. The loading process is also subject to weather conditions as a loading wave limit is placed. When the loading limit is breached during the loading process the vessel is detached and has to wait until the wave conditions fall below docking limits to re-attach to the HPU to re-start loading.

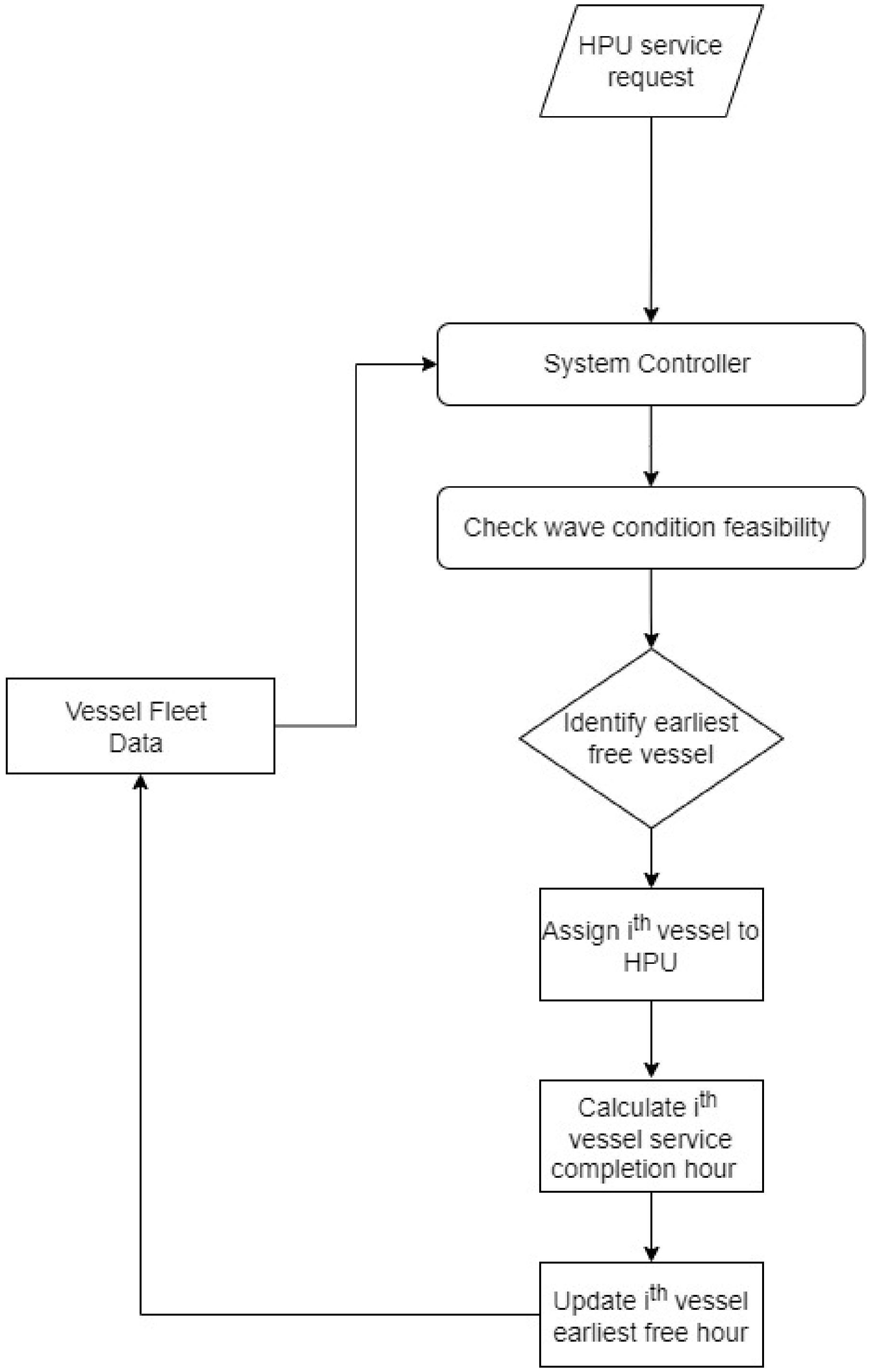

Figure 3.2: Vessel Scheduling - farm type III

The transit time between two inter-farm trips, is the time required from movement from one HPU to another for loading hydrogen. In the absence of a geographic information system with coordinates of the wind farm the transit time is conservatively calculated based on the longest distance a vessel needs to travel in the wind farm. The transit time is an input parameter to the model.

3.1.5. HPU controller

As discussed in the system overview the hydrogen production unit consists of all components necessary to produce hydrogen offshore in a localized manner. The operation of the HPU depends primarily on the wind availability and the method of transportation being used in the wind farm type. The HPU controller controls the interaction between different components required for hydrogen production. The controller logic for wind farm configuration III will be explained first as it has multiple operational modes and it includes all control aspects that are prevalent in farm type I and farm type II.

Farm III

The operational modes of the HPU in farm configuration type III primarily depend on the hydrogen storage available, $Storage_{avail}$, and the wind power generated,P_{gen} at a given time instant. The HPU is designed to generate maximum possible hydrogen at any given time. The control logic maintains the auxiliary power unit,APU, at maximum capacities at all times. In addition to supplying power to the electrolyzer all necessary auxiliary power requirements such as ventilation,heating and lighting loads given by, P_{aux}, are supplied by the wind turbine power generated, P_{gen}. Lastly, when the unit is producing hydrogen the component specific losses in the desalination unit and compression system are deducted as hydrogen losses. The controller logic is shown in the schematic in Figure 3.3 and the operational modes of the HPU are listed in Table 3.1.

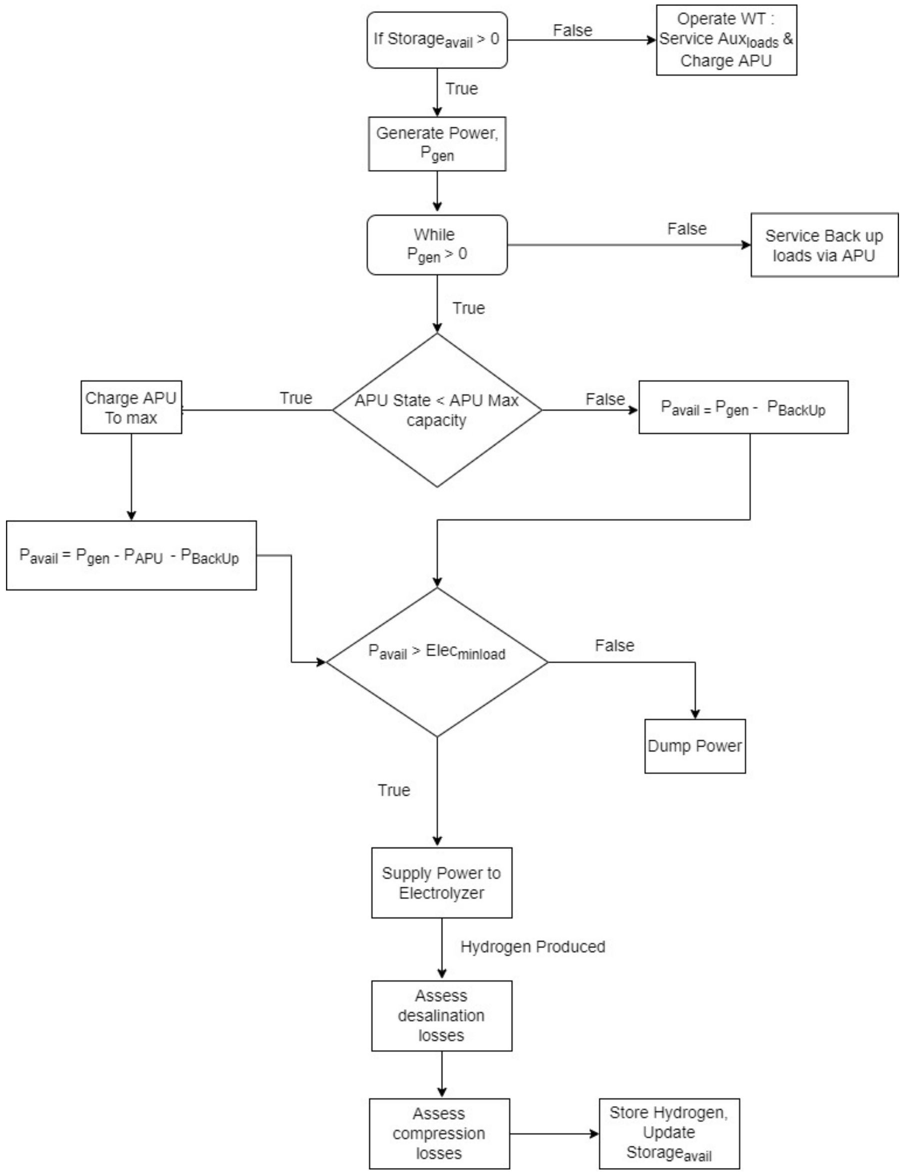

Figure 3.3: HPU Control strategy - farm type III

Operational Mode	Description	Hydrogen Production
I	Storage space available and power generation, greater than the minimum required input power into electrolyzer.	Yes
II	Storage space available and power generation equals zero. APU supports auxiliary power needs.	No
III	Storage space available, power generation less than the minimum required input power into electrolyzer.	No
IV	Storage space unavailable.	No

Table 3.1: HPU wind farm type III - Operational Modes

Farm I

The HPUs in this farm type are solely dependent on the wind power availability and are working at all times when there is power available for hydrogen production. There are three operational modes of the wind turbine and they are presented in the Table 3.2.

The HPU unit control strategy can also be illustrated from Table 3.1 with some modifications due to the absence of storage at site. These are : the removal of the first check to confirm storage space availability to generate power and the final hydrogen storage can be simply changed to an injection of hydrogen into the pipeline.

Operational Mode	Description	Hydrogen Production
I	Power generation greater than the minimum required input power into electrolyzer.	Yes
II	Power generation equals zero. APU supports auxiliary power needs.	No
III	Power generation is less than the minimum required input power into electrolyzer.	No

Table 3.2: HPU wind farm type I - Operational Modes

Farm II

Wind farm II is a hybrid configuration using both vessel and pipelines.
As the vessel swapping when storage is completely filled is assumed to happen at the instant when the working vessel is completely filled the operational modes of the individual HPUs remain similar to operational modes of farm type I. However during bad weather conditions the vessel is undocked from the common coupling point which leads to situations that are identical to farm type III when storage is unavailable. Therefore the operational modes of the HPU in this farm type remain identical to Table 3.1, stating that the storage space is available when the vessel is docked and the storage space is unavailable when the vessel is undocked.

3.2. Component Modeling:

This section describes the modelling of the components implemented in the hydrogen production unit and the components required for transport of gaseous hydrogen to shore. The component cost modeling and sizing is further discussed.

3.2.1. Floating wind power system

The floating wind power system compromises of the floating support structure and the wind turbine, which is the power generating unit of the system. The wind turbine selected dictates the sizing of components required for hydrogen generation whereas the space availability on the platform to accommodate the components is determined by support structure type.

The wind speed applied to the power generation formula is scaled upto hub height using Equation 3.2 [56]. V_{hub} the wind speed at hub height, is dependent on the product of wind speed measured at reference height given as V_{ref} and the ratio of hub height to measurement height scaled to the exponential power law coefficient.

$$V_{hub} = V_{ref}(\frac{h_{hub}}{h_{ref}})^{\alpha} \tag{3.2}$$

The wind turbine power generation is modeled based on the fundamental equation given by Equation 3.3 which is dependent on the wind speed, V_{hub} and density,ρ [57]. The power generation is also dependent on the turbine specific parameters such as the mechanical efficiency of the turbine,η_{mech} the power coefficient,C_P and the generator efficiency,η_{gen}. These parameters are turbine specific and are required input parameters.

$$Power_{wind} = 0.5 * \rho * A * V^3 * \eta_{mech} * \eta_{gen} * C_P \tag{3.3}$$

The power output of a wind turbine is namely dependent on the cut-in wind speed, rated wind speed and the cut-out wind speed[56]. These parameters are again turbine specific and are adopted by the model. The power generated is calculated as given by the following equations :

$$P(t) = \begin{cases} 0, & \text{V} \leq V_{cut-in} \\ Power_{wind}, & \text{V}_{cut-in} \leq V \leq V_{rated} \\ P_{rated}, & \text{V}_{rated} \leq V \leq V_{cut-out} \\ 0, & \text{V}_{cut-out} \geq V \end{cases}$$

No additional modeling is required for the floating support structure. However the space available on the platform to house the different components for hydrogen production are dependent on the semi-submersible platform. As the semi-submersible support structure is shaped like an equilateral triangle the available area is given by the equation below accounting for the area of tower base of the wind turbine.

$$AvailableArea = \frac{\sqrt{3}}{4} * OuterColumn_{distance} - Area_{towerbase} \tag{3.4}$$

The capital expense of the floating wind power system, C_{fwt}, and the annual operational expenses, OP_{fwt} of the floating wind power system are calculated as given in Equation 3.5 and Equation 3.6. They depend on the wind turbine rated power, RP_{fwt}, and the specific capital expense of the wind floating unit, C_{sfwt}, and the specific opex, OP_{sfwt}.

$$C_{fwt} = C_{sfwt} * RP_{fwt} \tag{3.5}$$

$$OP_{fwt} = RP_{fwt} * OP_{sfwt} \tag{3.6}$$

3.2.2. Auxiliary Power System :

The auxiliary power system is necessary to support the back up power requirement during times when there is no wind power available. The sizing of the battery in the auxiliary power system is dependent on the duration for which back up power is required and also the loads that need to be fulfilled by the back up power source.

The hourly power requirement during standby mode of the electrolyzer,Aux_{Elec} and battery, Aux_{Batt}, and wind turbine,Aux_{fwt}, are component specific input parameters.
The auxiliary power unit depends on the hourly back up power requirement and the duration of power back up,Cap_{Apu} is sized as given by the following Equation 3.7 :

$$Cap_{Apu} = (Aux_{fwt} + Aux_{Elec} + Aux_{Batt}) * Hours \tag{3.7}$$

The cost model scales linearly with respect to the battery capacity needed by the Cap_{Apu} and the capital costs,C_{Apu}, and the yearly operational costs,OP_{Apu} are respectively given by Equation 3.8 and Equation 3.9. They are dependent on the specific cost of the battery,C_{sApu}, and the yearly specific operation and maintenance cost, OP_{sApu}.

$$C_{Apu} = Cap_{Apu} * C_{sApu} \tag{3.8}$$

$$OP_{Apu} = C_{Apu} * OP_{sApu} \tag{3.9}$$

3.2.3. Electrolyzer

The electrolyzer size is matched by the model to the wind turbine size selected. The hydrogen produced depends on the power input into the electrolyzer and the efficiency of the electrolyzer. The efficiency of the electrolyzer is dependent on the components that fall within the system boundary as discussed in the component overview.

The overall system specific consumption, $Elec_{spec}$, and the power input,P_{in}, is used to calculate the hydrogen produced,Hyd_{prod}, and it is given by the equation Equation 3.10.

$$Hyd_{prod} = \frac{P_{in}}{Elec_{spec}} \tag{3.10}$$

The electrolyzer is operated in an on-off state. This is possible due to high ramp up and ramp down speeds of the PEM electrolyzer. However, a minimum load of 5% is required for hydrogen production[30],[58]. When the minimum load falls below this threshold the hydrogen production is set to zero and the electrolyzer is shutdown.
The electrolyzer capital expenditure,C_{Elec}, depends on the total system capacity,Cap_{Elec}, and the specific equipment cost of the electrolyzer,C_{selec}. The annual operating expenses,OP_{Elec}, depend on C_{Elec} and electrolyzer specific opex,OP_{selec}.The capital and operating cost model are as given by the equations below :

$$C_{Elec} = Cap_{Elec} * C_{selec} \tag{3.11}$$

$$OP_{Elec} = C_{Elec} * OP_{selec} \tag{3.12}$$

3.2.4. Desalination Unit

The desalination unit supplies the electrolyzer with water of tap water quality. The production of water and in turn the energy requirement of the desalination unit per instant of time depends on the water requirement of the electrolyzer for hydrogen production. The desalination unit is modeled to produce an equivalent amount water as required by the electrolyzer at a given instant of time.

The energy requirement of the desalination unit,$Energy_{desal}$ is the product of water required by the electrloyzer,$Elec_{wc}$ and the specific energy consumption,$Desal_{spec}$ of the desalination unit. To account for the energy losses due to desalination requirement,$Desal_{Ereq}$, the energy required is subtracted as a loss from the kilograms of hydrogen produced,$Desal_{Losses}$. This is calculated based on the energy content of one kilogram of hydrogen based on the higher heating value(HHV),$Hydenergy_{HHV}$ and the hydrogen produced at the instant,Hyd_{in}. The equations used to model the desalination unit are given by Equation 3.13 and Equation 3.14 :

$$Desal_{Ereq} = Elec_{wc} * Desal_{spec} \tag{3.13}$$

$$Desal_{Losses} = \frac{Desal_{Ereq}}{Hyd_{HHV} * Hyd_{in}} \tag{3.14}$$

The capital cost of desalination depends on the desalination unit capacity. The desalination unit capacity,Cap_{ds} is sized according to the max hourly requirement of water for the selected electrolyzer size. Desalination cost C_{ds} is a product of the rated electrolyzer capacity,Cap_{Elec} and desalination specific capital expense, C_{sds} as shown by [28]. The yearly operational expense OP_{ds} is calculated as a specific percentage,OP_{sds}, of the desalination capital expense. The costs are modelled as follows :

$$C_{ds} = Cap_{Elec} * C_{sds} \tag{3.15}$$

$$OP_{ds} = C_{ds} * OP_{sds} \tag{3.16}$$

3.2.5. Compressor

The sizing of compression system depends on the pressure elevation required for storage or the work required to be done to maintain a given mass flow rate.
The compressor working is based on a fixed speed compressor type. This implies that the compressor is operated in an on-off state, working at full power at all times it is required. However, in reality a variable speed compression system can be used. Variable speed compression system operate at higher part load efficiencies as it attains the pressure differential required to maintain a given mass flow at lower speed of the compressor drive[59], resulting in lower power consumption when compared to fixed speed compressors.

The equation used to calculate compression energy, is based on single stage polytropic compression and is given by Equation 3.17 [40].

$$E_{comp} = \frac{Q * R * T * Z}{M_h} * \frac{N_\gamma}{\gamma - 1} * \frac{1}{\eta_{comp}} * ((\frac{Pr_{out}}{Pr_{in}})^{\frac{\gamma}{N_\gamma - 1}} - 1) \tag{3.17}$$

The list of parameters required for the calculation are as follows,

- Pr_{in}, input pressure.
- Pr_{out}, output pressure.
- η_{comp}, compressor efficiency.
- Q, mass flow rate.
- R, real gas constant.
- T , Temperature.
- Z, compressibility factor.
- M_h, Molar mass of hydrogen.
- N_γ, number of compression stages.
- E_{comp} in KWh

The energy required by the compressor to perform compression work on hydrogen, is then subtracted as a loss in kilograms of hydrogen produced based on the HHV of hydrogen. The compression losses per hour are calculated as given by Equation 3.18.

$$Comp_{loss} = \frac{E_{comp}}{H_{HHV} * H_{in}} \tag{3.18}$$

The compressor system capital expense is based on the maximum energy requirements of the required compression system. The cost modeling of the compressor according to [43] varies linearly with the energy consumption. The capital expenditure includes the entire compressor package the driver and the ancillary components. The capital expenditure and the yearly operational expenses are calculated as given by Equation 3.19 and Equation 3.20 respectively.

$$C_{Comp} = Cap_{comp} * C_{scomp} \tag{3.19}$$

$$OP_{comp} = C_{Comp} * Op_{scomp} \tag{3.20}$$

3.2.6. Storage

The storage of hydrogen at HPU is required in wind farm configuration type III. As discussed in the system overview, hydrogen is stored in vertical tubes in twenty foot equivalent containers as proposed by [31].
The module storage capacity,Cap_{mod}, the module storage pressure,P_{mod}, and cost of storage modulesC_{mod} are input variables to the model. Depending on the required capacity of storage and the storage pressure defined by the user, the number of storage modules required are calculated as given in Equation 3.21.

$$Number_{mod} = \frac{RequiredCapacity}{Cap_{mod}} \tag{3.21}$$

Finally the capital expenditure of storage tubes,C_{st} are calculated as given by Equation 3.22.

$$C_{st} = Number_{mod} * C_{mod} \tag{3.22}$$

Lastly, the importance of maintaining a minimum pressure in the storage has been explained in the storage overview. The minimum pressure that a storage must maintain is set as an input parameter in the model. The minimum pressure that must be maintained in the storage impacts the loading operation in wind farm configuration type III and it limits the maximum hydrogen that can be removed from the storage units on the platform.

3.2.7. Pipeline

The pipeline is used to transport hydrogen from the farm to shore in configuration type I and it is also required to transport the farm output to the large vessel in farm configuration type II. The pipeline size depends on the maximum flow that is required to be transmitted and the permissible pressure drop over the distance that hydrogen needs to be transmitted[60],[52]. The diameter of the pipeline is calculated by based on the Bernoulli equation as given in Equation 3.23 without considering a change in head through the pipeline transmission[52].

$$Diameter(m) = \sqrt[5]{\frac{16 * \lambda * Z^2 * R^2 * T^2 * L * M_h^2}{\prod * (Z * R * T(Pr_{in}^2 - Pr_{out}^2))}} \tag{3.23}$$

The list of parameters required for the calculation are as follows,

- Pr_{in}, input pressure.
- Pr_{out}, output pressure.
- λ, friction coefficient.
- Q, mass flow rate.
- R, real gas constant.
- T , Temperature.
- Z, compressibility factor.
- M_h, Molar mass of hydrogen.
- L, length of the pipe.

The capital cost of the pipeline per km,C_{pipe} is calculated based on a methodology proposed by [61],[61], where the the overall cost of the pipeline is a quadratic function of the diameter of the pipe size in millimeter. The cost function incorporates the material costs, the labor costs and miscellaneous costs as detailed by [61]. It must be noted that the cost function for hydrogen pipelines is built based on data from past projects for onshore natural gas pipelines and is given by Equation 3.24.

$$C_{pipe} = 517174.12 + 762.8 * Dia_{pipe} + 2.306 * Dia_{pipe}^2 \quad (3.24)$$

The operational expense of the pipeline,Op_{pipe} is calculated as a function of the capital cost and is given by Equation 3.25.

$$Op_{pipe} = C_{pipe} * OP_{spipe} \quad (3.25)$$

3.2.8. Vessel

Hydrogen ships are required to transport hydrogen produced offshore for wind farm configurations type II and type III. The vessel storage volume,$Vessel_{storagevol}$ and the maximum storage pressure,$Storage_{press}$ are input parameters to the model. These input parameters dictate the compressor system sizing required on board the vessel.
The compression system on board the vessel maintains a constant hydrogen mass transfer rate.The cost of the compression system is calculated as described in Section 3.2.5.

The capital cost of the vessels are based on the cost of oil and gas tankers, smaller vessels used in the windfarm type III are compared to general purpose tankers whereas the large vessel required in configuration type II is compared to a Suezmax vessel [62]. These capital costs are given as input to the cost model block. As such the capital cost of the vessel include the manufacturing cost of vessel,MFC_{ves} and the cost compression system onboard,C_{comp}. The capital expense,C_{vess} is given by Equation 3.26.

$$C_{vess} = MFC_{ves} + C_{comp} \quad (3.26)$$

The yearly operational expenses,OP_{ves}, of the ship is the product of vessel operating cost per day,OP_{cost}, which is an input parameter to the model, and the number of days spent by the vessel at sea,OP_{days}, which includes days in transit to and from the shore. The days spent at sea are considered to be ship operational hours whereas the days the ship is at port offloading hydrogen - the operating expenses are assumed to be zero. The operational cost is given by Equation 3.27.

$$OP_{ves} = OP_{days} * OP_{cost} \quad (3.27)$$

3.3. Hydrogen Loading

Hydrogen loading is the process of transfer of hydrogen gas into the storage of a hydrogen carrier vessel. Hydrogen mass transfer occurs based on pressure difference between the incoming hydrogen and the existing vessel storage pressure. In the absence of a natural pressure difference for hydrogen mass transfer by free flow, the pressure of incoming hydrogen gas is raised using a compression system. The flow that occurs by use of a compression system for mass transfer from here is referred to as forced flow. This section details the model used to simulate the loading process during vessel operation in wind farm type II and III.

3.3.1. Farm type : II

In wind farm configuration type II the hydrogen is transported via an inter array pipeline system to the large carrier vessel. The operating pressure of the pipeline and the pressure of the incoming hydrogen gas is dependent on the output pressure of the PEM electrolyzer.
Hydrogen loading is done via free or by forced flow with the use of the compression system onboard the vessel. The vessel storage pressure is dynamic in nature and it increases as the mass of stored hydrogen increases for the given storage volume of the ship. The loading process imitates free flow behaviour when the pressure in the vessel storage is lesser than that of the incoming hydrogen,Hyd_P.

The schematic representation Figure 3.4 shows the model used for the loading process in the case of a large hydrogen carrier tied to the entire wind farm. The vessel storage pressure is updated at each time interval. The vessel pressure, V_{press} at each instant of time in the vessel is calculated as given in Equation 3.28 [63].
When the pressure in the vessel storage equals or becomes greater than the input hydrogen pressure, the model switches from free flow loading to forced flow. The comparison between the vessel storage pressure and the incoming hydrogen pressure is made at each instant of time. The power requirement and compressor sizing onboard the vessel are done as detailed in the compressor modeling section.

$$V_{press} = \frac{R * T}{V_{Vol}} \tag{3.28}$$

The loading process is continued till the vessel storage is completely filled to its maximum capacity. Then the system controller is notified and the substitute vessel is connected to the farm.

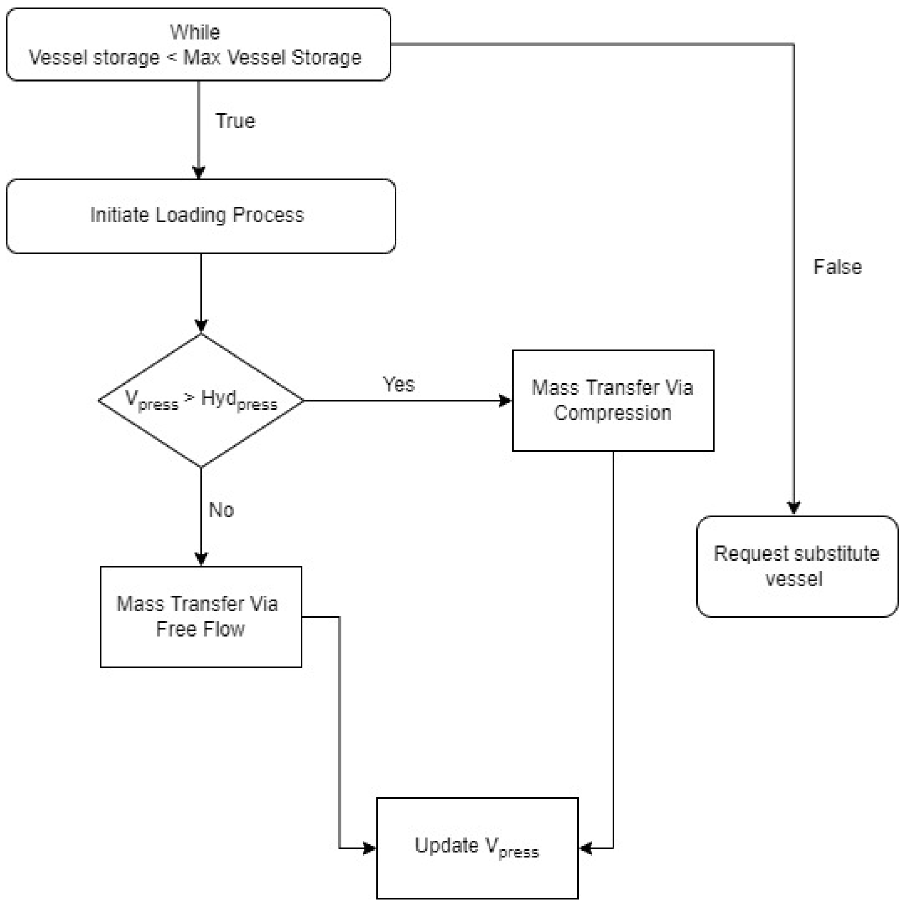

Figure 3.4: Loading control logic - farm type II

3.3.2. Farm type : III

In wind farm configuration type III the hydrogen is loaded in the vessel from the platform storage modules. The vessel loads hydrogen periodically from multiple such platforms. In this section the loading process from a single platform storage in an HPU to vessel is explained.

At the start of the loading process from the platform storage into the vessel the initial input hydrogen pressure is the maximum storage pressure on the platform. As the storage level in the vessel increases the pressure in it increases, simultaneously the pressure level on the platform storage decreases. Thus with each instant of time the pressure differential decreases between the incoming hydrogen and the

existing pressure in the vessel storage.
In this case, both the vessel storage pressure and the platform storage pressure are dynamic in nature. Due to this the mass flow rate varies over time during loading due to the changing pressures in both the storage compartments.

The instantaneous flow of hydrogen gas in a pipe resembles the flow of a compressed fluid through a pipe[63]. The mass flow rate of compressed gas in isothermal conditions can be calculated based on Equation 3.29. Isothermal conditions are assumed as mass flow due to isothermal conditions are lower when compared to adiabatic conditions [63]. The free flow mass flow rate depends on change in pressure energy, kinetic energy and friction losses over the length of the pipe. The mass flow rate that is attainable by free flow is ascertained by Equation 3.29 at each instant of time.

$$Mass_{rate} = Area_{pipe} * \sqrt{\frac{-(P_{vess}^2 - P_{sto}^2)}{2 * P_{sto} * Sto_{spcvol}} - (4\phi\frac{L}{d} + ln\frac{P_{sto}}{P_{vess}})} \tag{3.29}$$

The list of parameters required for the calculation as follows,

- P_{vess}, the vessel storage pressure.
- P_{sto}, platform storage pressure.
- Sto_{spcvol}, specific volume at storage pressure at given time instant.
- ϕ, pipe roughness.
- L, length of pipe.
- d , pipe diameter.
- $Area_{pipe}$, Area of cross section of the pipe

The pressure in the vessel storage and platform storage are updated based on the new mass of hydrogen present in the storage volumes using Equation 3.28 .

The time taken for pressure equalization and the mass flow rate due to free flow is numerically solved using conditional loop statements over the duration of the loading process. This iterative process is depicted in Figure 3.5. The required mass flow rate is a user defined input threshold value. To make sure the user input value is within safe limits, a safe check is performed. The maximum allowable mass flow through the pipe set up is limited by the maximum allowable gas velocity in the pipe. The maximum mass velocity is set to 30 m/s [64]. The maximum allowable mass flow M_{max} is calculated as the product of the density of hydrogen at initial storage pressure,ρ_{int}, area of cross section of pipe, $Area_{pipe}$, and the max velocity,V_{max} and is given by Equation 3.30.

$$M_{max} = Area_{pipe} * \rho_{int} * V_{max} \tag{3.30}$$

When the mass flow rate due to free flow is greater than the user defined threshold value, the mass flow rate is set to the user defined value and the mass transfer occurs due to free flow. When the mass flow rate drops below the user defined value, the compressor is switched on and the mass transfer is then maintained at the user defined value. The loading process is executed till the required hydrogen amount is loaded onto the vessel from the platform storage. An example of the loading set up can be seen in Appendix A. The compressor on board the vessel is sized based on the maximum work required to be done by it to maintain the required mass flow. Compressor sizing and losses are done based on the methodology detailed in compressor section.

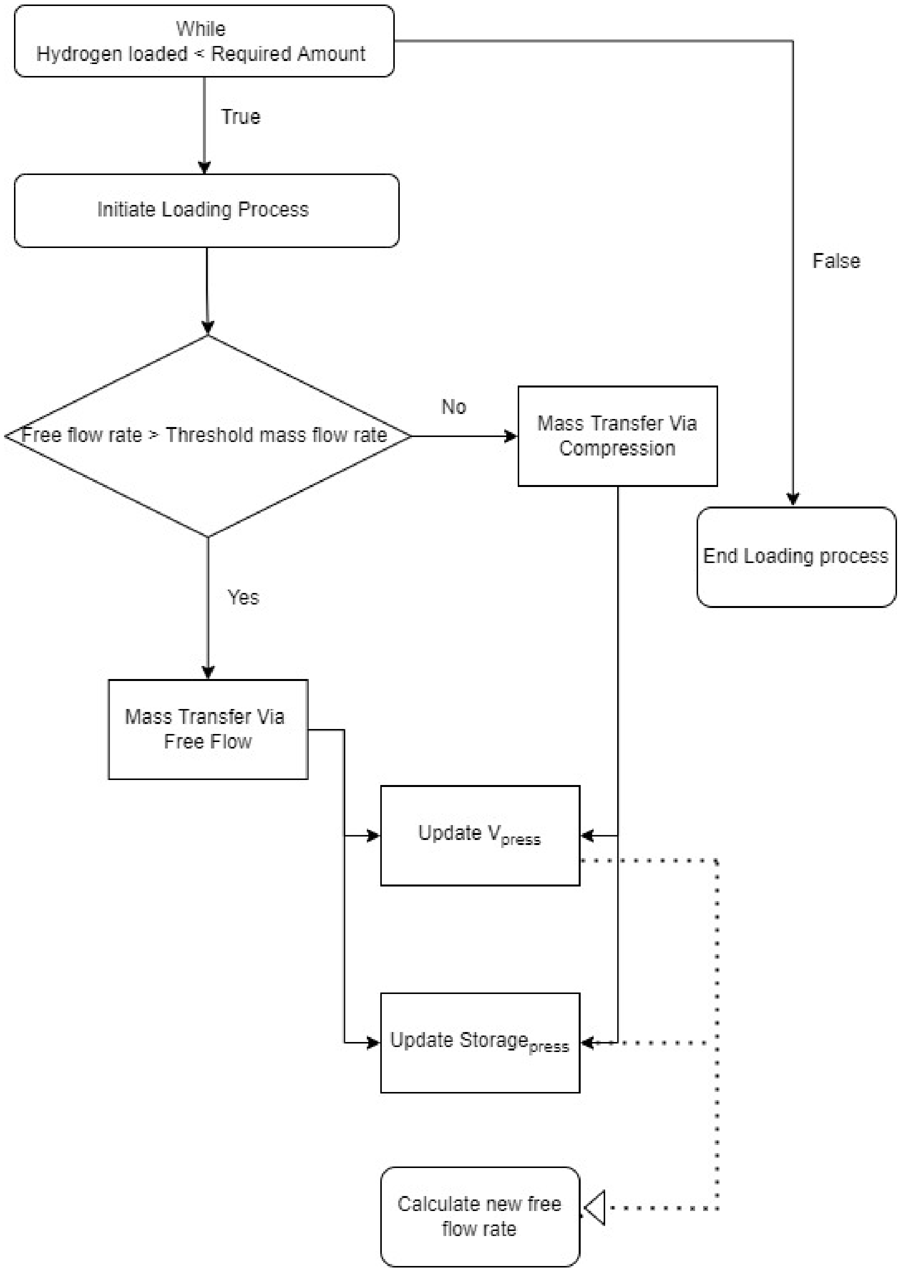

Figure 3.5: Loading control logic - farm type III

3.4. Vessel fleet working demonstration :

This section describes the steps taken to validate the vessel control in farm II and III.

3.4.1. Farm II

To validate the model built for wind farm type II, data values have been force fed to the model set up. Vessel operations are restricted in the event of higher significant waves than permissible for vessel operation. The weather data has been altered and this limits vessel operation during the same time window. The large vessel remains disconnected from the wind farm until wave conditions permit loading. In this farm type the storage in the form of large vessel is directly disconnected and the farm is shutdown, no hydrogen is produced. The applied wave input data is shown in Figure 3.6 and the corresponding vessel behaviour is depicted in Figure 3.7.

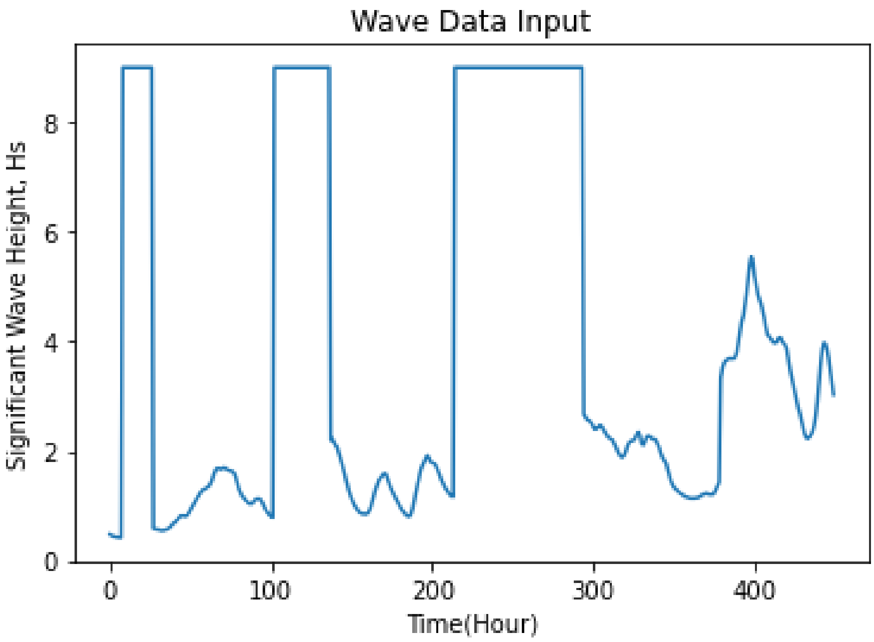

Figure 3.6: Weather Data - Applied for model demonstration

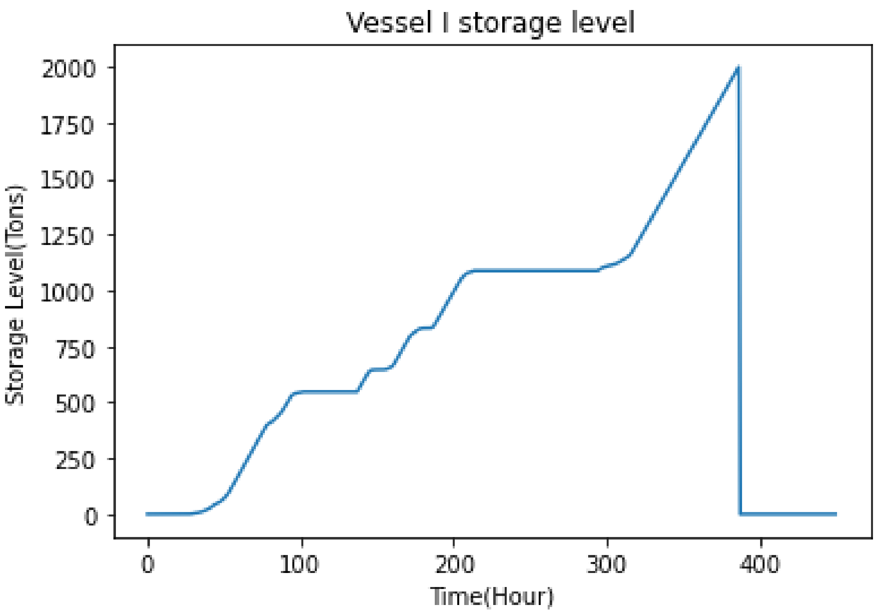

Figure 3.7: Impact of weather on vessel storage status

3.4.2. Farm III

To validate the model built for wind farm type III, data values have again been force fed to the model set up and the outcome is depicted in the images below. Vessel operations are restricted in the event of higher significant waves than permissible for vessel operation. When a vessel is called and the wave conditions are not suitable the transit is restricted. An altered weather data is applied and limits vessel operation during the same time window, the vessel remains in in-active until suitable weather conditions are arise. This is seen in Figure 3.8 and Figure 3.9.

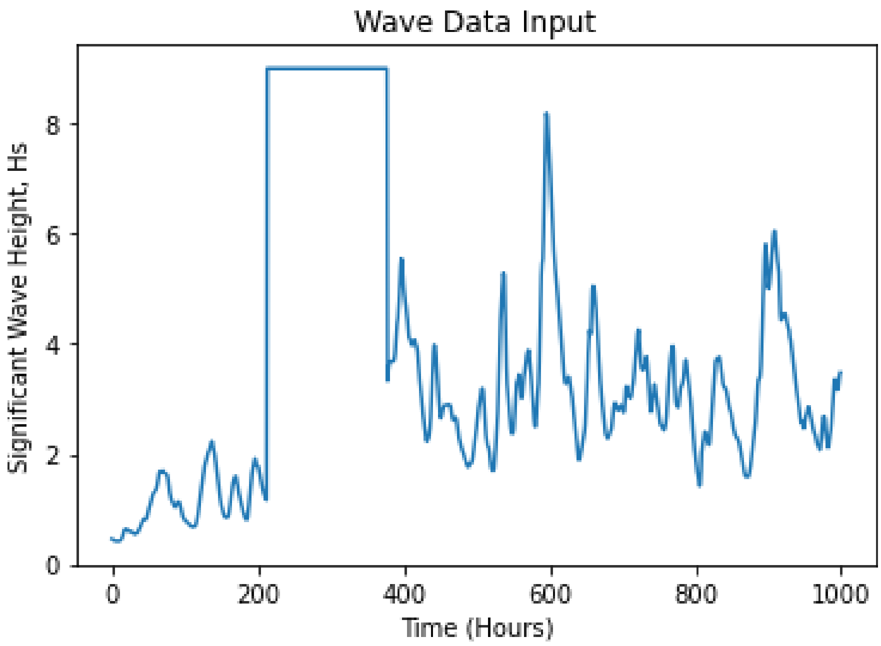

Figure 3.8: Weather Data - Applied for model demonstration for farm III

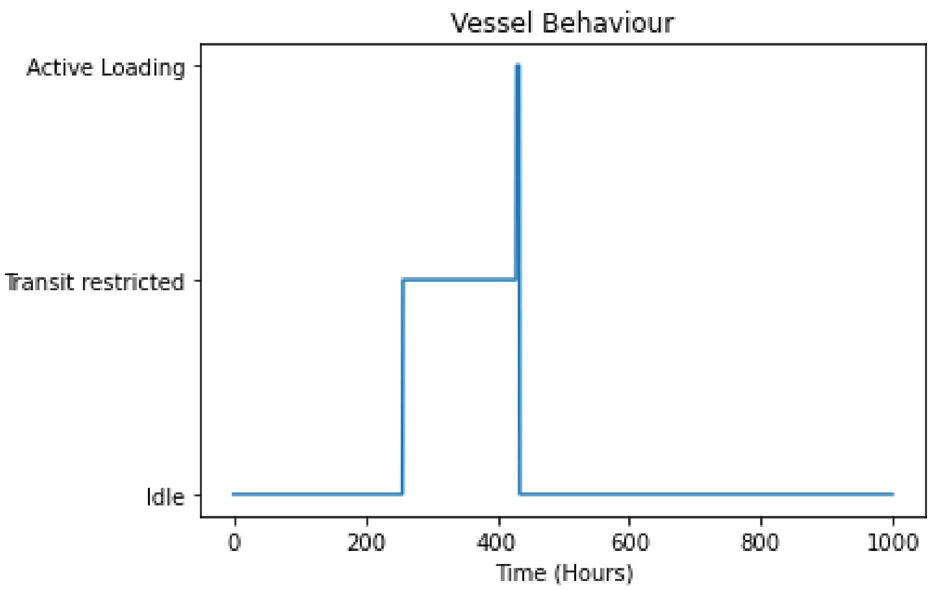

Figure 3.9: Vessel Behaviour

In **??** the vessel operation throughout a year is seen, this includes the periodic vessel offloading at port when the vessel storage is filled to maximum.

4
Results

In this chapter the model built is applied to investigate the different wind farm configurations. The first section of the chapter details the set up of the case study built to investigate the different wind farm configurations. This section includes the input parameters and assumptions made at a system level to establish the goals of the study. The next section details the case study done to build the baseline cost curves of wind farm configuration I and II for comparative purposes, it also presents the configuration specific input parameters and assumptions if any. The last section focuses on the study performed on the wind farm configuration type III, identifying the lowest cost configuration.

4.1. Case study set-up :

This section details the universal case study set up parameters common to all configurations.

4.1.1. Farm Set up :

The physical layout of the wind farm has implications specifically on the operation of multiple vessels in wind farm type III. However, it is universal to all wind farm configurations and hence discussed below.

For this study the wind farm is assumed to be of a square grid form. Each wind turbine is required to be spaced about 5-7 rotor diameters apart [65] to mitigate wake effects. In addition, to study the interaction between the vessel and windfarms, it is found that hourly operations assessed over a year provide quantifiable results. Hence hourly weather data is used for the simulation.The wind farm set up is presented in Table 4.1.
The input parameters both technical and economical for system components in the HPU and components universal to all configurations are presented in Table 4.2. It must be noted that the capex of all components of the HPU including the compressor and storage modules which are specific to farm type III are multiplied by an additional offshore installation factor of 2. The compressor is a critical component and a second back up compressor is also accounted for in the costing of the compressor.

Parameter	Value	Unit
Wind farm Capacity	750	MW
Turbine spacing	1	Km
Data Input	-	Hourly
Lifetime	20	Years

Table 4.1: Universal wind farm parameters

Input Parameter	Value	Unit	Reference
Wind Power System Capex	2.65	M€/MW	[6]
Wind Power System Opex	0.1	M€/MW	[6]
Electrolyzer Specific Consumption	0.058	Mwh/Kg	[30]
Electrolyzer Capex	1200	€/KW	[30]
Electrolyzer Opex	2	%/y/capex	[30]
Electrolyzer Specific Water Consumption	15	L/Kg	[30]
Desalinator Specific Consumption	4	Kwh/Kg	[66]
Desalinator Capex	9500	€/Elec$_{MW}$	[67]
Desalinator Opex	3	%/y/capex	[67],[12]
Compressor Capex	2545	€/KW	[43]
Compressor Opex	3	%/y/capex	[12]
Battery Capex	4000	€/KW	[38]
Battery opex	2	%/y/capex	-
Pipeline opex	2	%/y/capex	[43]
Offshore Factor	2	-	-

Table 4.2: System Input Parameters

4.1.2. Floating wind power unit :

The floating support structure selected for the case study is the semi-submersible design type. This is because there exists an extensive knowledge base on the design of such design platforms. These semi-submersibles are generally designed specifically for a selected wind turbine as also discussed in the system overview.

The combined set up of the U-Maine semi submersible and the IEA-15-240-RWT 15-megawatt (MW) reference turbine form the floating wind power unit for this cases study. The semi-submersible is designed specifically for the IEA-15-240-RWT 15-megawatt (MW) reference wind turbine [68][69].
The arrangement of the wind turbine is shown in Figure 4.1. The input parameters from the wind turbine and the designed semi-submersible are listed in the Table 4.3.

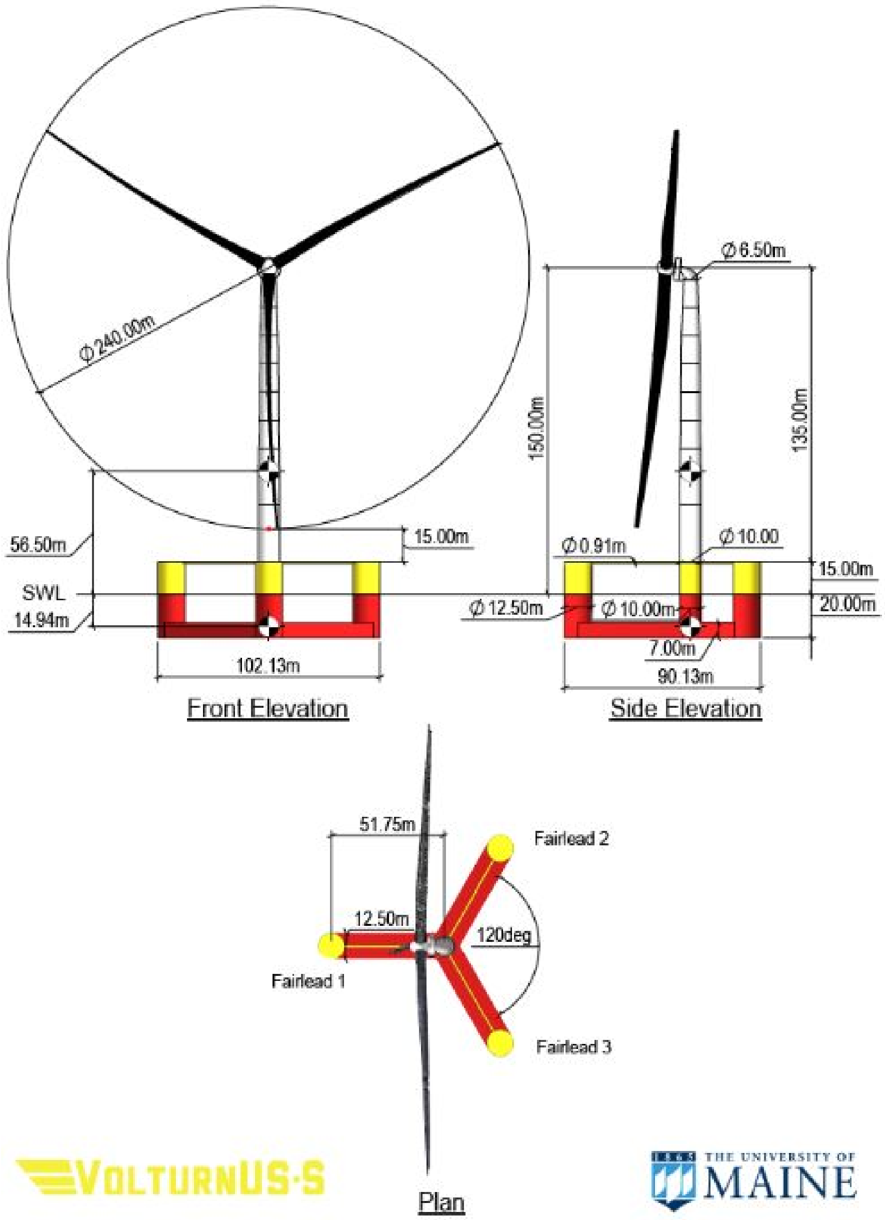

Figure 4.1: Arrangement of IEA-15 MW with designed semi-submersible
[68]

The auxiliary power requirements of the wind turbine consisting of the heating and lighting loads are assumed to be similar to the ones discussed by[70][71]. The energy required for cranking is calculated

Parameter	Value(units)
Outer Column Distance	89(m)
Hub Height	150(m)
Efficiency_{gen}	0.96
V cut-in	3(m/s)
V cut-out	10.59(m/s)
V rated	25(m/s)
Rated Power	15(MW)
Crank Energy	35(Kwh)
Backup power requirement	42(Kwh)
Power coefficent	0.489
Wind shear coefficent	0.11

Table 4.3: Floating wind power unit specifications[68][69][65]

for the specific turbine following the method used by [72].

4.1.3. Weather Data :

The study aims to investigate the performance of the different wind farm configurations over a range of distances. A fair comparison is drawn between the transportation modes of hydrogen between the wind farm configurations by simulating the same weather conditions over the range of distances studied. To this extent a single set of weather conditions is applied to the model and the performance and operation of the configurations are examined. The representative wind year of 2018 has been selected and repeated for the full lifetime.

The selected wind turbine is a class 1B type. The average wind speed of this class of wind turbines is 10 m/s [73]. Wind and wave data is selected from the south of the North Sea with location coordinates N54.25,E5.25. The location is highlighted in the Figure 4.2.

The line drawn through the highlighted location is representative of the range of distance, 0 - 700 km, over which the different farm types are studied. In general the entirety of the north sea has above average wind speeds of 10 m/s but for the purpose of the study the selected weather data is applied to the model.

Figure 4.2: Site Selection for Weather Data
[74]

The weather data is sourced from ESOX. ESOX weather data includes hourly data for four variables - mean wind speed at 10m height, at 100m height, the peak wave period and lastly the significant wave height. The data is based on medium range forecasts produced by European Unions Copernicus Climate Change Service (C3S)[74]. Wind speeds recorded at 100m height are scaled to hub height using the scaling formula described in the floating wind power unit modeling section. The wind and wave data for the year 2018 is used for the study and it is shown in Figure 4.3 and Figure 4.4 respectively.

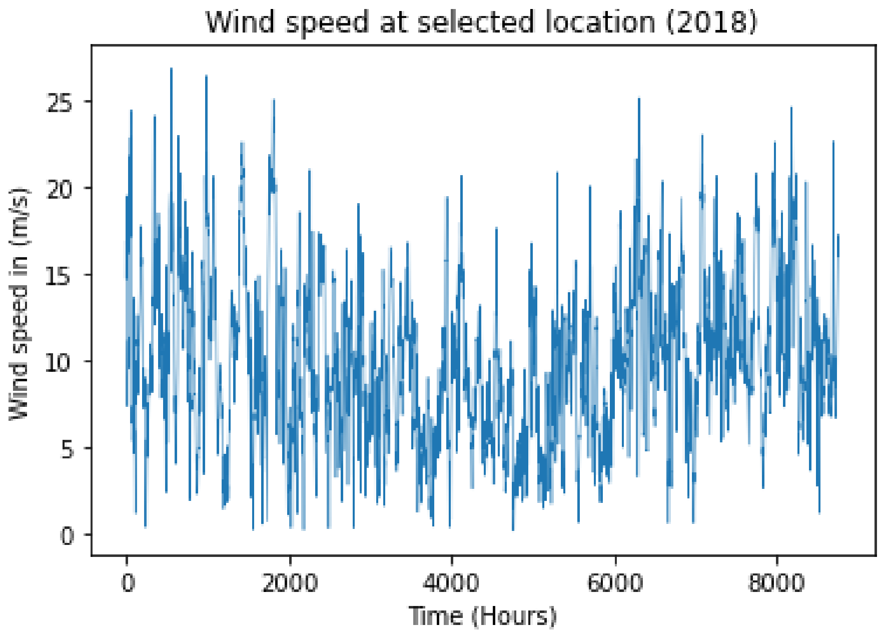

Figure 4.3: Wind conditions at hub height in 2018

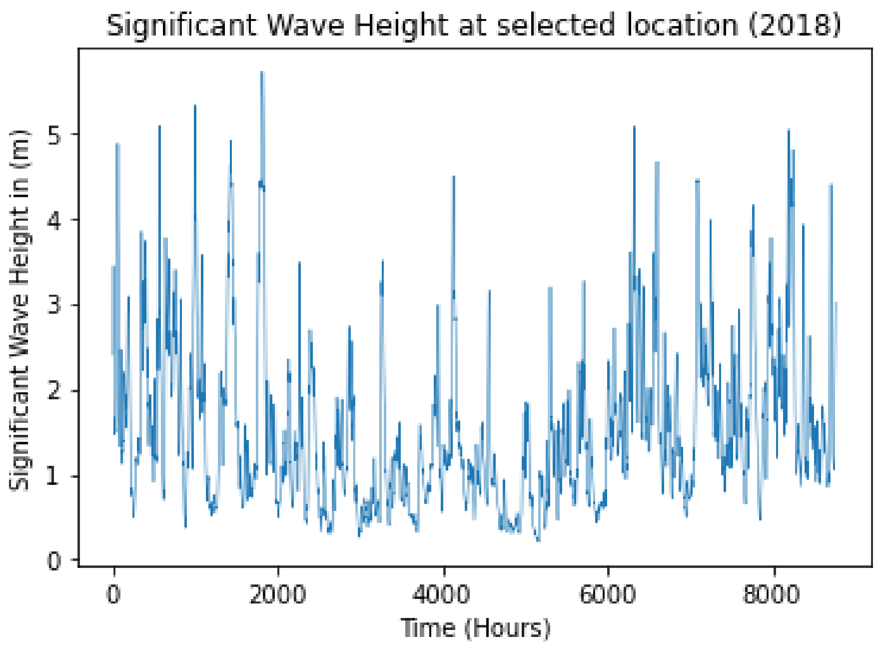

Figure 4.4: Wave conditions in 2018

4.2. Case Study : Farm I and II

This section establishes the comparative cost curves of wind farm type I and II. These cost curves are used later compared with the results obtained from the simulations of wind farm type III.

4.2.1. Farm I:

The wind farm using pipelines to transport hydrogen to shore and it is the simplest configuration to model and simulate owing to the limited operations during transportation of hydrogen to shore. The hydrogen is produced locally at turbine level and then shipped via the main pipeline to shore. A minimum output pressure is maintained at the exist of the pipeline at shore, and it is a user specific input the model. The input parameters specific to this configuration is given in table Table 4.4.

Input Parameter	Value	Unit	Reference
P_{in} into pipe	60	Bar	[15]
Pressure drop per km	0.3	Bar/km	[15],[52]
Minimum P_{out}	30	Bar/km	-

Table 4.4: System input parameters - Farm type I

The resultant cost curve over a lifetime of 20 years over a varying distance is shown in Figure 4.5.

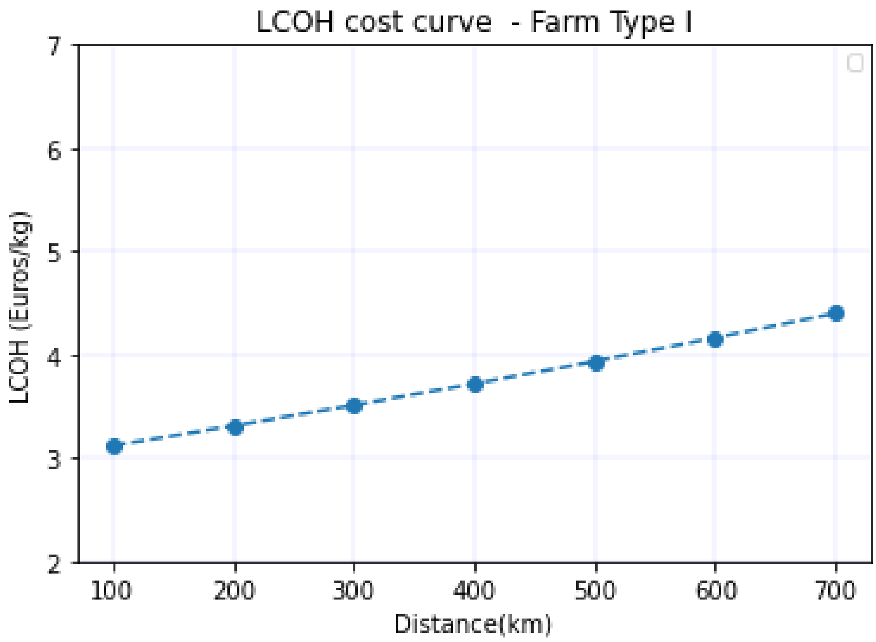

Figure 4.5: LCOH trend over distance : Farm type - I

The increase in cost over the range of distances is an expected outcome of the need for additional compression required to maintain the minimum output pressure and the cost increase of the pipeline with distance. The capex costs for the farm at 100 and 700 km are shown in Figure 4.6 and Figure 4.7.In addition the amount of hydrogen lost over the range of transmission also increases, due to the re-compression energy spent. Thus resulting in the cost increase with distance seen in Figure 4.5.

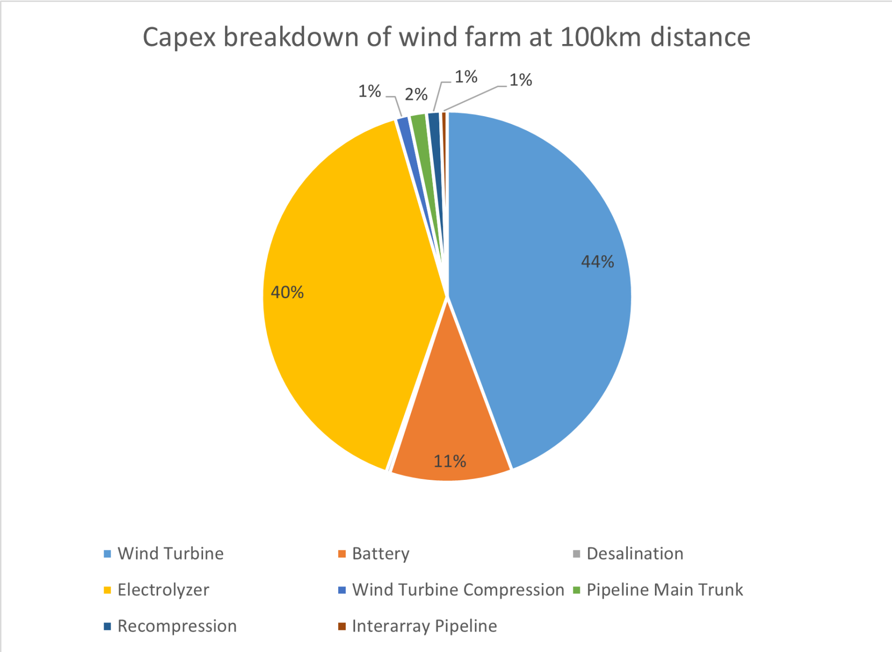

Figure 4.6: Capex Breakdown at 100km : Farm type - I

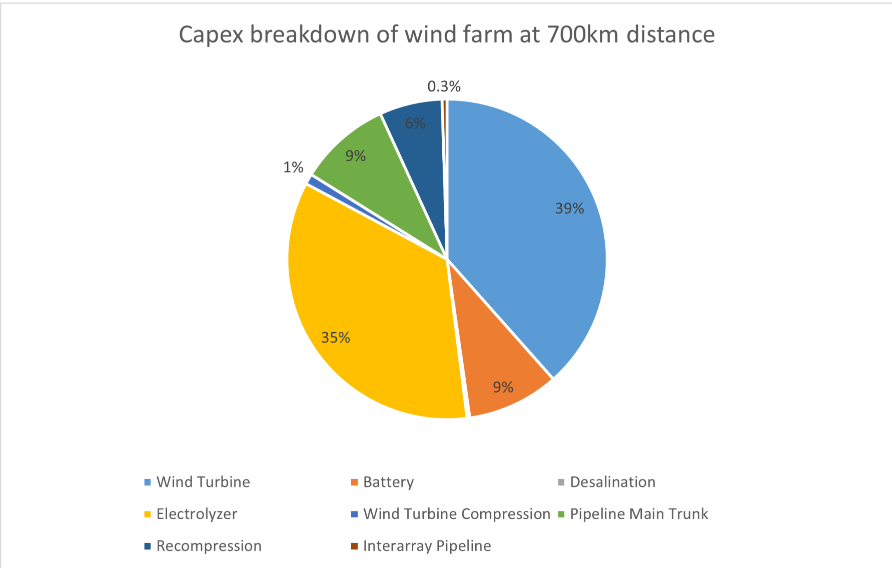

Figure 4.7: Capex Breakdown at 700km : Farm type - I

4.2.2. Farm II:

Farm type II requires more operations for the transport of hydrogen to shore when compared to wind farm type I, owing to the trips required to be made by the vessel to offload the hydrogen periodically. It is assumed that two vessels operate in tandem to support the wind farm. When one tanker is filled the second one substitutes it until the next tanker is required. The input parameters specific to this configuration are given Table 4.5. In addition the offloading rate is a user defined input to the system. Here it is assumed to be 20 tons per hour, which corresponds to 5.5 kg/s. Lastly, the wind farm is assumed to be connected to the vessel via a single anchor loading system as discussed in the system overview. The docking and loading limit used correspond to the SAL system.

Input Parameter	Value	Unit	Reference
P_{in} inter array grid	30	Bar	-
Vessel capex	109.3	Mil€	[62], [75]
Vessel Opex (excluding transit)	34716	€/day	[76]
Vessel Storage Capacity	2000	Tons	[77]
Vessel Storage Pressure	250	Bar	[77]
Single anchor loading system	15	Mil€	[55]
Vessel docking wave limit	4.5	m	[55]
Vessel loading wave limit	5.5	m	[55]
Vessel Cruise speed	28	km/h	[76]
Fuel Expense (transit)	19122	€/day	[76]
Offloading Rate	20	Ton/hour	-

Table 4.5: System input parameters - Farm type II

The resultant cost curve over a lifetime of 20 years over a varying distance is shown in Figure 4.8.

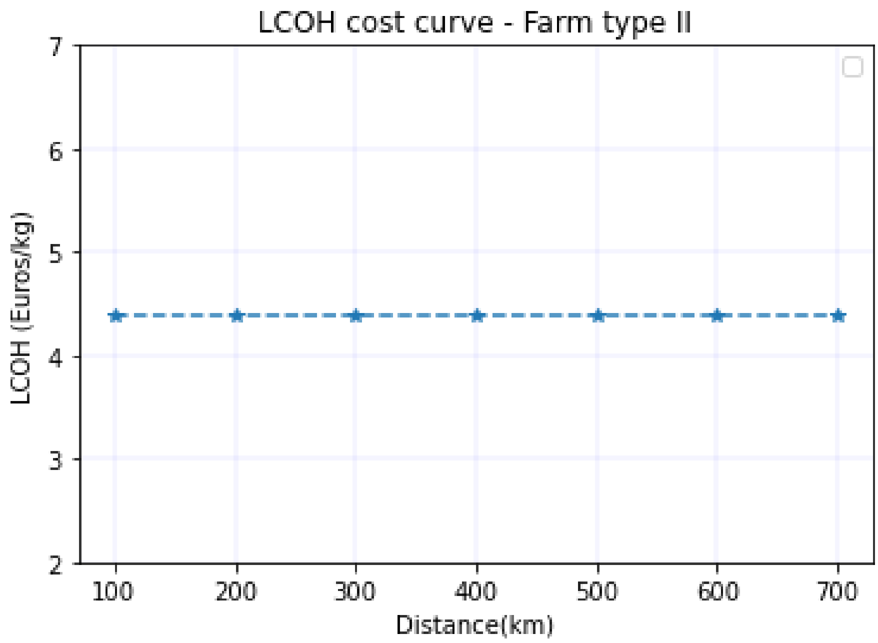

Figure 4.8: LCOH trend over distance : Farm type - II

As it can be seen from Figure 4.8, the LCOH remains unchanged over the range of distance studied. This is due to the fact that the capex breakdown as shown in Figure 4.9, hardly changes throughout the range of distance. The only additional expenses that occur with changing distance is the operational expense arising from vessel transit. The vessel transit costs are too small to influence the LCOH over the lifetime of a wind farm. The variation of the operational expense of one vessel over the range of 100-700 km is shown in Figure 4.10.

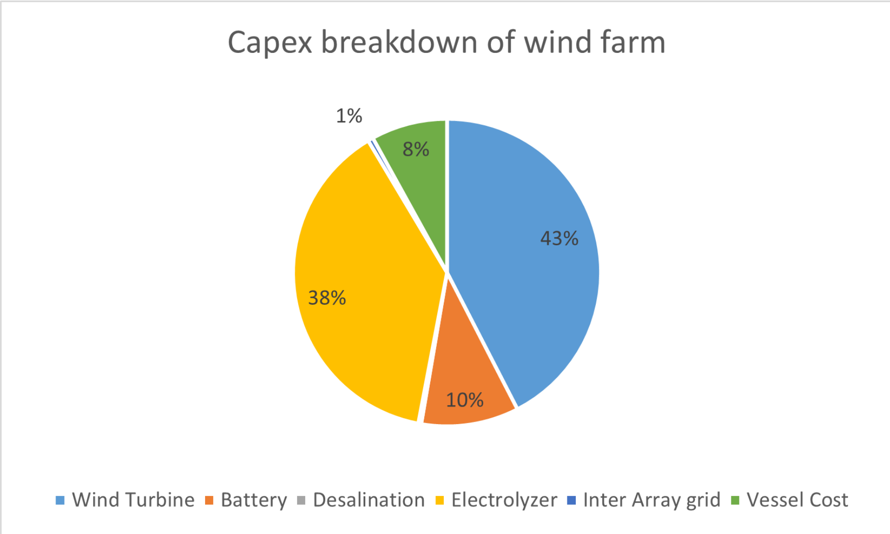

Figure 4.9: Capex breakdown of wind farm type II

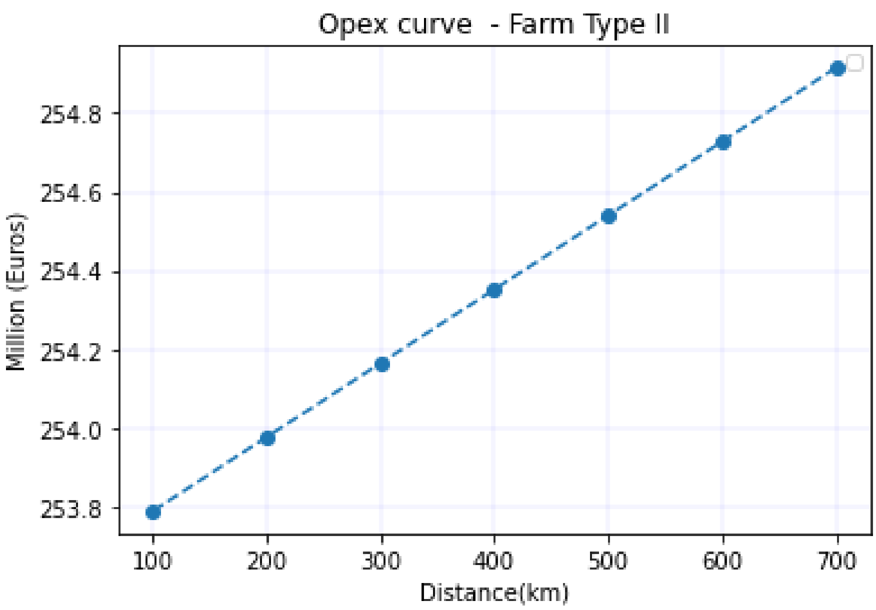

Figure 4.10: Opex over the range of distance for entire farm lifetime

Furthermore the vessel storage condition over a year is depicted in Figure 4.11. The horizontal lines at the bottom corresponding to a storage level of zero indicate that the vessel is idle while the secondary vessel is being loaded. It is found that the vessel is disconnected from the inter array grid due to poor weather for only 11 hours. This is due to the high operational loading limits.It can be inferred from Figure 4.11, that there is a significant number of hours the vessel spends idling at sea.

A break up of the operation of the vessels are provided in Figure 4.12. It can be seen that the amount of time spent by the vessel idling is more near the shore and decreases farther away from it. This is due to the fact that the transit hours increase as the farm moves further out to see. Hence a higher vessel efficacy is seen further out at sea. Near shore at 100 km distance the vessel idling is roughly 27%, this decreases to 19% at 700 km distance.

The vessel hourly break down points out that the vessel with 2000 ton storage is oversized as a large number of hours are spent idling by both vessels in the fleet. Therefore, for a specific wind farm the vessel has to be sized to adhere to a just in time process. It is also critical to take into account the transit hours that depend on the distance from shore as this negatively impacts the vessel availability for loading operations when distances increase.

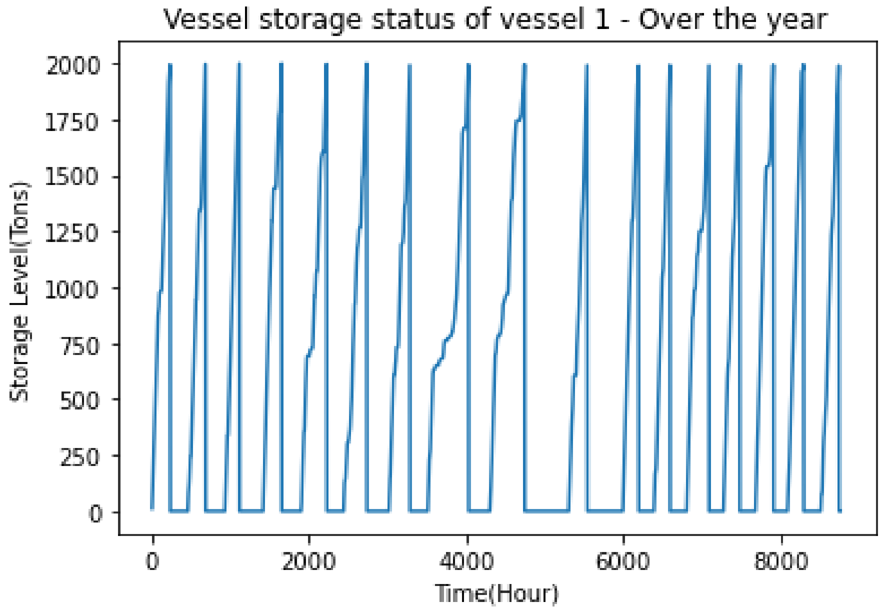

Figure 4.11: Vessel : 1 - Behaviour over the year

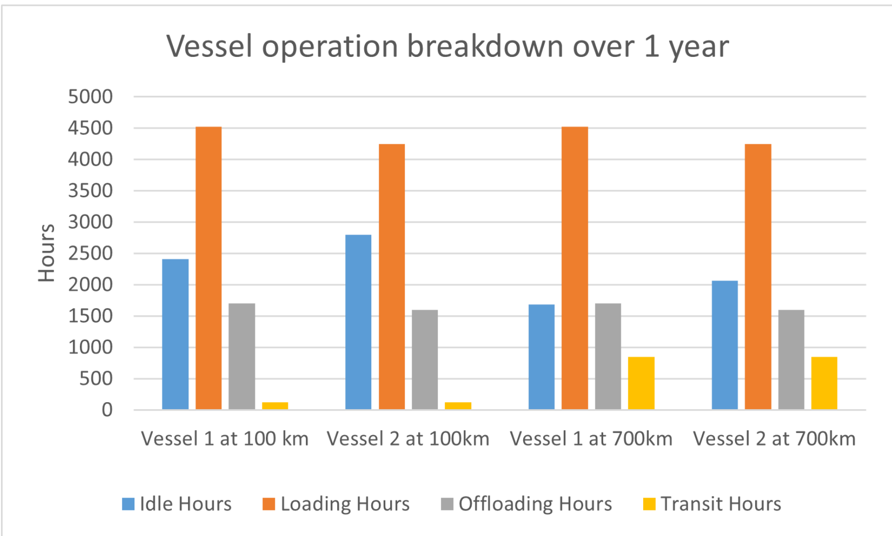

Figure 4.12: Vessel fleet yearly operation breakdown by hours

4.3. Case Study : Farm III

The goal of the study is to assess the competitiveness of hydrogen storage and transport from far off-shore wind turbines. To that extent, in the case study performed for farm III the goal is to find the ideal combination of the storage and number of vessels that need to operate on the wind farm.

To find the optimal configuration, a step by step approach is followed. It is listed as follows :

- The impact of distance from shore is studied for a given fleet size.
- LCOH cost curves are built for varying storage sizes and fleet sizes. From this the optimal vessel : storage combination is selected.
- As a final step the optimal storage pressure is found.

Configuration specific input parameters are provided in Table 4.6. The loading rate is set to 2 kg/s and the minimum percentage of hydrogen for which an inter-farm trip is made is set to 40% of the site storage amount. The minimum percentage implies that vessel storage must have storage capacity greater than 40% of the storage capacity at HPU site to perform a trip, else it is returned to shore for offloading.

Input Parameter	Value	Unit	Reference
Module cost at 350 Bar	250.43	K€/Module	[31]
Module cost at 200 Bar	141.94	K€/Module	[31]
Module cost at 100 Bar	70.585	K€/Module	[31]
Module storage at 350 Bar	300	kg/Module	[31]
Module storage at 200 Bar	180	kg/Module	[31]
Module storage at 100 Bar	93	kg/Module	[31]
Vessel capex	26.67	Mil€	[62]
Vessel Opex(excluding transit)	28.2	K€/day	[76]
Vessel Storage Capacity	430	Tons	[77]
Vessel Storage Pressure	250	Bar	[77]
Vessel docking limit	2.5	m	[55]
Vessel loading limit	4.5	m	[55]
Vessel Cruise speed	28	km/h	[76]
Fuel Expense Transit	12.5	K€/day	[76]
Loading rate	2	kg/s	-
OffLoading rate	2	kg/s	-
Minimum Collection Amount	40%	-	-

Table 4.6: System input parameters - Farm III

It is assumed that a minimum of two vessels shall be required to service the wind farm as a single vessel raises a high factor of dependence on it. The assessed storage term duration are based on the yearly production. The yearly production denotes the maximum hydrogen that can be transported via vessels. The storage term duration is calculated based on the average daily hydrogen production through the year when all hydrogen can be transported to shore. The storage term duration and the corresponding storage capacities studied are presented in Table 4.7.

Term Duration(Days)	Storage Capacity(Tons)
7	25
14	50
21	75
28	100

Table 4.7: Assessed storage term duration

4.3.1. Optimal Storage sizing:

The optimal storage size depends on the number of vessels and the hydrogen production rate that is influenced by weather. As mentioned earlier the weather data input is identical at all distances to assess the transportation performance.
First, a number of different combinations of vessel and storage at 350 bar capacity were simulated for distances ranging from 100-700km. The results of the operation of a 2 vessel fleet for varying storage amounts is shown in Figure 4.13. Similar results indicating no significant change in LCOH over distance were seen for different fleets operating on varying storage sizes.

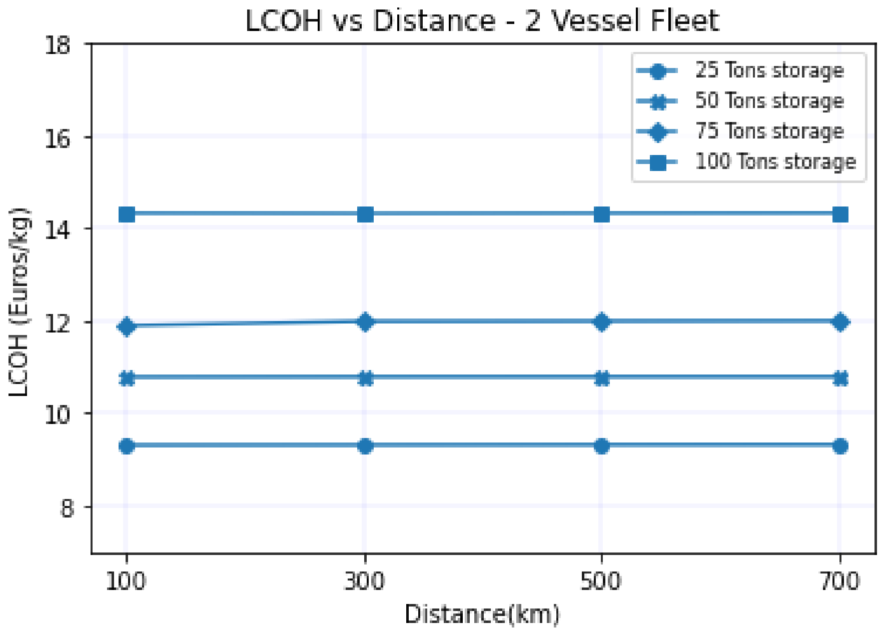

Figure 4.13: 2 vessel fleet operation on varying storage sizes

A clear trend is observed, that is the LCOH does not change with distance. This is primarily due to the minimal additional transit expense occurring with increase in distance.
When vessel docking is not affected by weather conditions, the number of inter-farm trips to a HPU for loading, remain the same for a given storage amount. Therefore, the time elapsed at sea till making a trip to shore for offloading the total vessel capacity are identical for all vessels of a given vessel fleet size.
It can also be seen from Figure 4.13 that the storage size of the configuration directly impacts the costs. This is because the storage contributes the largest share of costs for the HPU set up of farm type III. This can be observed in Figure 4.14 and Figure 4.15.

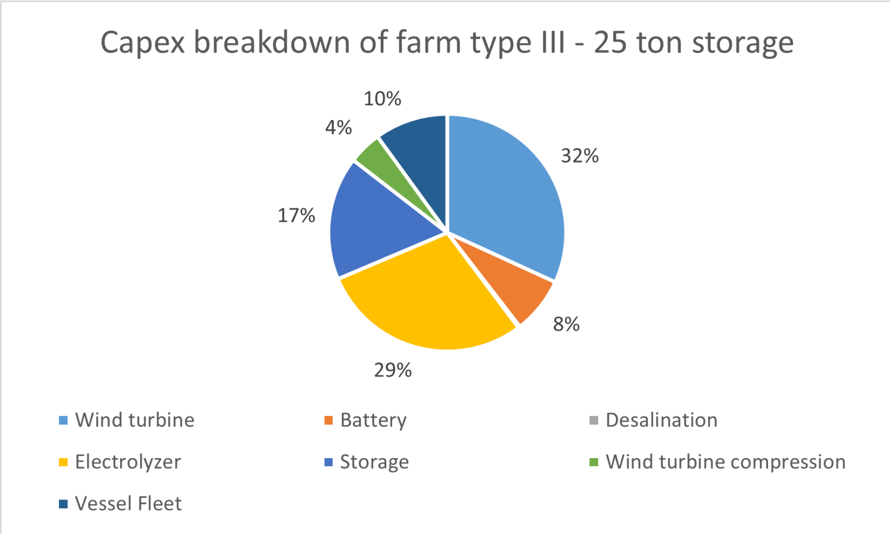

Figure 4.14: Capex breakdown of farm type III - 25 ton storage serviced by a 4 vessel fleet

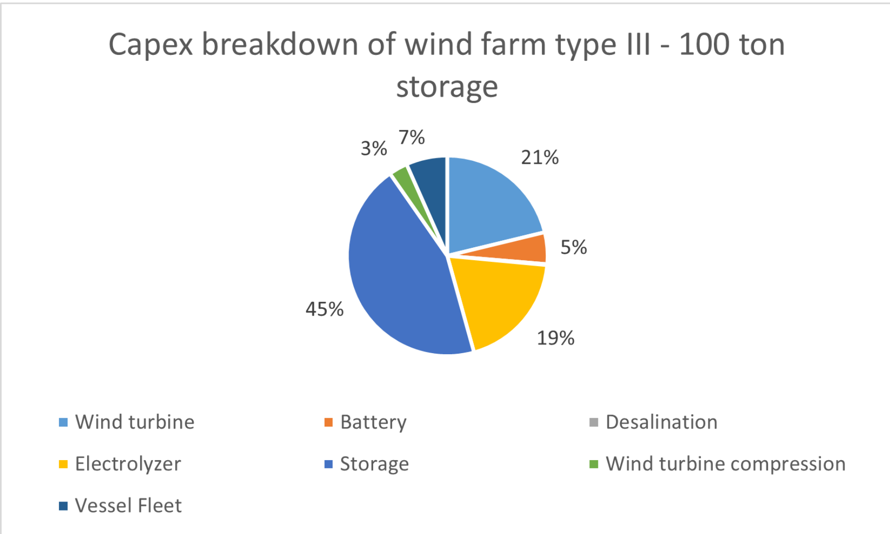

Figure 4.15: Capex breakdown of farm type III - 100 ton storage serviced by a 4 vessel fleet

To find the optimum vessel storage combination the model was simulated for varying fleet sizes increasing from 2-10 for the ealier discussed storage sizes. The results obtained are shown in Figure 4.16. It can be seen that the operation of a 4 Vessel fleet for the given cost parameters provides the optimal solution for any given storage. Starting from 4 vessel fleets the cost curve tends to rise upwards. Beyond this point the addition of a vessel doesn't improve the amount of hydrogen that has been shipped to port and it only adds to over head costs. 25 Ton storage along with a 4 fleet vessel is the optimum combination of vessels and storage from a cost perspective.

From Figure 4.16 it can be seen that there exists a large gap between 25-50 ton storage LCOH curve and 75-100 ton LCOH curve. For the first instance the jump in costs can be attributed to the lower storage costs. In the band of 50-75 tons hydrogen storage the cost curves are close together. This is because the amount of hydrogen transported to shore when storage is 75 tons is maximum. The increase in net hydrogen transported causes the squeezing of the cost curves at 50 and 75 tons. The number of inter farm trips reduce as the size of storage increases, as seen in Figure 4.17 but the number of trips to shore increase up till 75 tons and then tends to decrease.Hence the hydrogen transported, increases up till the 75 ton mark and then decreases. It can be inferred that the maximum hydrogen is produced at 75 ton storage but the hydrogen output is not significant to offset storage costs. The large jump at 100 ton storage can be attributed to two factors - first the rise in storage costs, and secondly due to the model working there is a large amount of hydrogen left behind in the storage at site at the end of the years simulation. This is because the vessel is only called to service the HPU when the storage is full leading to a lower number of trips made to shore.

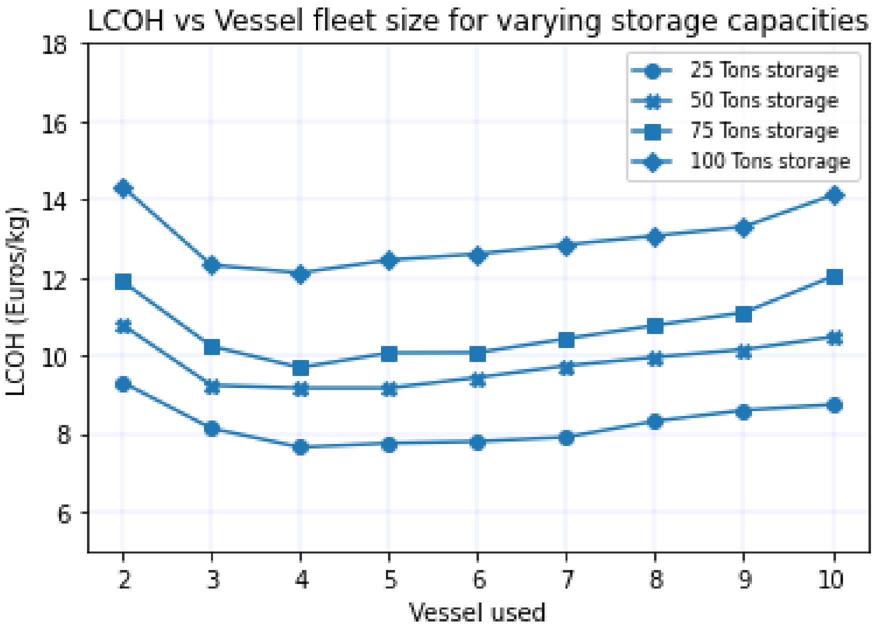

Figure 4.16: Variation of LCOH vs Vessel fleet size for varying storage sizes.

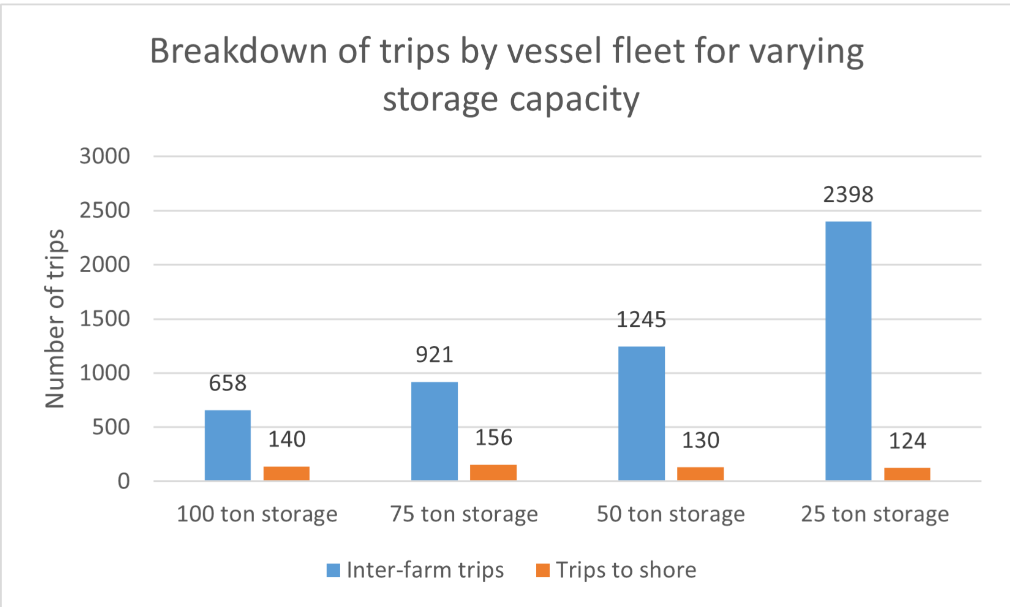

Figure 4.17: Breakdown of trips by a 4 vessel fleet and varying storage capacity

The variation in farm hydrogen production with respect to storage and vessel fleet size can also be observed from the standpoint of an HPU. From Figure 4.18 it can be seen that the average shutdown hours of a HPU show a consistent trend of decrease, with the increase in storage and the number of vessels used. Higher storage levels require less frequent loading and it also helps overcome poor weather windows when the docking of a vessel is not possible at frequent intervals. In addition, a larger vessel fleet reduces the waiting times of a HPU. This is due to a higher vessel availability at all times to service an HPU if required. It can be seen that the variation of shutdown hours for a vessel fleet size of 6 and 8, are not as large for vessel fleet size of 2 and 4. Thus, indicating that beyond a certain point an increase in vessel fleet size is unlikely to improve HPU operation as all vessels are limited by weather conditions.
The shutdown hours are halved when a 4 vessel fleet is used compared to 2 vessels with low storage amounts. At lower storage levels the reduced number of trips are an outcome of the reduced operational hours of the HPU units across the farm. The periods are also impacted by the weather. As storage is increased the shutdown periods of the HPU are reduced.

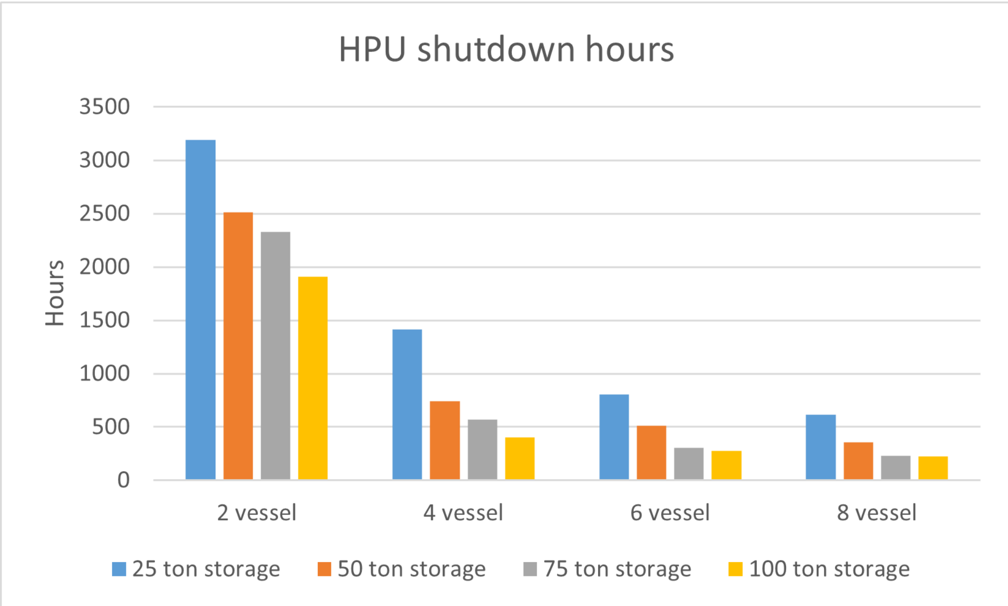

Figure 4.18: Average HPU shutdown hours

4.3.2. Storage pressure :

The optimal combination of storage capacity and vessel fleet size is found to be 4 vessels and 25 ton storage. Next the variation of LCOH is studied with respect to the available storage pressures for the same capacity of hydrogen storage and vessels.

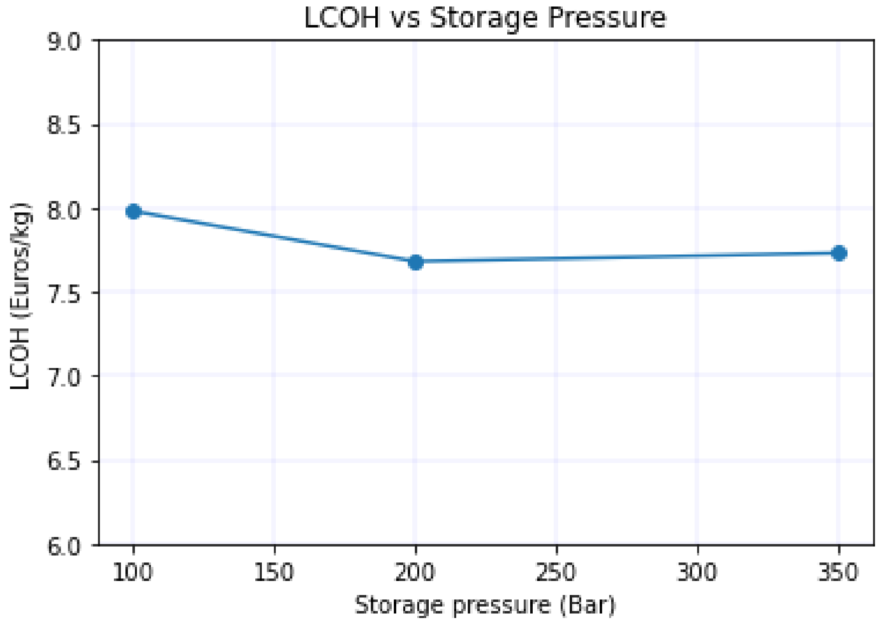

Figure 4.19: Impact of storage Pressure on LCOH

From Figure 4.19, it can be seen that the LCOH is the least at 200 bar pressure for the given set up. The cost breakdown at the studied pressure levels are shown in Table 4.8 This is due to the fact that by decreasing the storage pressure, initially the costs go down as storage and compressor size requirements reduce on the HPU. However it is seen that the cost is greater at 100 bar storage pressure, this can be attributed mainly to the increasing cost of compression on the vessel required at each vessel and to the increasing losses during transfer at lower pressure. It can be established that there exists a trade off between high pressure storage and higher power compressors on the ship. It is likely however that the latter will be selected owing to reduced dependency of compression at the HPU site.

These results indicate that further exploration is required to find the best strategy with regards to the right storage pressures which will balance the requirement of compression on both the HPU and the vessel. From now on 4 vessel and 200 bar storage of 25 tons is presented when discussing farm III results.

Storage Pressure(Bar)	LCOH(Euro/kg)	Loading losses (kg)	Wind farm net Compression cost(M\texteuro)	Storage Cost (M\texteuro)	Vessel fleet compression cost(M\texteuro)
350	7.73	566696	283.45735	1051.8396	516.383826
200	7.706	1073254	192.597697	986.51775	649.4781423
100	7.98	1805657	104.902285	942.30975	822.2710169

Table 4.8: Variation of HPU Parameters with Storage pressure

4.3.3. Impact of Weather conditions:

Farm type III depends largely on weather windows to load hydrogen periodically from HPUs. In this section the impact of weather on the farm is studied.

The cumulative distribution function of the significant wave height,Hs, for the year 2018 is shown in Figure 4.20. The vertical lines marked indicate the significant wave height, Hs, for which the availability to service a HPU in the farm varies from 50% to 95%.

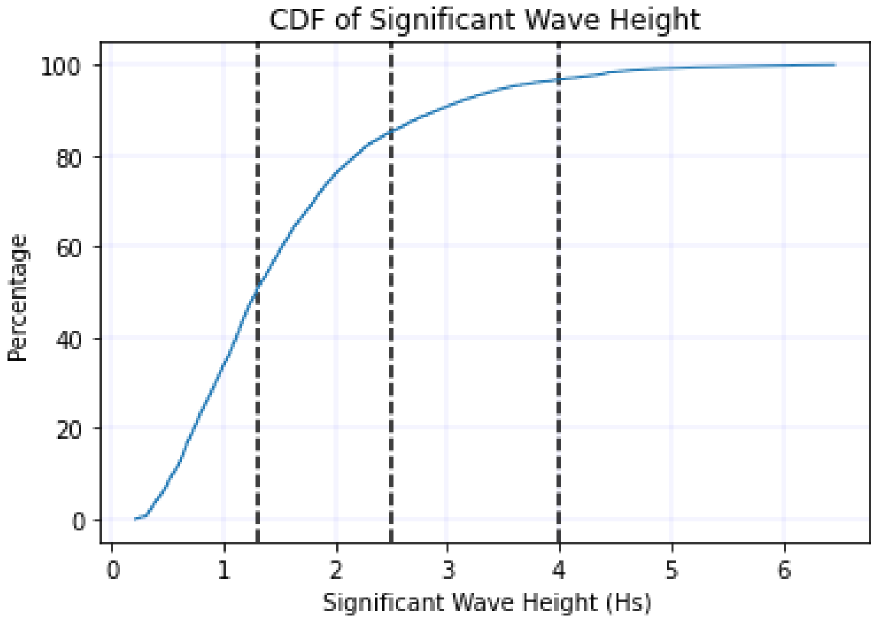

Figure 4.20: Cumulative Distribution Function of Significant Wave Height, Hs

The impact of availability is studied by changing the corresponding significant wave height, Hs, parameter in the model. The resultant LCOH curves are shown in Figure 4.21. It can be seen that at lower availability, the LCOH is greater at all storage capacities. This directly implies that lower availability leads to a reduced number of weather windows for loading and hence leads to an increased down time of the HPU leading to less transported hydrogen. This idea is also reinforced by Figure 4.22. It can be seen that at any given storage capacity the number of trips to shore reduces with decreasing availability. A close inspection of the LCOH curves with availability 80 and 90% indicate that as the storage increases the impact of weather is nullified. This can be explained by the coming together of the curves as storage increases in Figure 4.21 and also by the reduction in the difference of number of trips per storage capacity in Figure 4.22.

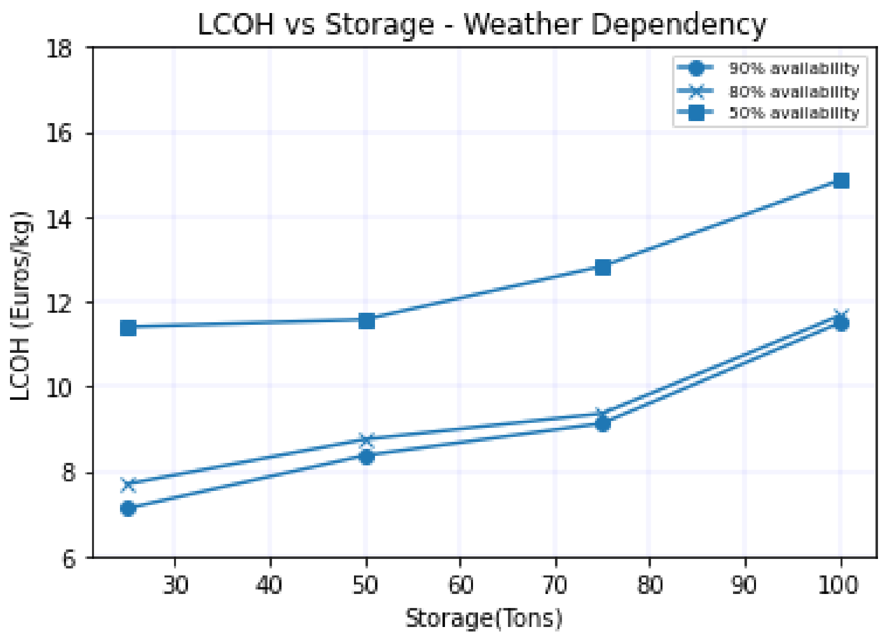

Figure 4.21: Variation of LCOH with Availability

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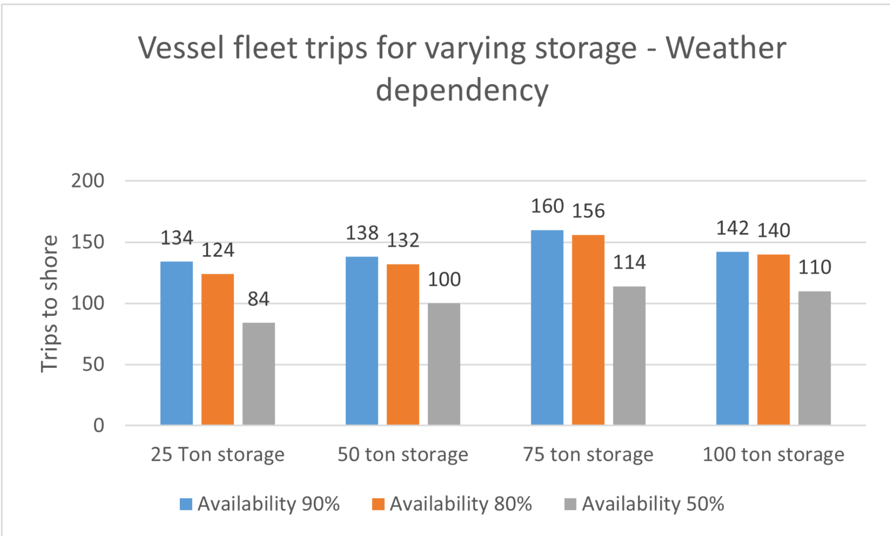

Figure 4.22: Distribution of number of trips due to varying weather availability

5 Discussion

The goal of the research was to find out the competitiveness of far offshore hydrogen storage and transport via vessels when compared to standard pipeline transport and transport via a large storage vessel. In addition, the impact of various system design choices made for different configurations has been examined. In particular the impact of distance has been studied with respect to each configuration type and the major cost contributing components of each farm type have been identified.
As an extension of the results chapter, this chapter discusses the outcomes of the case study. A comparison is made in the first section between the different wind farm configurations. Following this, the sensitivity of the three different wind farm types is studied with respect to the largest cost contributing components of the supply chain. Lastly in the hydrogen from wind farms section different aspects such as positive outcomes and potential pit falls of the wind farm types are discussed.

5.1. Overall wind farm configuration comparison

Three wind farm types have been studied. Each wind farm type is unique in its mode of supply of hydrogen. Farm type II and farm type III depend extensively on novel methods to transport hydrogen. They are both dependent on storage in vessel and at site, at high pressures. As such there is a heavy reliance on compression systems for the transfer of hydrogen gas from one storage to another. The effect of this is two fold : increasing compression requirements lead to higher costs and greater losses. The pipeline transport of hydrogen in wind farm type I operates at the lowest pressure rating when compared to vessel and site storage pressure levels in farm type II and III.

The optimal configuration of farm type III consisting of a fleet size of 4 vessels and localized hydrogen storage of 25 tons at 200 bar pressure is used for comparison with the results of farm type I and II. In Figure 5.1 a comparison is made between the LCOH curves of the three farm types obtained from the results section. It is clear that pipeline transport of hydrogen remains the cheapest mode of transport until the 680 km mark. At this point farm type II appears to be cost competitive with farm type I.

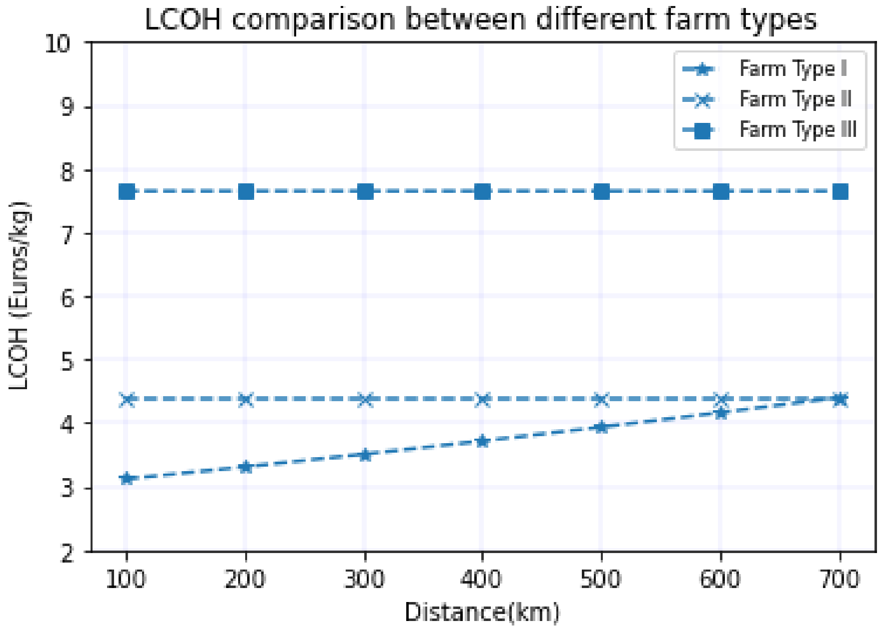

Figure 5.1: LCOH comprarison between different farm types

Farm type III, is the most expensive among the three farms studied and this is primarily due to high capital cost of storage and the additional cost of the vessel fleet. The operation of the vessel fleet is also an additional expense. The Capex breakdown of the different farm types is shown in Figure 5.2. It is clear that the overall capital expenses are higher for farm type III, which leads to a higher operational expense over the lifetime shown in Figure 5.3. The capital investment cost is lowest for farm type I, moderate for farm type II and highest for farm type III. The HPU costs form a substantial part of the capital expense in all farm types. In farm III however, the net capital expense of the components on a HPU platform increase due to the additional costs occurring from the storage and compression systems required.

The operational expense that occur in farm II and farm III are mainly due to the maintenance cost of the vessel fleet. As there is no maintenance cost accounted for the storage, the operational expenses of farm II and III are comparable but it is slightly greater for farm III due to the operation of more number of vessels. Farm I operation and maintenance costs are the least owing to the minimal maintenance costs of the pipeline system.

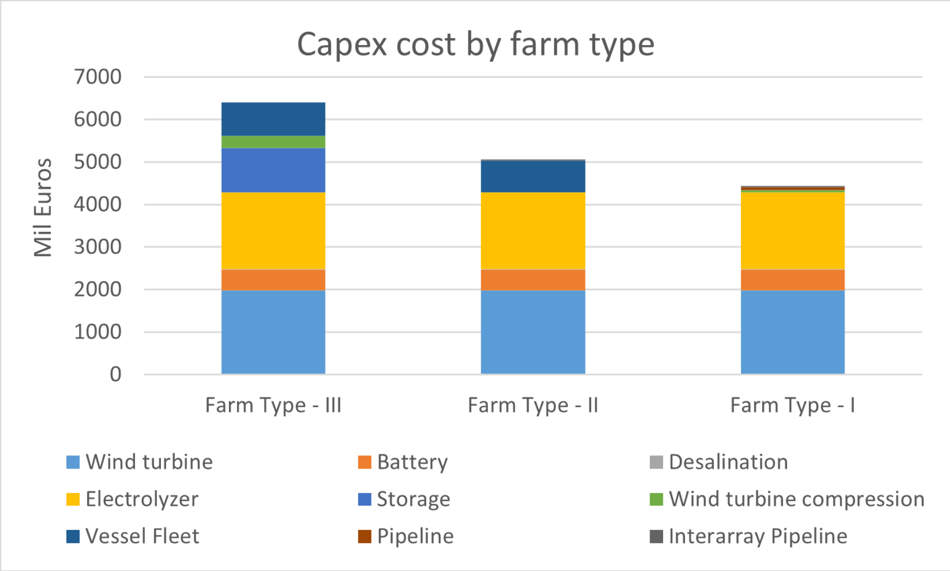

Figure 5.2: Capex breakdown of farm types - 100 km offshore

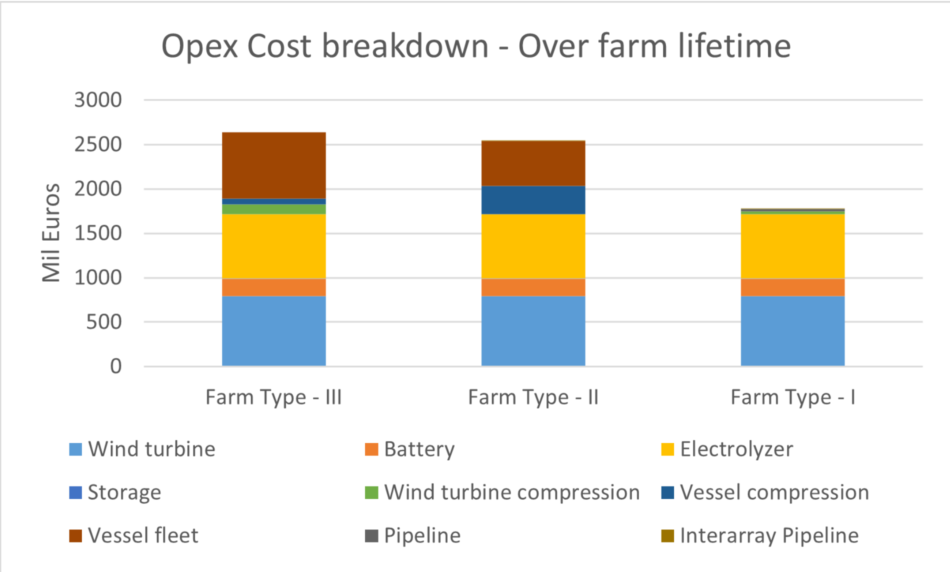

Figure 5.3: Opex breakdown of farm types - 100 km offshore

Another contributing factor to the cost curve trends seen in Figure 5.1 can be explained by the amount of hydrogen produced by each wind farm. The breakdown of hydrogen produced by farm type can be seen in Table 5.1.

Farm Type	Hydrogen Produced(Tons/year)	Percentage of Farm type I
Farm III	52948	75.8
Farm II	66000	94.4
Farm I	69860	-

Table 5.1: Breakdown of Hydrogen produced by farm type

The transportation mode in farm I has no dependency on weather conditions. In farm II, due to the introduction of vessels, the weather conditions impact the hydrogen produced. However, due to the superior docking ability of the assumed Single anchor loading system very few hours are lost due to vessel being unavailable for storage. The reduction in hydrogen produced occur primarily due to losses in compression when storing in the large vessel.
In farm type III, the hydrogen production is least. This is due to the fact that the HPU is shut down when the vessel is not present for loading, and, the compression losses that occur both at the platform for storage requirements and during loading. The vessel is also delayed further when poor weather conditions exist. As such farm type III show cases the highest sensitivity to weather conditions and has a high number of vessel operations that take place.
The hydrogen transported by farm type III and farm type II as a percentage of hydrogen transported by farm type I to shore, is 75% and 94% respectively.

5.2. Sensitivity study - Farm type I

A sensitivity study was performed on farm type I, by varying the pipeline costs by ±50%. The resulting cost curve is shown in Figure 5.4. Pipeline transport of hydrogen remains cost competitive until 600 km mark, beyond which farm type II is more favourable. The variation of pipeline costs doesn't influence the larger outcome wherein the pipeline transport remains the most favourable mode of transport of hydrogen from the farm to shore.
In addition the pipeline capex is a relatively small proportion of the capex of farm type I. As such the LCOH of via pipeline transportation shows a low sensitivity.

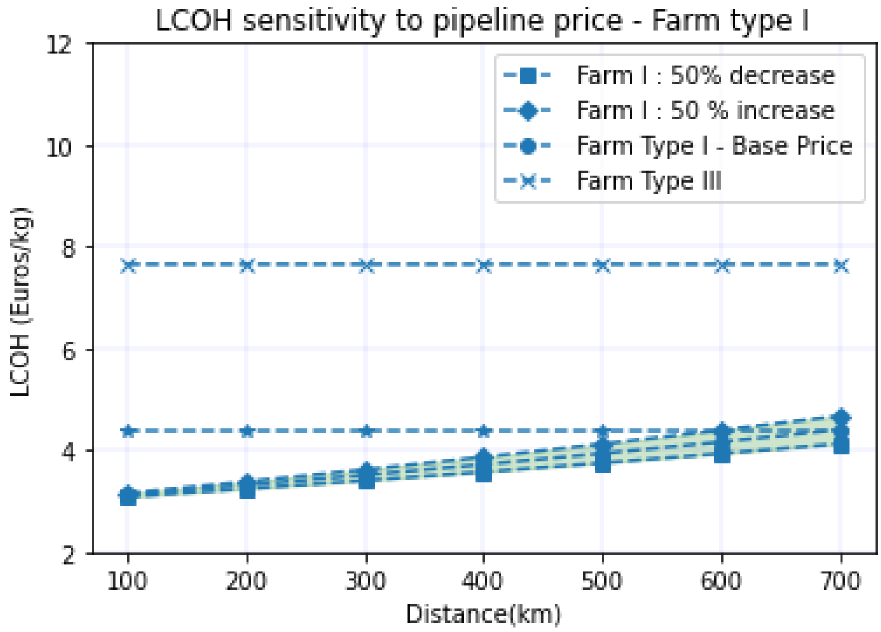

Figure 5.4: Senstivity Study Farm Type I

5.3. Sensitivity study - Farm type II

The capex of the large vessel required to transport hydrogen is the major cost contributor to the supply chain of farm type II. Earlier in the results section it has been established that there is no impact of the operational expenses of the vessel on the cost curve with increase in distance. The capex of the vessel was varied by ±50 % and the results are shown in Figure 5.5.
The decrease in capex of the vessel can be interpreted in two ways, one way of looking at the results suggests that a direct decrease in the cost of the vessel makes the farm type more competitive at lower distances.
A second and more intuitive manner of looking at the price sensitivity can be that, if the performance of the two vessel in tandem is replicated by the use of one vessel, or a fleet of smaller vessels for the same cost, the LCOH would reduce as shown by the 50% decrease line. Such a condition can happen with one vessel if the hydrogen that is being produced while the vessel is away may be stored in the inter array pipeline grid until the vessel returns to the farm following offload of the hydrogen at shore.
The vessel fleet cost forms a significant part of the capex of the transport method of farm II, however as it is not comparable to the total farm costs for wind turbines and electrolyzers the impact on the LCOH is limited. The farm however becomes cost competitive at 550-600 kms when a decrease in vessel costs is applied.

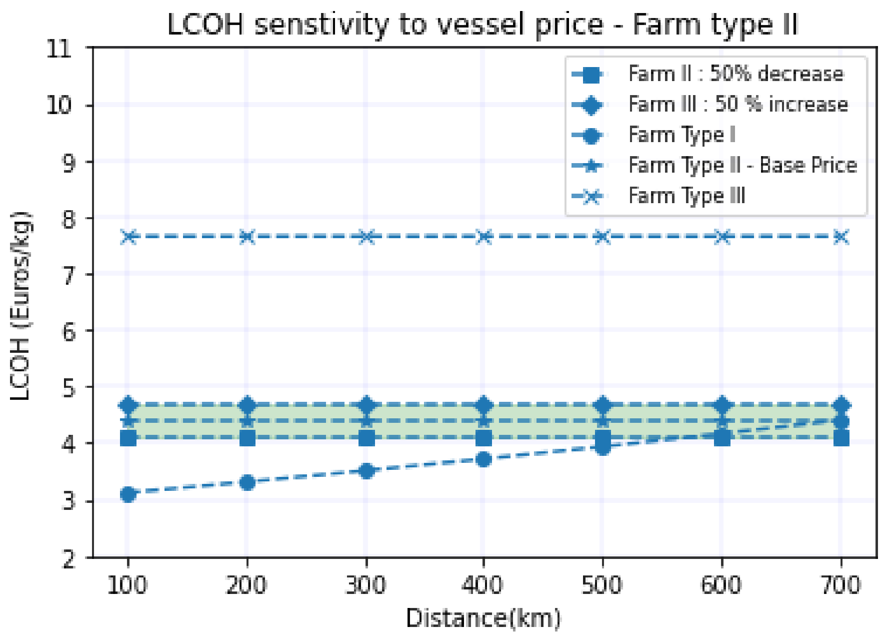

Figure 5.5: Senstivity Study Farm Type II

5.4. Sensitivity study - Farm type III

The supply chain of farm type III among other aspects includes the vessel fleet and the storage at site. Sensitivity to the price of storage and vessels has been studied in the sections ahead.

5.4.1. Senstivity to storage cost

In Figure 5.6 the variation of the cost curve with a $\pm$50 % change in capex of storage is plotted. Again, the resultant plot of farm type III can be viewed in two ways. One, the variation in price of storage leads to a change in the cost per kilogram of hydrogen produced.
Two, if the same amount of hydrogen can transported by vessels with half the storage of 25 tons, that is 12.5 tons, the LCOH would be depicted by the line marking a 50% decrease in storage costs. This can occur if the number of vessels in the fleet can be increased, for the same cost price of the current vessel fleet of the size of 4 vessels. The vessel size can be reduced as long as frequent loading can be done when required at the turbine.

An over arching conclusion still remains that a direct reduction in storage costs is not enough to make farm type III cost competitive with other types studied.

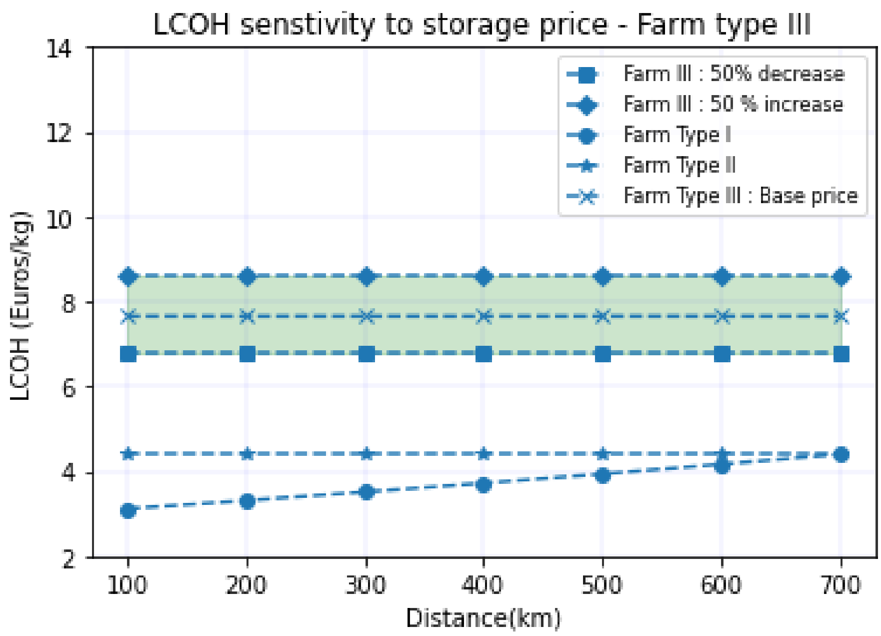

Figure 5.6: Senstivity Study Farm Type III - Storage

5.4.2. Sensitivity to vessel fleet cost

The variation in cost due to a $\pm$ 50% price sensitivity of the 4 vessel fleet is plotted in Figure 5.7. It can be seen that the variation of prices impacts the outcome similar to the storage prices, by shifting the LCOH curve about the horizontal. However, the impact is smaller due to the low percentage of capital expense due to the vessel fleet.
From the plot it may be reasoned that, if three vessels at the same fleet cost could perform similarly as the four vessel fleet . This would require a further improvement of the vessel functioning such as a greater speed of loading, higher work ability during rough weather conditions.
Lastly, due to the low contribution of the vessel fleet to the overall capex, the difference in prices, do not make farm type III competitive to farm I and II.

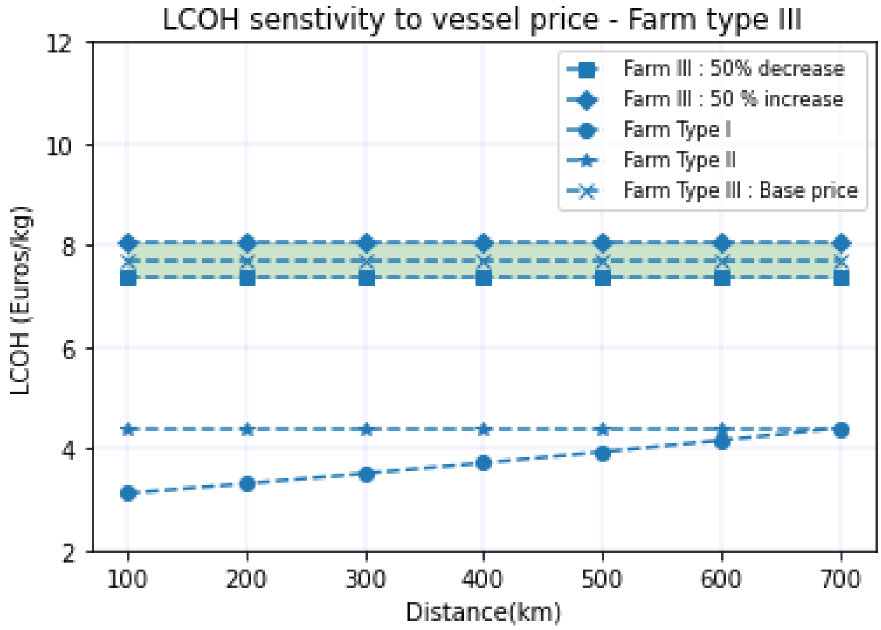

Figure 5.7: Senstivity Study Farm Type III - Vessel

5.5. Hydrogen from wind farms

This study has focused on wind farms for hydrogen production with localized in-turbine hydrogen production. In-turbine hydrogen production has its own challenges, as it has two systems operating on the floating support platform, namely the wind turbine power generation system and the hydrogen production system. A combination of such systems will require additional maintenance at individual unit level when compared to centralised offshore electrolysis platforms. However, in-turbine hydrogen production when compared to central electrolysis, does not require a separate additional platform. It also reduces the dependency of hydrogen production on one platform, and, as a result it is a more flexible topology. Three different farm types have been studied. These farm types can be differentiated based on the supply chain used to transport hydrogen to shore.

Looking into the farm types, with regard to their flexibility to the markets where hydrogen can be transported, pipeline transport of hydrogen provides flexibility when the pipeline connecting the wind farm to shore is part of an existing broader sub-sea pipeline network. The hydrogen can then be transported through this network of pipelines to different markets. In comparison both farm type II and farm type III provide a much higher flexibility by virtue of the increased reach of the vessel. The vessels used in both farm II and III can be used to ship hydrogen to ports that are capable of handling the hydrogen cargo.
Among the three farm types, farm I has the highest level of asset dependency, as the entire farm production is dependent on the the pipeline connecting the farm to shore. Farm II has a lowered dependency based on the fleet size and the health of the vessels used. Lastly, asset dependency in farm III is the least and the dependency is spread across the vessel fleet and wind farm.
The operational requirement of farm types is inversely related to the level of dependency on assets. In farm III localized storage increases regular vessel operations, in comparison farm II by virtue of the larger storage capacity has less frequent vessel movement and operations followed by pipeline transport where there are no operational requirements for pipeline transport.

According to [78] hydrogen storage is possible in pipelines, this opens up the possibility for farm type I and II to store hydrogen in the inter farm array and also in the main pipeline for farm I when the demand for hydrogen in the market drops. In addition the possibility to store hydrogen in the inter array grid positively affects the business case of farm II. Pipeline storage may reduce the size of the secondary vessel required or even remove the requirement of the secondary vessel if adequate storage can be

provided by the pipeline when the main vessel is offloading.
It must also be noted that the operation and maintenance of the HPU units increase with the complexity of the the HPU. The larger compression requirement and storage at high pressures in farm III will also add to the costs of auxiliary components such as piping systems and valves. At higher pressure auxiliary components are also likely to be more expensive.
Lastly, the selection of farm type for dedicated in-turbine hydrogen production leans towards the pipeline type from cost perspective. However, the time required to build pipelines and the ease of commissioning of such farms may also play an important role from a developers perspective.

6
Short comings and recommendation

To perform this study assumptions have been made both at system and component level. The novel nature of farm II and III, have led to assumptions made in the techno-economic aspects of hydrogen carrier vessels. The idea of the vessel structure and design is taken from [77] but there is no information on the cost of such vessels. While the assumptions made regarding the cost of oil and gas tankers helps to view the feasibility of the farms, it is not an accurate cost representation which may negatively affect the performance of such farms.
A fixed vessel size has been applied to the study. It is however possible that the vessel sizes can be made smaller and fleet size may be increased if it is cost effective. Therefore thorough search can be performed for optimal vessel size and the optimal storage required on site.
The semi-submersible floating platform has been selected as the support structure of choice, however different support structure options may be considered when there is no requirement for on-site storage. This may in turn reduce the costs incurred by farm I and farm II for a rather large support structure design.

Furthermore, with respect to the vessel operational strategy in farm III, the vessel fleet is operated in a first come fist serve basis. The model used assumes vessel work-ability during both day and night, night time work ability of vessels may or may not be possible and further research is required to assess the limits of the same. Weather forecasting techniques can be applied to improve the performance of a vessel fleet when rough weather windows are known before hand.
To the reader it is clear that the wind farm wake effects have not been accounted for. This is done to maintain uniformity between the three wind farm types. While the wind farm effects may be aggregated for farm I and farm II as farm level losses, the wake losses may affect the system operation in farm III in a more critical manner. This is because in farm III, the hydrogen production may vary due to the wake effect leading to varied fill rates which can have implications on the vessel fleet operation.

Next, the search for optimal storage pressure in farm III is based on a comparison between three different storage pressure values. In reality, different approaches can be taken towards the loading process, such as cascading pressure flow. A more elaborate study needs to be performed in this arena to minimize the losses arising during compression, and make sure that the hydrogen transfer happens purely due to free flow. Operational strategies to use the back up compressor at the HPU for loading may be examined. This can reduce the requirement for large compression systems on the vessel.

The sensitivity of the farm types with respect to improvements in the technical operation of components must be further studied. As an example, according to [30] the output pressure of PEM electrolyzer are likely to be upto 60 bar. This could reduce compression requirements for all farm types and hence lower compression losses. Further research at component level is also required to make the model more realistic and the results more accurate.

7 Conclusion

The aim of the study was to study the techno economic feasibility of hydrogen storage and transport from far offshore wind farms via hydrogen vessels. In addition to localized hydrogen storage on the platform and transport via vessels, two other farm types were studied with respect to their transportation methods - hydrogen transport via pipelines and hydrogen transport via a large vessel coupled to the entire wind farm. The results were condensed into the levelized cost of hydrogen(LCOH) for varying distances between farm and shore. LCOH was used as a metric to compare and contrast the performance of each wind farm.

The component breakdown for hydrogen production in each farm type remains similar. However, compression and storage requirements are dependent on the transport option of the wind farm. The storage requirement is obvious for the farm with on site hydrogen storage and there is no requirement for pipelines in this type. Farms with pipeline transport to shore and the farm connected to the wind farm by large vessel both require an inter array grid. The large vessel transport option further requires a single point mooring system such as a single anchor loading (SAL) system for connection the entire wind farm. Next, the compression requirement at site vary for each farm type, if pipelines are used to transport hydrogen, compression is required to maintain pressure in the pipeline. With increasing distance from shore re-compression systems are required to further maintain the pipeline pressure. In the farm with large vessel connection, a compressor is required to compress the hydrogen gas to higher pressures such that it can be store in the vessel. In farms with localized storage and vessel operation, the compressor is required to compress hydrogen for storage as well as for the mass transfer of gas during loading into the vessel.

The distance from shore of the wind farm had no significant effects on the LCOH for farms which used vessels for transport of hydrogen when compared to the farm using pipelines for hydrogen transport. In farms with pipeline transport, the cost of re-compression systems to compensate pipeline pressure loss and the cost of the pipeline itself cause a linear rise in cost of hydrogen production as distance increases. Whereas for farms with vessels, the cost increase is negligible as distance increases. This is because the operational expense of the fleets form a negligible portion of the total costs of the farm over its lifetime.

Pipeline transport appears to be the cheapest transport option, however, at a little below the 600km mark the large vessels used for transport appear to be a more cost effective solution. This range at which large vessels become more cost effective than pipelines depends both on the pipeline costs and the cost of the large vessel fleet. The farm type with localized storage is the most expensive farm set up over the range of distances studied. It showcases a high sensitivity to storage prices due to the requirement of storage at each wind turbine platform. Reduced storage and vessel fleet prices improve the business case of such a farm. However, even a combined effect of the price reduction of these two components is unlikely to make such farms competitive with the pipeline hydrogen transport type.
With respect to farms with localized hydrogen storage, there is a high level of dependency on weather conditions. This is because of the periodic docking requirements of the vessel on the floating wind

platform. Poor weather conditions give rise to higher shutdown hours of the wind turbine and hydrogen production unit. This is due to the fact that if the storage is full, production will need to be stopped. In addition to this, there is a two fold requirement of compression, one for storage and second for transfer of the hydrogen from storage to vessels. Smaller storage options in the temporal range of one week have performed well with respect to the LCOH. This is because of the cheaper cost of storage. It is also seen that this storage size causes a large downtime of the hydrogen producing unit owing to more frequent vessel operations. Hydrogen production increases with an increase in storage size due to the decrease in the hydrogen production unit downtime, due to reduced docking requirements, which, reduce the impact of weather conditions. However, a trade off will likely occur when the storage becomes large enough to delay subsequent loading operations. However, such large storage is unlikely due to the high costs of storage modules.

The amount of hydrogen transported by the optimal configuration in this case study is about a quarter less than that of the amount transported via pipelines. Farms with hydrogen transport via a large vessel perform slightly better with almost 95% of hydrogen produced when compared to the amount of hydrogen produced by pipelines. However, the losses and the cost of the ship and compression systems outweigh the transportation link costs in farms with pipelines. Hence, transport via pipelines is still likely to be the most preferred option when there exist no hurdles to pipeline laying in the selected site.

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A

Loading Process

The working of the loading process set up is further detailed here with an exemplary set up and its conditions.
Goal of the model :

1 - Calculate the amount of time mass transfer is possible by free flow.

2 - Calculate the equalization pressure.

A.1. Set up

:
The hydrogen flow through pipes is a compressible fluid flow. The pressure difference causes the flow. This pressure difference also varies dynamically over time in both the tanks, platform storage is initially at 250 Bar and vessel storage is at 1 bar initially. The two tanks are assumed to be identical. Equalization pressure can be found through Ideal gas Law, PV = NRT. To find mass flow rate and time to reach equalization pressure, ideal gas laws in combination with compressed gas flow through a pipe are numerically solved over time. Isothermal condition gas mass flows are lower than adiabatic condition gas mass flows and hence this condition is selected for steady state mass flow approximation. In reality for mass flow control valves will be required to maintain the required mass flow at each instant of time.

A.1.1. Conditions to be satisfied

:

1 - Mass flow rate can not exceed the choked flow rate at any given instant. This condition is maintained by limiting the velocity of gas through the pipe to 30 m/s.

A.2. Model steps

Step 1 - Calculations for compressed gas flow through pipe :

1- Calculate mass flow at the instant of time for given Pressures in storage and vessel.

Step 2 - Update Steady Calculations for each interval of time :

2 - Mass flow rate for ith instant of time determines the steady state conditions of the next iteration, that is the new pressure in storage and vessel.

3 - The maximum mass flow rate is the admissible mass flow rate at 30 m/s gas velocity, if the natural pressure mass flow is greater than the required mass flow it is set to the required mass flow.

4 - The maximum mass flow at an instant of time is given by : Q(kg/sec) = Specific density(i) * Area * 30.

5 - Pressure in Tank A(storage tank) and B(vessel tank), are calculated based on the number of moles exiting Tank A and number of Moles entering Tank B. New pressure in Tank A and B are updated for next iteration.

Step 3 : Process simulation while Pressure in tank A > Pressure in tank B:

1 - Numerically solve for equalization pressure.

2 - Calculate the number of moles in tank A at convergence, the number of iterations gives the time taken.

A.2.1. Model demonstration

Figure A.1 and Figure A.2, show the difference in time when the mass flow rate is fixed to a lower amount than possible. It can be seen that when mass flow happens at maximum velocity the pressure equalization happens at the earliest, and when the mass flow is further controlled to a fixed value which is lower than what is possible the time taken for normalization is higher.
Laslty, the normalization pressure for two indentical 250 bar storage units is roughly 125 bar and is shown in Figure A.3.

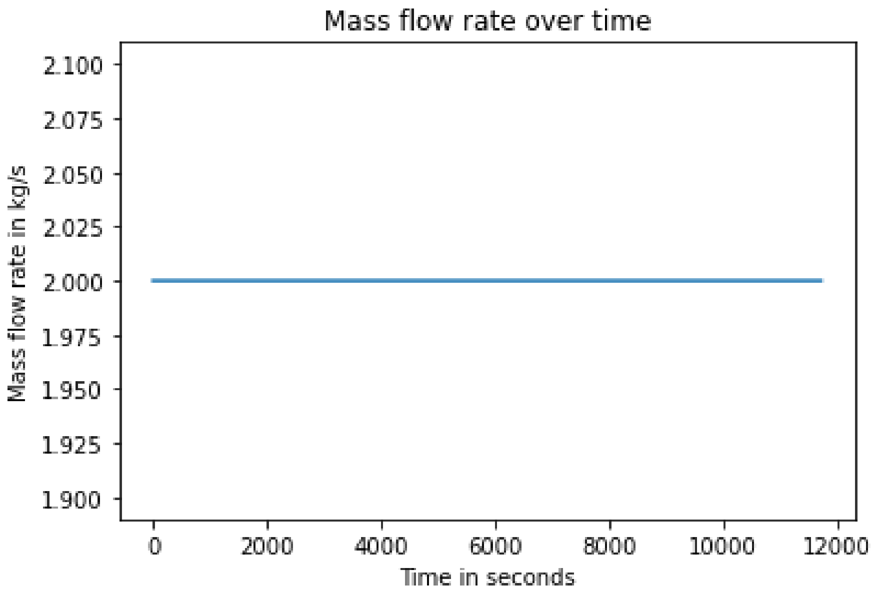

Figure A.1: Mass flow rate set at 2 kg/s

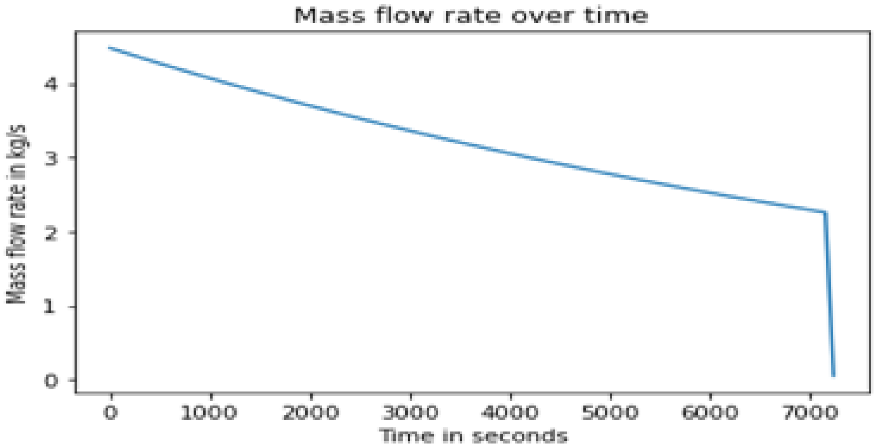

Figure A.2: Mass flow rate at maximum velocity of 30 m/s

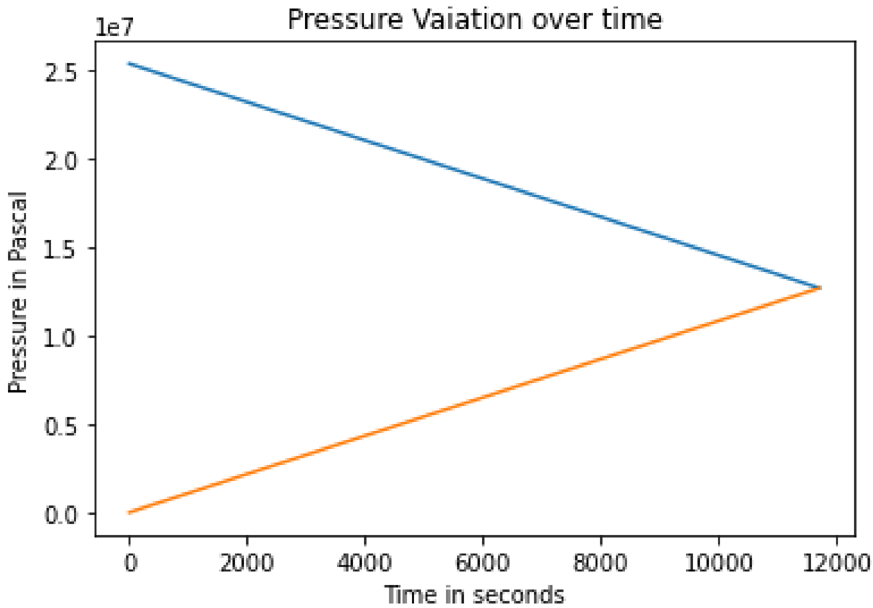

Figure A.3: Pressure equalization curve