Cornwall FLOW Accelerator

UNIVERSITY OF EXETER

Low carbon vessel and energy vector analysis: Integration of floating offshore wind

Document Title		Low carbon vessel and energy vector analysis: Integration of floating offshore wind	
Document Reference			
Date of Issue		30/09/2022	
Author		Chen, Barton	
Revision History	**Date**	**Amended by**	**Reviewed By**
First Draft			
Second Draft			
First Issue	30/09/2022		Dr Mi Tian, Dr Kanchan Joshi, Jiaxin Chen Justin Olosunde
Approved	30/09/2022		Prof Lars Johanning
Rev 1			
Rev 2			
Rev 3			
Rev 4			

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Executive summary

This report has investigated energy vectors and low-carbon vessel options in relation to floating offshore wind systems. The energy vectors that can be produced by the floating offshore wind farms were reviewed, and their use to decarbonise the shipping sector was discussed. An assessment framework developed by the University of Exeter team was introduced to tackle the research challenge within floating offshore wind farms for integrating different energy vectors and low-carbon vessel solutions. The capability of the framework was first demonstrated in the analysis of a 500 MW example wind farm. The framework was then used to provide a preliminary analysis of the integration of floating offshore wind with energy vectors and low-carbon vessels. Detailed technical parameters and site-specific data are required to carry out a comprehensive assessment.

1 Introduction

Cornwall FLOW Accelerator (CFA) is a collaboration project with research institutes and industry partners aiming to accelerate the development of the floating offshore wind industry in Cornwall by providing cooperation and consultation to the stakeholders. The University of Exeter is one of the project partners in the CFA project. One of the tasks for the University of Exeter is developing the E^c simulator that can evaluate floating offshore wind farm's key performance indicators (i.e., levelised cost of energy, carbon emissions, and energy return on energy invested) by simulating the processes in the lifetime of the system, such as installation and operations and maintenance (O&M) activities.

The simulator consists of various modules that evaluate the design or simulate the operation of floating offshore wind systems, e.g., wind farm design module, installation module, operational and maintenance module, and energy system integration module. By integrating these modules within a holistic simulation and assessment framework, the outcome produced from the simulator can provide evidence to the stakeholders in the decision-making process during the development of the floating offshore wind industry.

The aim of this report is to provide an overview of energy vector analysis and low-carbon vessel technologies, and how they can be integrated with the floating offshore wind system. Nevertheless, a floating offshore wind assessment framework (a part of the E^c simulator) is introduced to investigate the impact of integrating wind farms with low-carbon vessels and energy vector options.

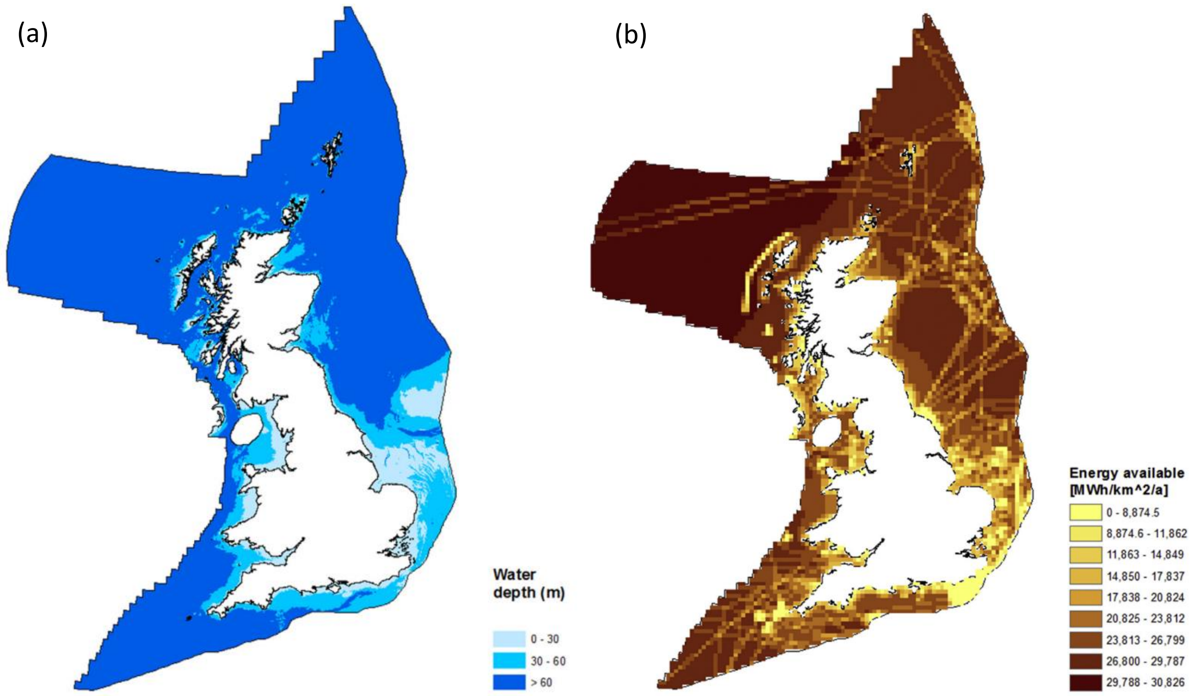


Figure 1.1 – (a) water depth and (b) energy available in UK renewable energy zone (Cavazzi & Dutton, 2016)

1.1 Floating offshore wind in the future's energy system

Wind power is one of the key low-carbon energy sources to decarbonise the UK's energy system. In National Grid's Future Energy Scenarios (National Grid ESO, 2022), 40-55% of the UK's primary energy sources come from wind power in 2050 net-zero scenarios. How to integrate large amounts of intermittent wind power into the energy system is one of the key aspects to be considered while decarbonising the energy system. In an electricity generation system that has a high share of wind power, whether it is windy or not has a significant impact on the energy system.

The development of floating offshore wind technologies is the key to increasing the utilisation of wind power. Most of the wind resources in the world are in deep water regions which fixed structures are unlikely to be cost-effective (Cavazzi & Dutton, 2016). In the UK, about 75% of available offshore wind resources are located at the water with a depth over 60 metres (see Figure 1.1). For some regions in the UK (e.g. South West), bottom-fixed offshore wind technologies are not an option and the development of floating offshore wind is necessary (Regen, 2022).

1.2 Grid integration of floating offshore wind farms

Floating offshore wind technologies enable the utilisation of wind power that is located far away from the shoreline. Although some of the components in the FOW system (e.g. floating platform and mooring system) have been used in other fields such as the oil and gas industry, the operational and environmental conditions in FOW are different and therefore those components need to be redesigned and tested. Besides developing the FOW technology, how to integrate the gigawatts-scale of intermittency power into the energy system is the challenge to be addressed (Energy System Catapult, 2020). This involves many factors, such as environmental conditions and constraints for transmission systems, the distance to the grid connection points, the capacity and extensibility of the grid, and the energy demand in the regional/national energy systems.

To bring offshore wind power to the shoreline effectively, various system configurations have been investigated or proposed (Franco et al., 2021). Each pathway may be suitable for certain applications with its limitations and challenges. Selecting the suitable system configuration not only affects the overall cost and efficiency of the system, but also what form of energy is produced and how it is integrated with the energy system.

Transferring electricity via submarine high voltage alternating current (HVAC) electrical cables is the most common way to bring offshore wind power to the shoreline. However, the capital cost of offshore export cables is not cheap due to the requirement of specific vessels for installation and the long distance to the electrical grid. A study (NREL, 2022) showed that electrical infrastructure (e.g., array cables, export cables, substation) accounted for 6.0% of the levelised cost of energy (LCOE) of onshore wind farms. This figure increases to 11.7% for bottom-fixed offshore wind farms. A high voltage direct current (HVDC) system is another type of electrical transmission system. It is more cost-effective than HVAC when the transmission distance is over hundreds of kilometres (Kalair et al., 2016).

Transferring compressed hydrogen via submarine pipelines is a merging alternative to bring offshore wind power to the energy system. The cost of offshore pipelines can be lower than offshore electrical cables at large power and long distances, and the cost can be further reduced if existing oil and gas pipelines are used (ORE Catapult, 2020). Moreover, hydrogen is easier to be stored in a large scale compared to other electrical energy storage technologies such as lithium-ion batteries. An underground salt cavern can store gigawatts-hours of energy with a comparatively very low storage cost (Caglayan et al., 2020). Large-scale hydrogen storage can be used to balance the mismatch between energy supply and demand, and therefore enable more wind power to be integrated into the energy system. The limitations of using hydrogen are high energy loss during conversion and significant infrastructure changes required.

Other pathways (e.g. liquid hydrogen or ammonia with carrier vessels) were investigated in several studies (Franco et al., 2021). These pathways have the potential for long-distance transport (e.g. over thousands of kilometres) but are still in the early stages of development.

1.3 Offshore wind power and sector coupling

The transition to a net-zero energy system needs transformation in all sectors such as electricity, heating, and transport. To decarbonise the whole energy system effectively, not just electricity generation but all energy vectors should be considered.

Wind power not only can be used to generate electricity but also other energy vectors such as hydrogen if additional components are incorporated into the system. This creates the opportunity to use wind power to decarbonise multiple sectors with a lower cost and energy loss. Currently, wind power is mainly used to produce electricity because of its competitive cost in the power sector. However, to achieve the net-zero target, decarbonising other sectors (e.g., heating and transport) need to be considered in designing energy generation systems, especially for wind power systems which can produce a large amount of power in a single wind farm. In an energy system that already has a high share of low-carbon electricity generation, converting wind power into other forms could accelerate the decarbonisation of the whole energy system.

Integrating regional renewable energy sources to decarbonise multiple sectors can be achieved by developing sector coupling energy hubs. Milford Haven: Energy Kingdom project explores how to decarbonise a local energy system by integrating renewable energy and sector coupling via hydrogen production (Energy System Catapult, 2021). Offshore wind power is one of the energy sources that can be used to decarbonise various sectors. For example, hydrogen fuel cell vehicles and a hybrid heating system are demonstrated through the project.

The development of offshore wind power creates the opportunity to decarbonise the maritime sector through sector coupling. Offshore wind farms not only produce large amounts of energy but also require maritime vessels for installation and O&M activities. Using offshore wind energy to power the vessels at the wind farm or nearby ports could reduce the cost and energy loss in energy transmission. This can reduce the cost and energy loss to bring offshore power to the shore. Offshore wind power has been investigated to decarbonise the maritime sector. In 2021, five UK projects are funded to investigate the technologies to decarbonise shipping with offshore wind power (Adrijana Buljan, 2021). Those projects enable wind farm support vessels to be charged at the offshore site.

2 Energy vectors and offshore wind farm

2.1 Overview of energy vector

Different definitions of 'energy vector' can be found in the literature. It can be an "energy-rich substance that facilitates the translocation and/or storage of energy" (Abdin et al., 2020), or "an energy vector allows to transfer, in space and time, a quantity of energy" (ORECCHINI, 2006). From the energy system's point of view, energy vectors are the links between primary energy sources and energy end uses. Today's energy systems are highly dependent on fossil fuels as energy vectors. To achieve the net-zero target, fossil fuels need to be replaced by low-carbon energy sources, and therefore future energy systems will be built upon new energy vectors.

Fossil fuels are the main energy sources in today's energy system, especially for the heating and transport sectors. Figure 2.1 showed the UK's energy flow in 2020. Primary energy sources (i.e. natural gas, electricity, bioresource and other fuels) are transferred and/or converted to other forms that can be used in different sectors (i.e., industrial & commercial, residential, road and rail transport, electricity export). Although more than half of the electricity comes from low-carbon energy sources such as renewable energy and nuclear, near 80% of primary energy sources still come from fossil fuels.

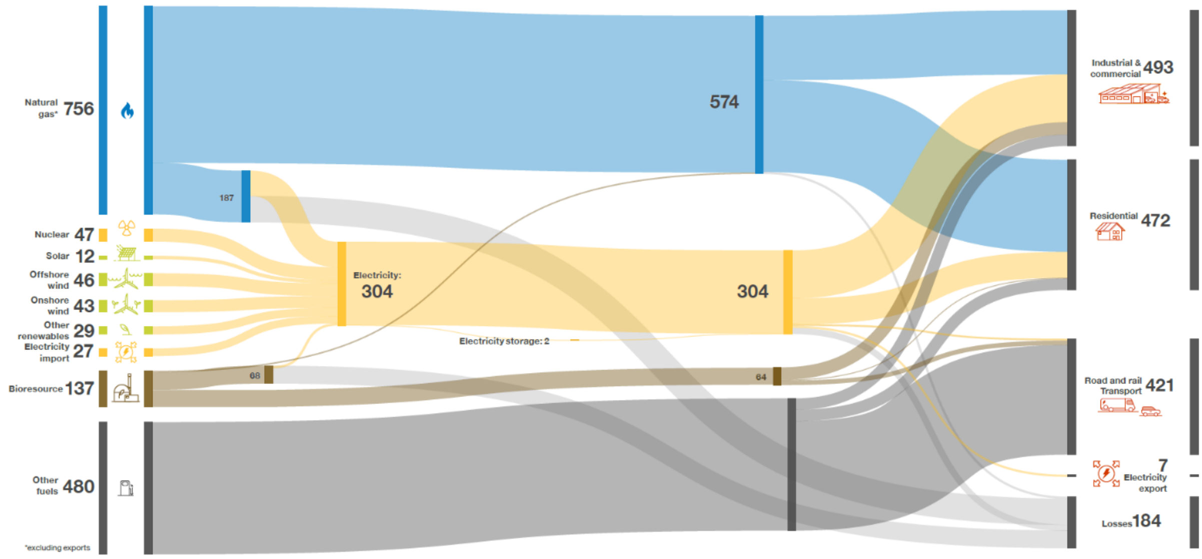


Figure 2.1 – UK's energy flow in 2020 (National Grid ESO, 2021)

The energy vectors in a net-zero energy system will be very different from what is in today's energy system. In National Grid ESO's report (National Grid ESO, 2022), electricity and hydrogen are two key energy vectors in the 2050 net-zero scenarios. About 57-84% of primary energy is produced in the form of electricity and about 10-35% is hydrogen.

Floating offshore wind systems can convert wind power into different forms of energy, such as electricity and hydrogen. Various system configurations with different conversion components and transmission systems have been proposed and studied for different environmental conditions or scenarios. In this report, several common configurations are introduced in the following subsections.

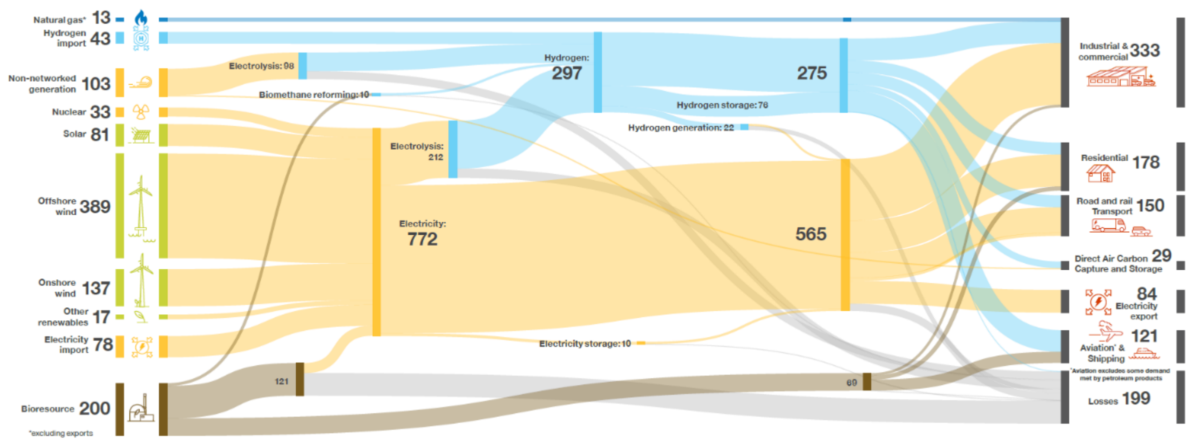


Figure 2.2 – 2050 future energy scenario – leading the way (National Grid ESO, 2021)

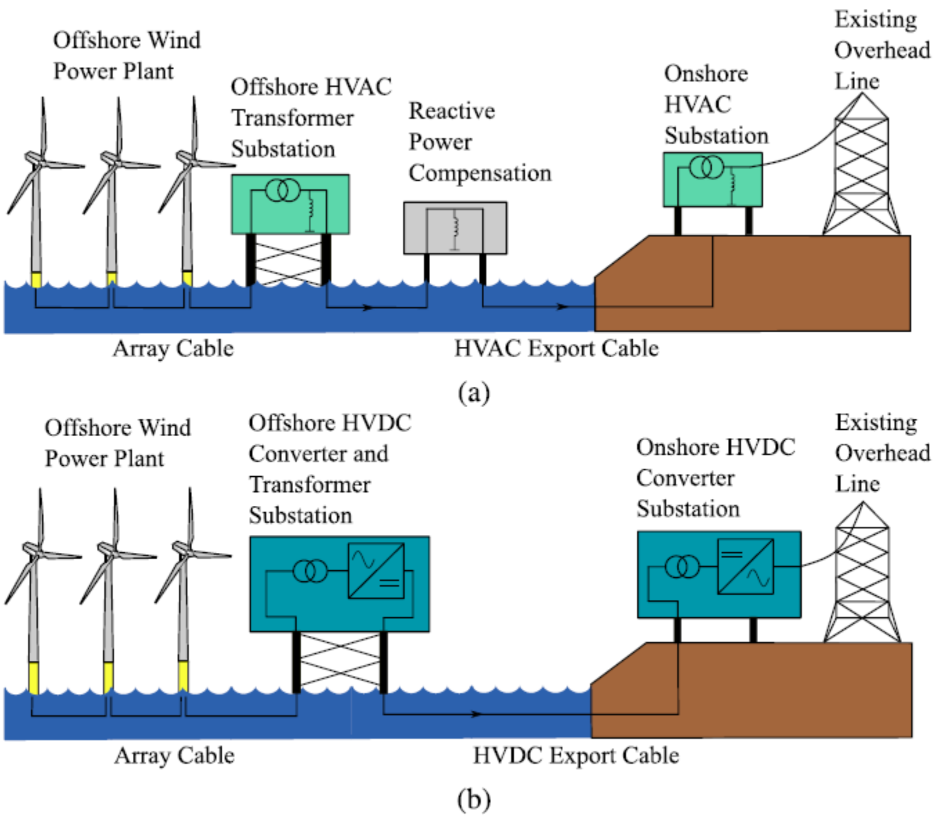


Figure 2.3 – Schematic of (a) HVAC with reactive power compensation and (b) HVDC transmission system (Dakic et al., 2021)

2.1.1 Electricity

Electricity has been widely used in today's energy system and it can be converted into different forms of energy easily, such as mechanical power via electric motors and thermal energy via electric heaters or heat pumps. Electricity is expected to be the major energy vector due to its comparatively low energy cost to be produced from renewable energy and comparatively low energy loss from generation to end use. However, if the electricity is generated at the undesired time, it is not easy to be stored and therefore is normally converted into another form of energy for storage, such as electrochemical energy (e.g., battery), mechanical energy (e.g., pump hydro), chemical energy (e.g., synthetic fuels).

Today, most offshore wind turbines are producing electricity that supplies to the electrical grid via transmission systems. For small-scale wind farms, the electricity produced from the wind turbines could connect to the grid without voltage change (e.g. 33 kV). For large-scale wind farms especially with a long distance to the grid, a high voltage alternative current (HVAC) system that operates at a higher voltage (e.g. over 132 kV) can be used to reduce the energy loss in transmission by running at a lower current (see Figure 2.3a). The capital cost of the HVAC transmission system is higher than the system without the rise of voltage, due to additional equipment such as substations being required to step up/down the voltage. But the levelised cost of energy of the system could be lower due to the increase in energy production.

The energy loss during transmission could be further reduced by using high voltage direct current (HVDC) system (see Figure 2.3b). Compared to the HVAC system, HVDC systems has converters to convert between alternating current (AC) and direct current (DC), and therefore the cost for the substation is higher. However, the overall energy cost for HVDC could be lower when the transmission distance is over hundreds of kilometres (Dakic et al., 2021; Kalair et al., 2016). Figure 2.4 shows the total cost and energy cost of wind farms with different transmission distances in three-dimension diagrams. The line of intersection (red line in the figures) indicates the energy costs of HVAC and HVDC are equal. When the distance is higher than the line, the HVDC system has a lower energy cost than HVAC system.

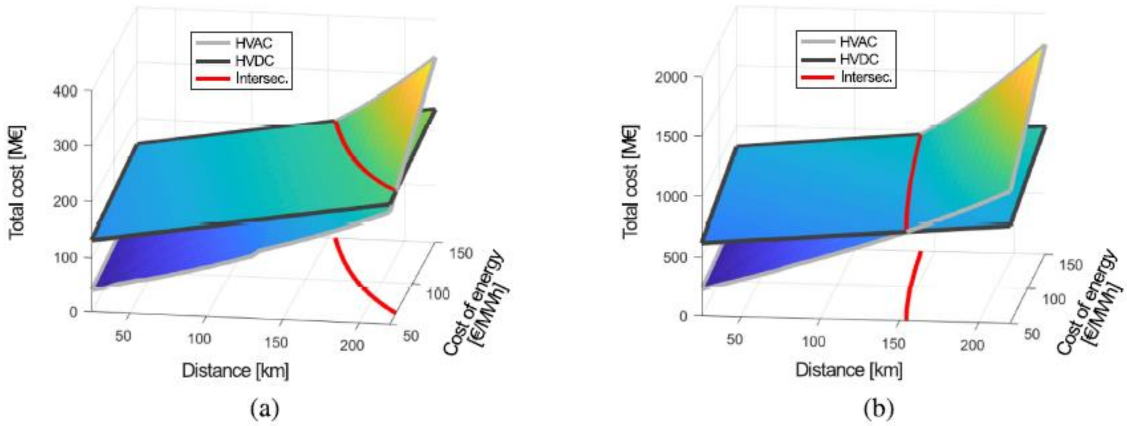


Figure 2.4 – Sensitivity analysis of HVAC and HVDC transmission systems on total cost, distance, and cost of energy at (a) 100 MW wind farm and (b) 1000 MW wind farm (Dakic et al., 2021)

2.1.2 Hydrogen

Hydrogen is expected to be the new energy vector in the energy system with a high share of renewable energy. Hydrogen can be produced from electricity through electrolysis, or from natural gas via steam reforming. It can be used in multiple applications, such as fuels for transport, heating, and electricity generation. Compared to fossil fuels, hydrogen has a low energy density and therefore requires a large space to store the same amount of energy. However, hydrogen can be stored underground in terawatt-hours scales and the system cost can be much cheaper than other electrical energy storage technologies such as lithium-ion batteries and pump hydro (ERA, 2022). Using hydrogen as an energy vector has several drawbacks and limitations, such as hydrogen production and storage consume significant amounts of energy; existing facilities (e.g. gas pipelines) and equipment (e.g. gas boilers) require modification to use hydrogen.

In an offshore wind farm, hydrogen can be produced by the electricity generated from wind power through water electrolysis. Purified water can be obtained from seawater desalination, and the produced hydrogen can be transferred to the users via pipelines or carrier vessels. AC/DC converters are needed to convert AC power (generated from wind turbines) to DC that powers electrolysers. Hydrogen compressors are needed to raise the pressure to the operation pressure (e.g. 60 bar) of hydrogen transmission systems.

For a gigawatt-scale offshore wind system, the capital cost of hydrogen transmission system could be lower than the cost of electrical transmission systems (ORE Catapult, 2020). It is because a single hydrogen pipeline can transfer a large amount of hydrogen. For example, the energy can be transported in a large hydrogen pipeline (e.g. 100 cm in diameter) is higher than the energy can be transported by a 2 GW electrical cables. The typical power capacity of a high voltage cable is around 500 MW.

Based on where the hydrogen production system is located and the technology for hydrogen transmission, the wind power system that produces hydrogen can be classified into three configurations:

- onshore hydrogen production
- offshore hydrogen production with pipelines
- offshore hydrogen production with carrier vessels

2.1.2.1 Onshore hydrogen production

Onshore hydrogen production systems have the same electricity generation and transmission systems in traditional offshore wind power systems. The system then integrates with an onshore hydrogen production system (see Figure 2.5). This type of system does not require implementing new technologies (e.g. offshore hydrogen production), but the cost could be higher than the system using a hydrogen transmission system when the power capacity and/or transmission distance is high.

A hybrid hydrogen production system can produce hydrogen and/or electricity if the electrical transmission is also connected to the grid. This additional grid connection increases the overall system cost but also enables the capability to switch production between electricity and hydrogen. This can maximise both the revenue of the wind farms and the utilisation of wind power by changing the ratio of electricity and hydrogen production with the demand or market prices.

Oyster project (Oyster project, n.d.) is launched in 2021 with the aim to build an onshore hydrogen production system to investigate the technology to combine offshore wind turbines directly with hydrogen production systems. A compact electrolysis system will be designed to fit into a single offshore wind turbine. The system will integrate a desalination system to produce the purified water that feeds into the electrolyser.

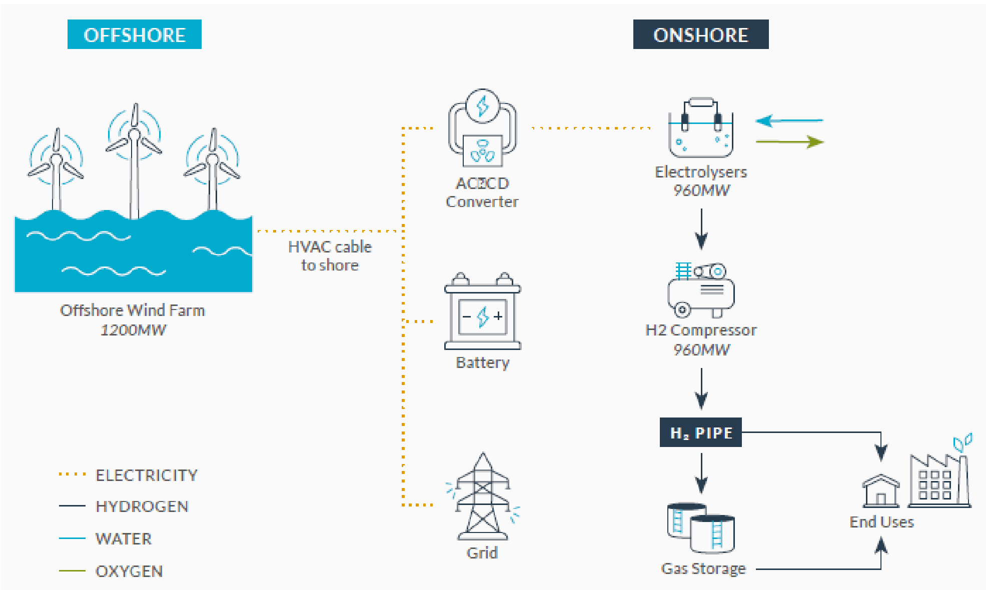


Figure 2.5 – Example of a 1200 MW offshore wind farm for onshore hydrogen production (ORE Catapult, 2020)

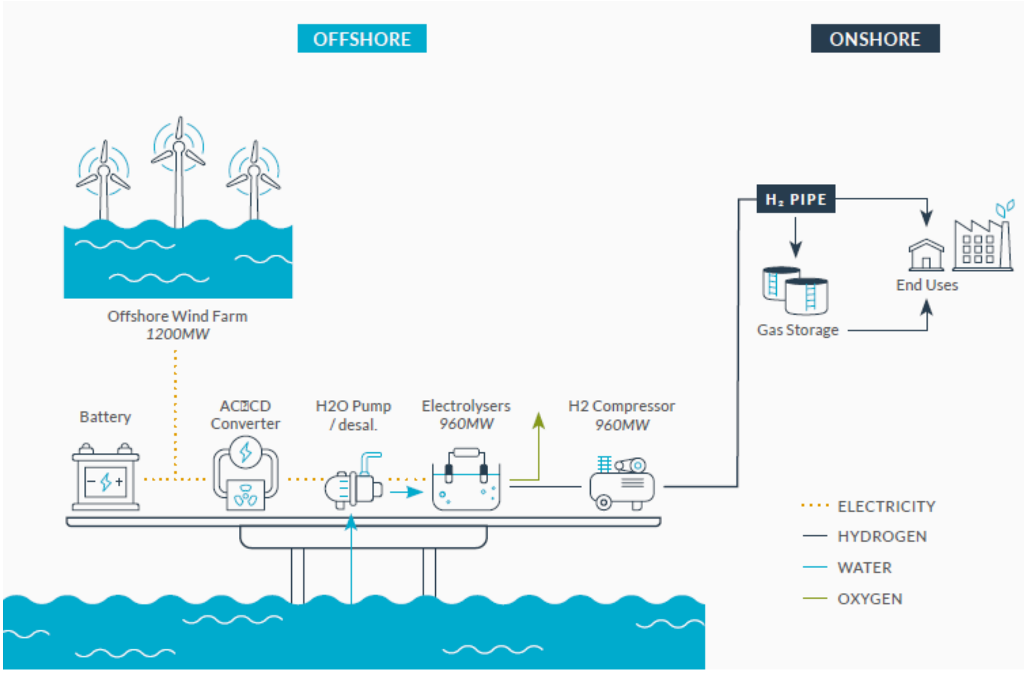


Figure 2.6 – Example of a 1200 MW offshore wind farm for offshore hydrogen production (ORE Catapult, 2020)

2.1.2.2 Offshore hydrogen production with pipelines

Offshore hydrogen production systems with pipelines produce hydrogen at centralised offshore platforms (see Figure 2.6) or the platform at each wind turbine (see Figure 2.7), and the hydrogen is compressed and transferred to the shore through offshore pipelines.

A report published by the American Bureau Shipping gave a comprehensive review of offshore green hydrogen production (ABS, 2022). The challenges to design a hydrogen production system that can operate in an offshore environment were discussed. For example, a hydrogen production system occupies significant space, and the available space on an offshore wind turbine or an offshore platform is limited. The environmental factors such as metocean and geotechnical conditions vary with each offshore site, and these parameters need to be collected and then considered in the design process. The system needs to be able to operate in harsh offshore environments with intermittent input power.

PosHYdon project (PosHYdon, n.d.) is the world's first pilot project of offshore hydrogen production on an offshore platform and brings hydrogen transported to the shore via pipelines. A 1 MW electrolyser will be installed on an existing oil and gas platform to test the operation in an offshore environment. The produced hydrogen is blended with natural gas and transported to the shore through an existing pipeline.

Dolphyn project (Baraniuk, 2021) is developing an offshore hydrogen production system that installs on a platform of floating offshore wind turbines. The offshore hydrogen production plan to consists of seawater desalination units, electrolyser units, and solar panels. The produced hydrogen at each platform can be transported to nearby export pipelines or other offshore units (e.g. offshore hydrogen compression platforms) through flexible compress hydrogen pipelines.

Lhyfe, a green hydrogen solution supplier, launched the world's first offshore hydrogen production platform in 2022 (Lhyfe, 2022). The platform has 1 MW electrolyser and will be integrated with a floating wind turbine about 20 kilometres from the shore.

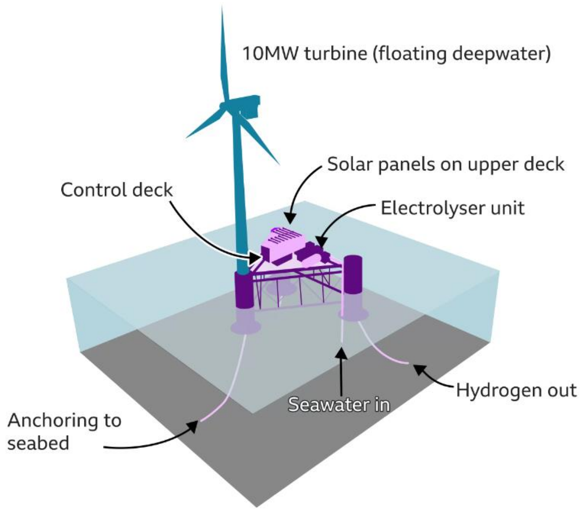


Figure 2.7 – The illustration of an offshore hydrogen production installed on the platform of floating wind generators (Baraniuk, 2021)

2.1.2.3 Offshore hydrogen production with carrier vessels

The hydrogen produced at offshore platforms can be transported to the shore by carrier vessels. For example, hydrogen is liquefied and then stored in liquid hydrogen carrier vessels at a cryogenic temperature (-253 ˚C). In this type of system, hydrogen is likely to be produced on centralised platforms which consist of hydrogen production, process units (e.g. liquefaction), storage, and offloading units.

The offshore wind system that produces liquid hydrogen has been identified as one of the potential solutions in the offshore hydrogen supply chain. A part of this system is similar to a floating liquefied natural gas (FLNG) facility (Gallagher, 2018), which stores liquefied natural gas (LNG) at -162 ˚C on an offshore floating platform and offloads LNG onto carrier vessels.

This system can be suitable for long-distance international hydrogen trading (e.g., over hundreds or thousands of kilometres) especially when pipelines installation is technically or economically infeasible. However, this type of system is still in the conceptual study and several required technologies are still under development, such as liquid hydrogen vessels and offshore hydrogen liquefication and storage units. The world's first liquid hydrogen carrier vessel (see Figure 2.8) just finished its first trip in earlier 2022 (Pekic, 2022). The liquid hydrogen was loaded to the vessel at Victoria's Port of Hastings in Australia and then delivered to Kobe in Japan. The capacity of this demonstration vessel is 1,250 m^3, which is far smaller than the LNG carrier vessels that have capacity over 250,000 m^3.

Figure 2.8 – The photo of Suiso Frontier, the world's first liquid hydrogen carrier vessel with 1250 m^3 of vacuum-insulated hydrogen container (HESC, n.d.)

2.1.2.4 Liquid organic hydrogen carrier

Hydrogen can also be stored in liquid organic hydrogen carrier (LOHC) instead of storing liquid hydrogen at a cryogenic temperature. LOHC is a merging solution for long-distance hydrogen transport. One of the advantages of LOHC is existing infrastructure for crude oil can be used with no major modifications.

Hydrogen carriers store hydrogen in the form of chemical compounds instead of free hydrogen molecules during storage and transport. The hydrogen is stored in chemicals by hydrogenation reactions before transport, and the hydrogen is released via dehydrogenation processes before use (see Figure 2.9). It is noteworthy that the dehydrogenated chemical needs to transport back to the hydrogen source for the next transport cycle. Several chemicals or materials are studied to be hydrogen carriers such as metal hydrides and liquid organic compounds.

Liquid organic hydrogen carrier is a promising solution and attracted many attentions in the past few years. LOHCs are safe, non-toxic, and easy to be managed. It can be a cost-effective solution to be implement in the supply chain due to many existing infrastructure and ships can be used. Various chemicals are studied as LOHCs, such as toluene, dibenzyltoluene, and N-ethylcarbazole.

The offshore wind system using LOHCs to transport hydrogen to the shore has been investigated (Franco et al., 2021). Compared to the system producing liquid hydrogen, the system using LOHC for transport requires hydrogenation units at the offshore site and dehydrogenation units at the port. The concept of LOHCs is developing in serval projects (European Commission, n.d.; *Project SherLOHCk*, n.d.) but none of them focus on offshore application.

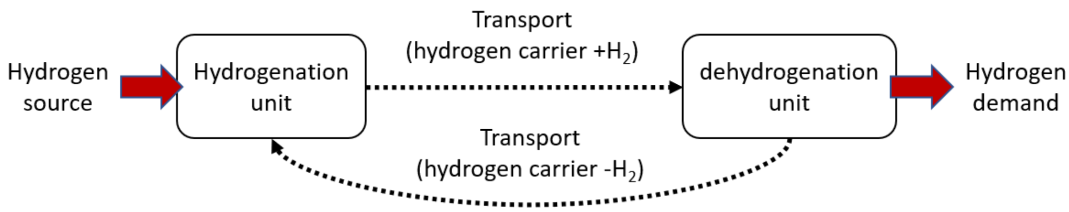


Figure 2.9 – A schematic process of hydrogen transport via hydrogen carriers

2.1.3 Ammonia

Ammonia is a commodity that can be used in different applications such as fertilisers, textiles and pharmaceuticals. In 2021, the global ammonia production is about 230 million tonnes, which generated around 650 million tonnes of carbon dioxide emissions (Jain et al., 2022). As the important raw material for fertilisers, ammonia has been transported by carrier vessels and pipelines (see Figure 2.10).

Ammonia can be used as a hydrogen carrier or a new energy vector (Salmon & Bañares-Alcántara, 2021). Today most of the ammonia in the world is synthesised from nitrogen gas and hydrogen gas via Haber-Bosch process. If the nitrogen (obtained from the air through the air separation process) and hydrogen (obtained from water through the electrolysis process) are produced by using renewable energy, green ammonia can be produced if the synthesis process is also powered by renewable energy (see Figure 2.11). Compared to hydrogen, ammonia has a higher energy density and is easier to be stored in a liquid state (i.e., -34 ˚C or 8.6 bar) than compressed hydrogen (350-700 bar) and liquid hydrogen (-253 ˚C).

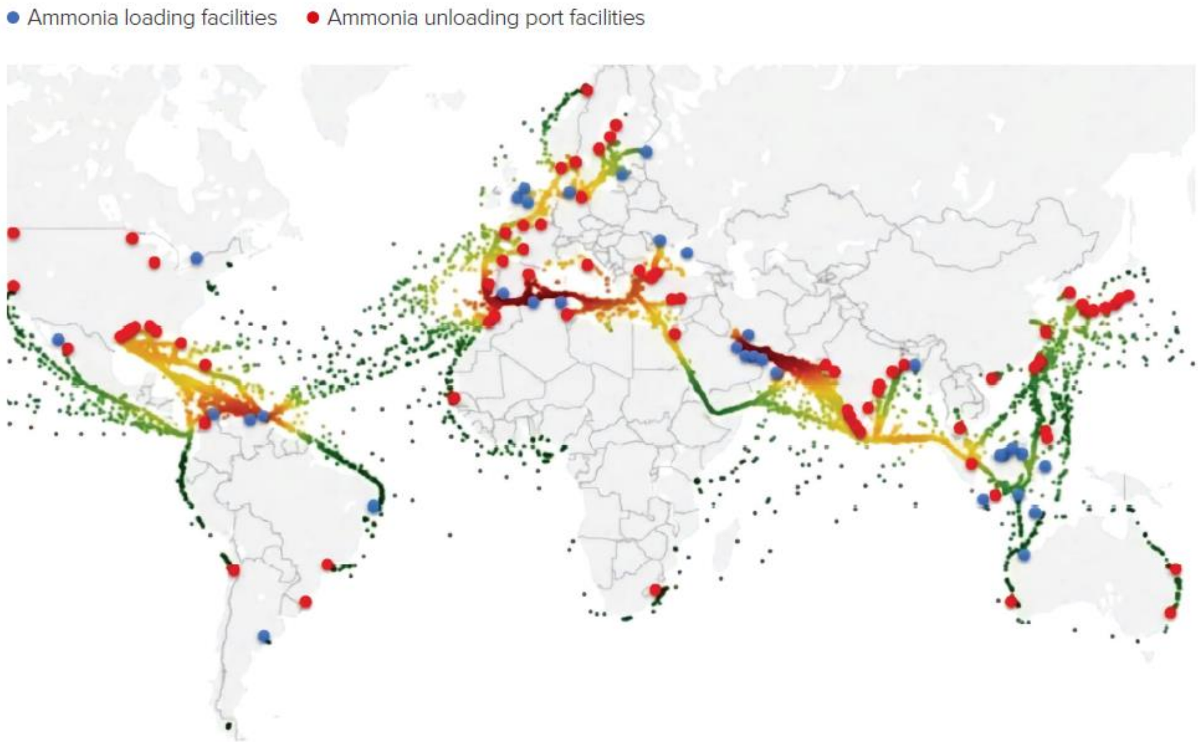


Figure 2.10 – Global ammonia shipping infrastructure and the heat map of liquid ammonia carriers (The Royal Society, 2020)

An offshore hydrogen production system can be upgraded to produce green ammonia if two units are added: the air separation unit (to produce nitrogen) and Haber-Bosch process unit (to synthesise ammonia from hydrogen and nitrogen). Both process units are mature and have been widely used in the industry for decades.

Green ammonia technology is demonstrated on land and the offshore system is still in the conceptual study. In 2017, ammonia energy storage system is built outside Oxford in the UK (Siemens Energy, n.d.). The demonstration system uses electricity to produce ammonia from water and air as feedstocks, and the ammonia is used to generate electricity via ammonia engines or fuel cells. In 2022, an industrial scale concept of offshore green ammonia production awarded Approval in Principle from DNV (DNV, 2022). An existing Very Large Gas Carrier will be studied to convert into a floating, production, storage and offloading unit that can produce ammonia. The technical challenges of offshore ammonia production and hazard management for ammonia and hydrogen will be investigated.

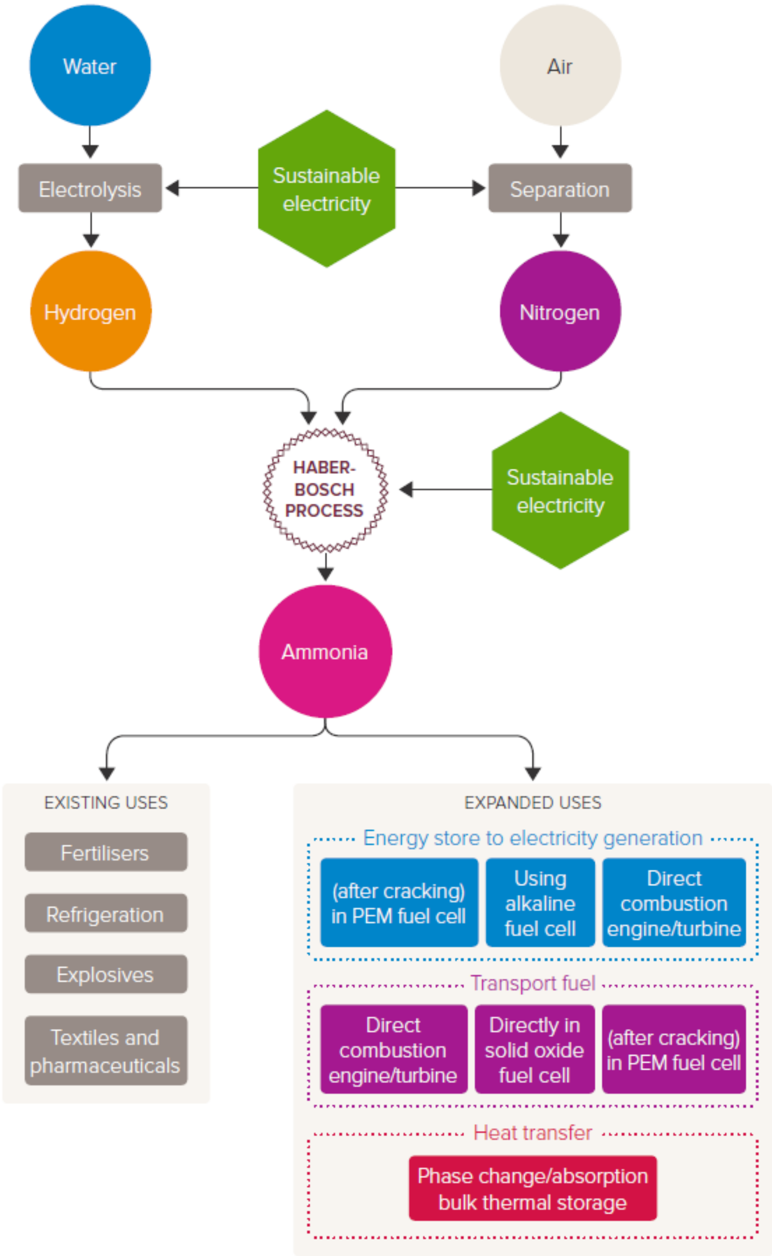


Figure 2.11 – Green ammonia production and use (The Royal Society, 2020)

2.1.4 Synthetic fuel

Except for hydrogen and ammonia, chemicals such as methane and methanol can be synthesised via chemical reactions powered by renewable electricity (Rego de Vasconcelos & Lavoie, 2019). These chemicals that have higher energy density than hydrogen and ammonia can be used as fuels. However, these synthetic fuels consist of carbon and therefore require carbon oxide or other carbon sources as feedstock. To be a low-carbon fuel, the carbon source needs to be carbon-neutral such as biomass or carbon capture (IRENA, 2021b).

Several studies are investigating the system of synthetic fuel production by wind power (Berger et al., 2021; Crivellari & Cozzani, 2020), but there is no demonstration project in synthetic fuel production directly powered by offshore wind power that can be found.

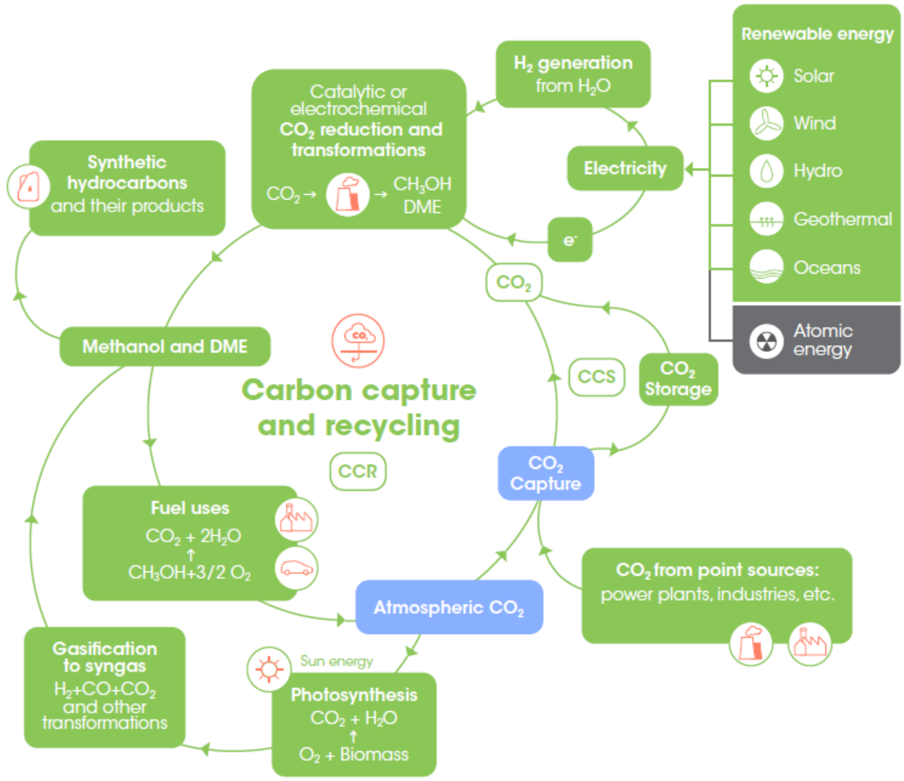


Figure 2.12 – Anthropogenic carbon cycle with renewable energy and carbon capture (IRENA, 2021b)

2.2 Floating offshore wind system for different energy vectors

This section studies the floating offshore wind systems that can generate power for different energy vectors. Firstly, the pathways from offshore wind farms to the distribution networks of different energy vectors are reviewed. Secondly, the factors that influence the section and/or the design of the system are discussed.

2.2.1 Pathway from offshore wind to the grid

Floating offshore wind systems can convert wind power into different forms of energy. How to select and design floating offshore wind systems is one of the questions that need to be answered before building a wind farm. Five pathways from offshore wind power to energy distribution networks are selected to be discussed in this report. Figure 2.13 shows the pathways and their major conversion and transmission systems.

Pathway 1 (electricity only) has a conventional offshore wind power system that produces electricity and exports it to the electrical grid via electrical transmission systems. Wind power is converted into electricity by floating wind turbine generators, which consist of wind turbines, floating platforms, mooring lines, and anchors. The electricity from each turbine is transferred to offshore substations via inter-array cables. The electrical power is converted into HVAC or HVDC by the substations and then transferred to the shore via offshore export cables. Onshore substations are used to adjust the electrical power to the required voltage or current type before the grid connection. Noted that substations can be skipped in certain situations, such as short distances between wind turbines to the onshore connection points.

Pathway 2 (onshore hydrogen production) has an onshore hydrogen production system that is powered by the electricity generated from floating offshore wind turbines and transported via electrical transmission systems. In this pathway, the components from wind turbines to onshore substations are the same as the components in Pathway 1. Then the electrical power from onshore substations feeds to a hydrogen production system. A typical hydrogen production system consists of AC/DC converters, desalination units, electrolysers, and hydrogen compressors. The hydrogen is then exported to the gas network via pipelines.

Pathway 3 (offshore hydrogen production and pipeline) has an offshore hydrogen production system that is powered by electricity from wind turbines, and the produced hydrogen is transported to the shore in gas pipelines. Instead of using electrical cables, the wind power is transported to the shore in the form of compressed hydrogen through submarine pipelines. The offshore hydrogen production can be built on a centralised platform or the floating platform of each floating wind turbine generator. A battery system may be needed to provide backup power for auxiliary components such as desalination units and hydrogen compressors.

Pathway 4 (offshore hydrogen production and carrier vessel) has the same offshore hydrogen production system as Pathway 3, and the hydrogen is liquefied and stored in an offshore liquid hydrogen terminal. The liquid hydrogen is offloaded to liquid hydrogen carrier vessels and then transported and unloaded to the onshore liquid hydrogen terminals.

Pathway 5 (offshore ammonia production and carrier vessel) has the same offshore hydrogen production system as Pathway 3 and two more systems (i.e., nitrogen production and ammonia production systems) to produce ammonia. The ammonia is stored in offshore storage in a liquid state and later transported to onshore ammonia terminals via ammonia carrier vessels.

This is not an exhaustive list of the pathways from offshore wind to different energy vectors. There are other possible pathways, such as offshore methanol production using hydrogen (from seawater via electrolysis) and carbon dioxide (from the air or seawater via carbon capture). The framework developed in the project has the flexibility to investigate customised system configuration if required data are provided.

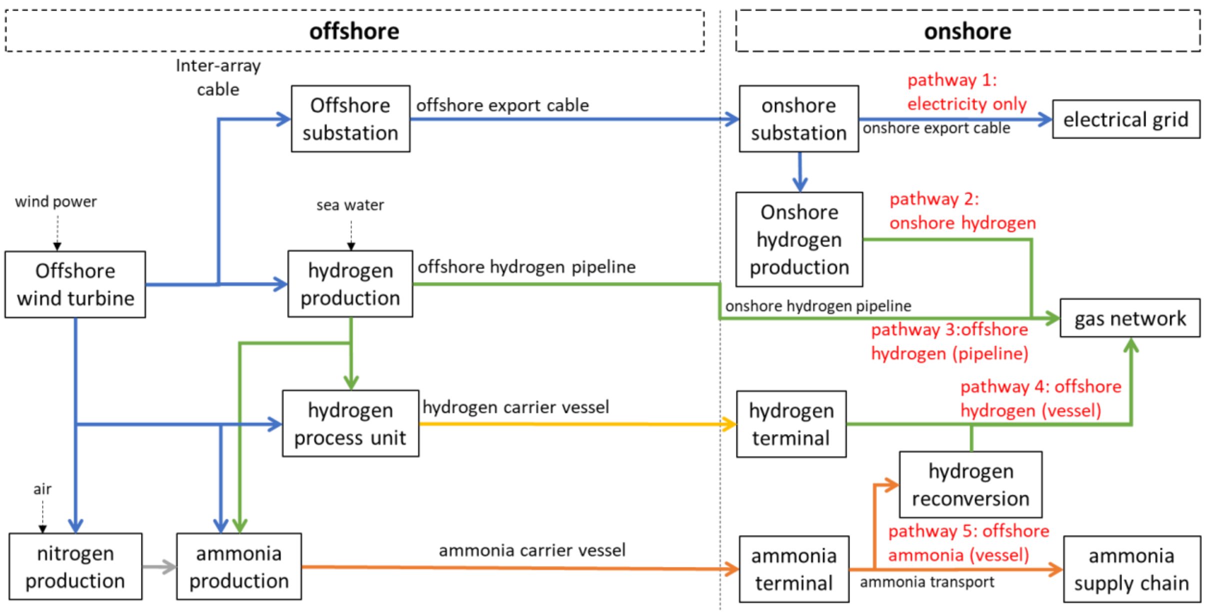


Figure 2.13 – The pathways and components of five pathways from offshore wind turbines to the electrical grid or the gas network

2.2.2 Factors influence the selection and design of offshore wind systems

Many factors affect the selection of the configuration of a generation unit. Based on the scope of the wind farm, those factors can be divided into internal and external factors.

Internal factors are directly related to the development of the wind farm, such as environmental conditions, technology selection (e.g. type of wind turbines and floating platforms), and configuration selection (e.g. electricity generation or offshore hydrogen production). External factors are generally not involved in wind farm development but have a significant impact on the design and operation of the system. For example, the capability of the transmission network, the demand in the energy system, and the market price of energy.

The framework proposed in section 4 (see Figure 4.1) can be used to evaluate both the internal and external factors. The base modules can evaluate the KPIs of the wind farm with different system configurations and key design parameters. The advanced modules (i.e. energy generation simulation and energy system simulation) can study the impact of the energy prices and the energy demand on the selection of system configuration.

In the case study (see section 5), the costs of three selected system configurations are analysed by the base modules with the sensitivity analysis of key design parameters (i.e. power capacity of wind farm and transmission distance). Site-specific data (e.g. energy generation and demand profiles, the topology and capacity of transmission systems) are required to run advanced modules.

3 Low carbon vessels and offshore wind farm

3.1 The challenges of decarbonising the shipping sector

Water transport is one of the sectors that are difficult to decarbonise due to the requirement of high energy density for long-distance transport. A study (IMO, 2020) reported that the global shipping energy demand in 2020 is nearly 11 exajoules (EJ) or 3,000 terawatt hours (TWh), which accounts for 3% of global greenhouse gas emissions. Today around 80-90% of global trade is transported via maritime shipping, and the maritime trade could increase 40-115% in comparison to 2020 levels.

International Renewable Energy Agency (IRENA) published a study on decarbonising the shipping sector by 2050 (IRENA, 2021a). Four key measures and their estimated contribution to carbon reduction are:

- Indirect electrification by employing powerfuels (60%)
- Employment of advanced biofuels (3%)
- Improvement of vessels' energy efficiency performance (20%)
- Reduction of sectoral demand due to systemic changes in global trade dynamics (17%)

Implementing powerfuels that are produced by low-carbon energy sources is the key measure to decarbonise the shipping sector. About 99% of marine fuels are from fossil fuels such as heavy fuel oil (HFO), marine gas oil (MGO), very low-sulphur fuel oil (VLFSO) and a small scale of liquid natural gas (LNG). Those fuels have high energy density (21-36 MJ/litre), compared to 700-bar hydrogen (6.8 MJ/litre) and lithium-ion batteries (1.2 MJ/litre) (statista, 2020). For long-distance transport such as thousands of kilometres, the vessel fuels need to be high energy density to maintain the fuel tanks in a suitable size. To address this issue, the fuels (e.g. ammonia and methanol; 12-16 MJ/litre) that have relatively high energy density and can be produced by low-carbon energy sources are proposed to be alternative fuels (DNV GL, 2019).

The IRENA's report (IRENA, 2021a) analysed various decarbonisation pathways and concluded that green hydrogen-based fuels will be the foundation of the decarbonised international shipping sector. In IRENA 1.5˚C Scenario, 70% of the shipping can be powered by the fuels that are produced by renewable energy by 2050 (see Figure 3.1). In this section, using FOW to produce low-carbon fuels will be further discussed.

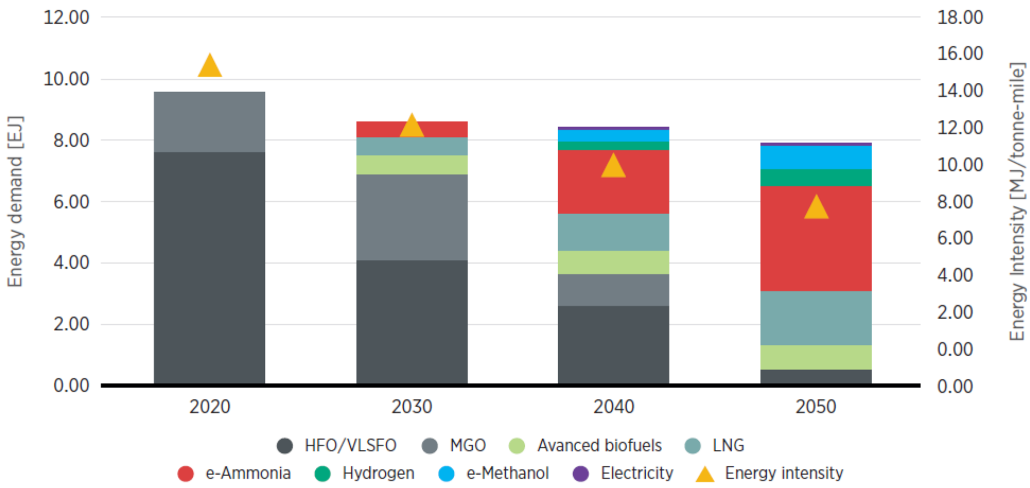


Figure 3.1 – Energy demand, fuel type, and energy intensity of global shipping sector in 2020-2050, IRENA 1.5˚C scenario (IRENA, 2021a)

(1) Taking into account maturity and availability of technology and fuel.
(2) GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.
(3) Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.
(4) Large regional variations.
(5) Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 3.2 – The summary of the alternative fuel evaluation on selected assessment parameters (DNV GL, 2019)

3.2 Alternative marine fuels

To decarbonise the shipping sector, various alternative marine fuels have been reviewed in several studies (DNV GL, 2019; IRENA, 2021a). Figure 3.2 summarised the key assessment parameters for each alternative fuel. Several key parameters are selected to assess each potential alternatives fuels, e.g., energy density, technological maturity, greenhouse gas emissions, energy cost, capital cost, and bunkering availability. The above parameters directly affect the applicability and economics of each fuel. The other parameters related to safety and scalability are examined, e.g., flammability and toxicity, and global production capacity.

Alternative marine fuels can be divided into two types. Transitional fuels (i.e., liquid natural gas, liquefied petroleum gas) have lower carbon emissions and pollutants than traditional fuels but still emit greenhouse gas during operation. Low-carbon fuels (i.e., hydrogen, ammonia, methanol, and biodiesel) are the fuels that are produced by low-carbon or carbon-neutral processes. Another way to decarbonise shipping is using electric motors and batteries powered by low-carbon electricity.

In this report, the focus is on the fuels that can be produced from floating offshore wind systems, i.e., electricity, hydrogen, ammonia, and methanol.

Table 3.1 – The energy density and storage conditions of each fuel or storage technology (IRENA, 2021a)

	Specific energy, LHV (MJ/kg)	Energy density (MJ/litre)	Storage pressure (Bar)	Storage temperature (˚C)
heavy fuel oil, HFO	33.4 - 41.8	33.4	1	40
marine gas oil, MGO	42.7	36.6	1	120
liquefied natural gas, LNG	50.0	23.4	1	-162
methanol	19.9	15.8	1	20
ammonia (sub-zero)	18.6	12.7	1	-34
(compressed)	18.6	12.7	8.6	20
hydrogen (liquid)	120.0	8.5	1	-253
(compressed)	120.0	7.5	700	20
Lithium-ion battery	0.2 - 1.0	0.9 - 2.5	1	-20 to 60

3.2.1 Electricity

Vessels can be powered by electricity if the power system is based on electric motors and batteries. Due to the low energy density of batteries (see Table 3.1), the electric power system is only being used for vessels operating short distances, or hybrid vessels that also have conventional engines for high-power or long-duration operation. Electric vessels are normally charged through an onshore connection to the electric grid at the port, but some projects are developing the technology to charge the vessels at the offshore wind farm (Durakovic, 2022). The electricity needs to be produced from low-carbon sources to reduce the lifetime carbon emissions of the vessels.

3.2.2 Hydrogen

Hydrogen can be converted into power in two technologies: fuel cell and internal combustion engine. Fuel cells have a higher energy conversion efficiency (50-60%) than internal combustion engines (40-50%) and emit zero pollutants (e.g. nitrogen oxides, sulphur oxide, and particulate matter). Fuel cell vessels use an electric power system, and both electric propulsion systems and batteries are therefore required.

The challenge of using hydrogen as a fuel is how to store it on vessels. Hydrogen has low volumetric density, so normally being stored in either high pressure (350 or 700 bar) or cryogenic temperature (-253 ˚C). The storage container for both types of hydrogen requires a significant amount of weight and volume. This limits the application of hydrogen-based vessels to short-distance transport or second fuels in hybrid vessels.

3.2.3 Ammonia

Ammonia can be used as a fuel for internal combustion engines but has several disadvantages such as high auto-ignition temperature, and low flame speed, narrow flammability limits. Two maritime engine manufacturers (i.e. MAN and Wärtsilä) are developing ammonia-based internal combustion engines (IEA, 2021), which are expected to be commercially available by 2024.

Ammonia can be used in ammonia-based fuel cells or hydrogen-based fuel cells, which require an ammonia decomposition process to produce hydrogen. The latter requires additional process units and the former technology is still in the early stages of development (Xing et al., 2021).

Ammonia has a volumetric energy density that is 50% higher than liquid hydrogen and has no requirement for high pressure or cryogenic temperature for storage (see Table 3.1). Ammonia can also be produced from electricity with widely available resources (i.e., water for hydrogen and air for nitrogen). Thus, ammonia has been identified as the most likely alternative low-carbon fuel for long-distance vessels (DNV GL, 2019; IRENA, 2021a). Many challenges need to be overcome to use ammonia as fuel, such as the safety measures to deal with its toxicity and the requirement of nitrogen oxides reduction systems for ammonia-based engines.

3.2.4 Methanol

Similar to ammonia, methanol can be fed into fuel cells or internal combustion engines. Methanol is being used as a fuel since 2015, including a new concept of methanol-powered Offshore Support Vessel that is developing since 2020 (Methanol Institute, 2022). Methanol-based fuel cell technologies were developed and tested in 2017 (DNV GL, 2019).

Methanol is liquid under standard conditions, and the cost of the storage system is lower than hydrogen and ammonia. The main drawback of methanol is that it consists of carbon. Producing low-carbon methanol requires carbon as a raw material (e.g. carbon dioxide from carbon capture and storage). Burning methanol also emits carbon dioxide locally.

3.3 Vessel charging/refilling at offshore wind farm

Wind power produced at the offshore wind farm can be used to power the vessels at the nearby ports or the offshore site. The charging or refilling process is easier to be done at the ports due to its more controlled environment. Various offshore electric charging technologies have been reviewed (Sæmundsson & Henriksen, 2020), and those can be divided into four types of charging configuration (see Figure 3.3):

1. directly from wind turbines
2. directly from offshore substations
3. separate transformers connected to wind turbines
4. separate transformer connected to offshore substations.

The configuration affects the connection point to the existing system, whether additional transformers are needed, and the voltage level of the charging system.

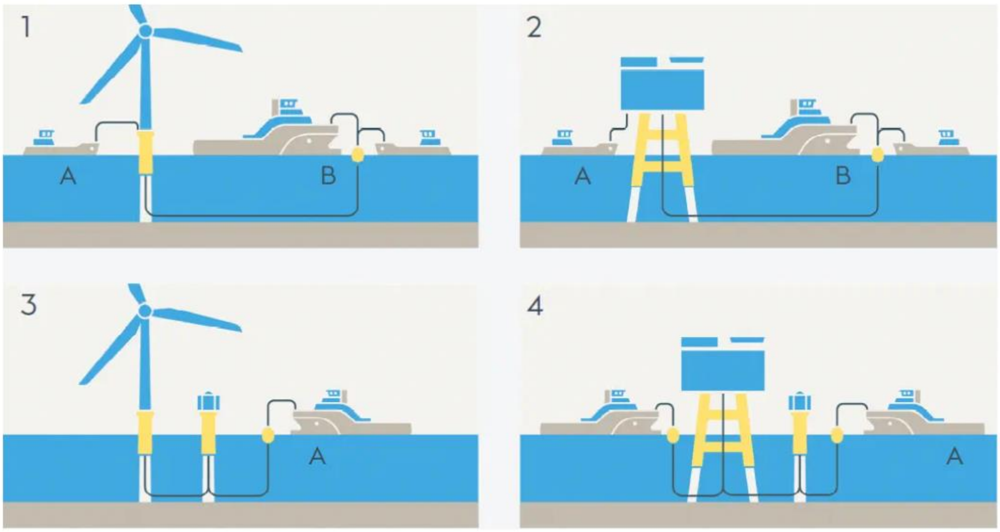


Figure 3.3 – The schematic of four different offshore electric charging configurations (Sæmundsson & Henriksen, 2020)

The offshore electric charging system powered by offshore wind farm has demonstrated in 2022 (Maersk Supply Service, 2022). Charging buoys that connected to offshore wind farms could charge electric vessels or provide electric power for idle vessels, such as service operations vessels for offshore wind farms.

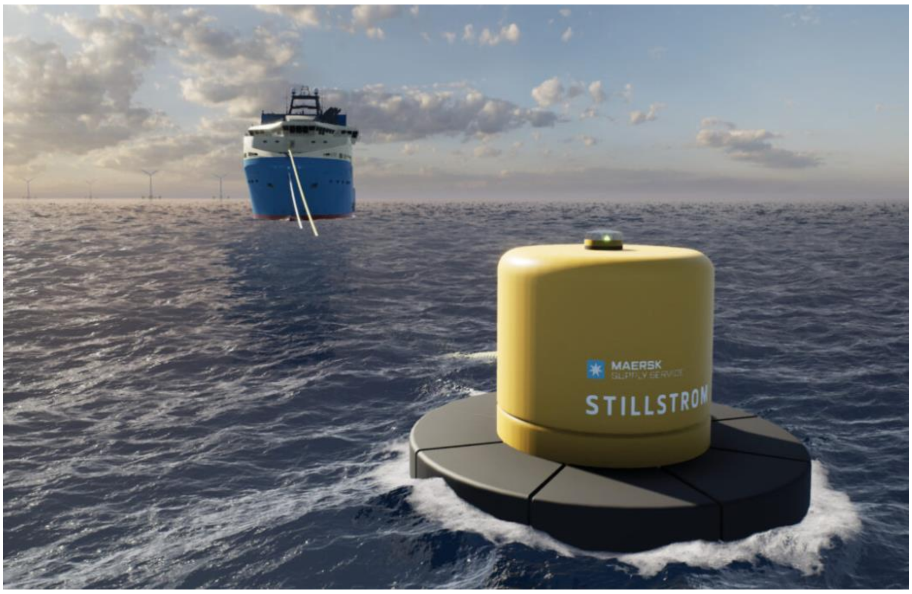


Figure 3.4 – A offshore charging buoy powered by an offshore wind farm (Maersk Supply Service, 2022)

Hydrogen can be produced at the offshore wind farm and then potentially be used to refill hydrogen-powered vessels. In 2021, Hydrogen Offshore Transfer System project is launched to develop the offshore hydrogen filling technology (cenex, 2021). A ship refuelling buoy that can transfer hydrogen to vessels is designed to enable efficiency and safe low-carbon maritime transport.

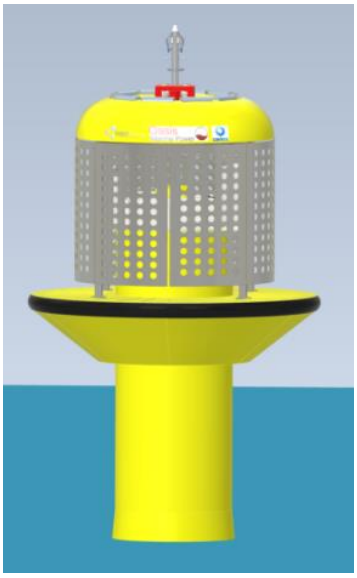


Figure 3.5 – An offshore hydrogen refilling buoy (Oasis Marine, n.d.)

4 Assessment framework of floating offshore wind farms

This section introduces the assessment framework developed by the University of Exeter to investigate the integration of floating offshore wind farms with energy vectors and low carbon vessels. Figure 4.1 shows the modules and input/output data included in the framework. Base modules evaluate the key performance indicators (KPIs) of the floating offshore wind farm, such as levelised cost of energy, carbon intensity, and energy return on energy invested. Advanced modules investigate the impact of energy prices and energy systems on the design of offshore wind farms.

In this report, the base and advanced modules are demonstrated using the data of an example wind farm. The base modules are later used in the analysis in the other sections.

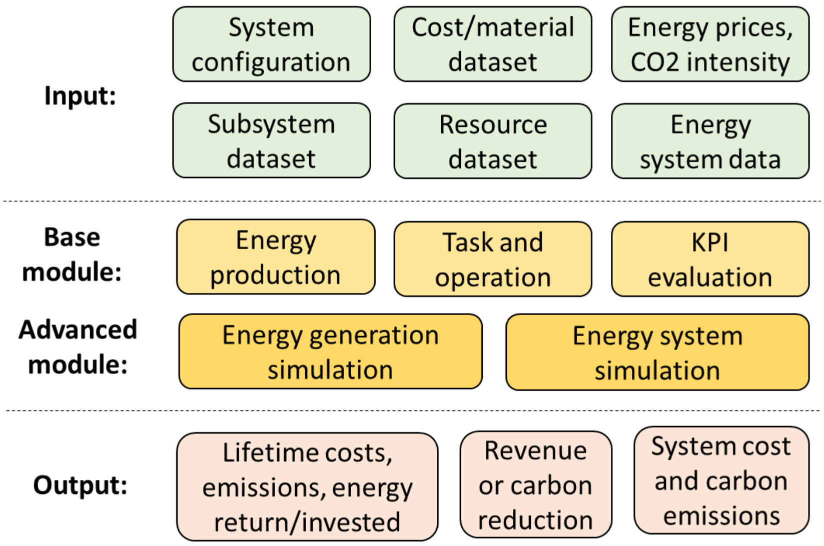


Figure 4.1 – The diagram of the data and modules in the floating offshore wind assessment framework

4.1 Base modules

Three base modules are developed in the assessment framework to evaluate the costs, carbon emissions, and energy return/investment of wind farms. Their functions and required data are introduced in the following subsections.

4.1.1 Input data

The structure of input data for base modules is shown in Figure 4.2. The configuration of floating offshore wind systems is defined in system configuration files, which include the selection of subsystems, the number of each subsystem, and the connection between each subsystem. The specification of the subsystem (e.g. wind turbines, floating platforms, and cables) in the floating offshore wind systems are stored in the subsystem dataset. The characteristic parameters of each subsystem are defined in the characteristic dataset (i.e. cost parameters, components in the subsystem, power curves for wind turbines only). The component data is linked to the material dataset, which stores the embodied carbon and energy of different materials. Each subsystem can link to the tasks in the task dataset, which stores the key parameters of activities in the lifetime of the system (e.g. assembly, installation, O&M, and decommissioning). Each task can link the data in Resource Dataset, such as the vessels and fuels used for the activity, the metocean data at the location for the activity, and the transport distance between ports and/or offshore locations.

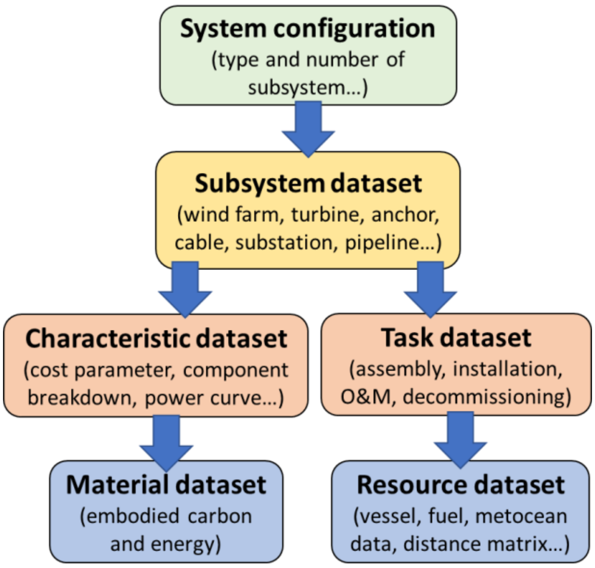


Figure 4.2 – The structure of input data for base modules

4.1.2 Energy production

The energy production module estimates the energy production of the system by considering energy generation, conversion, and loss within the wind farm. The wind power generation of wind turbines is calculated based on time-series wind speed data and the power curve of the turbine. The energy consumption and loss in energy conversion units (e.g. substations, electrolysers, and compressors) and transmission (e.g. electric cables) are considered to calculate the energy exported to the grid (e.g. electricity grid and hydrogen network).

4.1.3 Task and operation

The task and operation module evaluates the costs, carbon emissions, and energy investment in four types of operations in wind farms: assembly, installation, maintenance, and decommissioning.

Assembly tasks are the activities after manufacturing and before installation, such as transporting components or parts from manufacturing sites to assembly sites, storage of components or parts at the port, assembly activities at the site, and staging. The outputs related to KPIs of assembly tasks are component transport cost and fuel consumption, the cost of storage at the port, and the cost and fuel consumption for assembly activities at the port or shipyard (e.g., lifting by cranes). Noted that fuel consumption can be used to estimate fuel costs and energy consumption.

Installation tasks are the activities after assembly and before the commissioning of the wind farm, such as installing mooring lines and anchors, installing electrical cables and substations, transporting wind turbine generators to the offshore site, and connecting floating platforms to pre-installed mooring lines. The output related to KPIs of installation tasks are mainly vessel costs and fuel consumption.

Maintenance tasks are the activities to maintain the operation of wind farms, such as preventive and corrective maintenance. The outputs related to KPIs of O&M tasks are vessel costs, and repair and maintenance costs.

4.1.4 KPI evaluation

The KPI evaluation module uses both the input data and the results from the other modules to calculate the data in three KPI groups: cost, carbon emissions, and energy return and investment.

The lifetime cost of a floating offshore wind farm can be breakdown into five development phases, i.e., manufacturing cost, assembly cost, installation cost, O&M cost, and decommissioning cost. The first three costs combined are the capital cost. Those costs could come from user inputs (e.g. manufacturing cost), and the outcome of the modules (e.g. Task calculator).

The lifetime carbon emissions and energy investment can be calculated by two types of activity: indirect activity and direct activity. Indirect activities are not recorded in the development of the wind farm but can be provided by the supplier. For example, the manufacturer of wind turbine components (e.g., blades and nacelles) can provide the carbon emissions and energy consumption for manufacturing the components. They are also called embodied carbon and embodied energy. Direct carbon emissions and energy investment come from the activity in the development of wind farms, such as assembly, installation, O&M, and decommissioning. They mainly come from fuel usage or energy consumption. For example, fuel consumption from vessel operations or crane usage.

The lifetime energy generation can be calculated in various ways. It can be calculated based on the capacity factor estimated by the data from existing wind farms or calculated based on the power curve of the wind turbine and wind speed data.

4.1.5 Key output data

Based on the data calculated in the above steps, three KPIs are calculated: levelised cost of energy (LCOE), carbon intensity, and energy return on energy invested (ERoEI).

The levelised cost of energy can be calculated by net present value (NPV) of lifetime costs and NPV of lifetime energy generation (BIES, 2020) as follow:

$$LCOE = \frac{\sum_n \frac{total\ capex\ and\ opex\ costs_n}{(1 + discount\ rate)^n}}{\sum_n \frac{energy\ generation_n}{(1 + discount\ rate)^n}}, n = time\ period$$

The one of the typical units for electricity generation is £/MWh. The same concept can apply to hydrogen (i.e. levelised cost of hydrogen, typical unit is £/kgH_2). Detailed calculation is shown in Appendix A.

Carbon intensity is calculated by lifetime carbon emissions and lifetime energy generation (Zhang et al., 2022) and can be calculated by:

$$carbon\ intensity = \frac{\sum C_{pd} + C_c + C_{op} + C_d}{\sum E_g}$$

where C_{pd} is the carbon emissions during the pre-development phase, C_c is the carbon emissions during the construction phase, C_{op} is the carbon emissions during the operation phase, C_d is the carbon emissions during the decommissioning phase, and E_g is the energy production. The typical unit of carbon intensity for electricity generation is kgCO2-eq/MWh.

ERoEI is calculated based on lifetime energy generation and energy investment (Murphy et al., 2011). ERoEI can be calculated by:

$$ERoEI = \frac{\sum E_g}{\sum E_{pd} + E_c + E_{op} + E_d}$$

where E_{pd} is the energy consumption during the pre-development phase, E_c is the energy consumption during the construction phase, E_{op} is the energy consumption during the operation phase, and E_d is the energy consumption during the decommissioning phase. ERoEI is a ratio and therefore has no unit.

Detailed parameters to calculate KPIs can be obtained from this framework. For example, the breakdown of cost, carbon emissions, and energy invested in each subsystem and task, and time-series electricity and hydrogen export data.

4.2 Advanced modules

Two advanced modules (i.e. energy production simulation and energy system simulation) are developed to investigate the external factors that are usually not in the scope of wind farm development but could affect the design of the floating offshore wind farms. For example, the energy prices (e.g. electricity and hydrogen) could affect the decision of building wind farms for electricity or hydrogen generation. The parameters in the scope of the energy system (e.g. demand profile, transmission capacity, existing energy sources) can also affect the design of the wind farm. For example, in a region that has low share of low-carbon electricity, the wind farm generating electricity can effectively reduce the carbon emission in the energy sector. In a region that has limited electrical transmission capacity and high gas demand, the wind farm producing hydrogen could reduce the carbon emissions in the region without spending high capital costs on upgrading the electrical network.

4.2.1 Energy generation simulation

The energy generation simulation module simulates the operation of the system that can adjust its energy generation to maximise it revenue or other objective functions (e.g. minimise carbon emissions). For example, electricity-hydrogen hybrid wind farms can manipulate the ratio between electricity and hydrogen production with the market prices to maximise their revenues. Another example is the wind farm integrated with a storage system (e.g. batteries or hydrogen storage). Electricity or hydrogen can be stored when the electricity price is low and discharged when the price is high. If the objective function is to minimise carbon emissions, wind power is stored when the carbon intensity of the electricity is low, and the stored energy is discharged when carbon intensity is high.

This module is built on a mixed-integer linear program (MILP) mathematical model considering the constraints of system capacity and operational limits and an objective function. The model is searching for the optimal values of selected variables (e.g. amount of power for electricity and hydrogen production) within the boundaries to meet the target defined in objective functions. The typical input parameters and variables of the module are:

- System specifications (e.g. power capacity of wind turbines, hydrogen production systems)
- Power input data (e.g. wind speed profile)
- Energy conversion parameters (e.g. power curve, energy consumption and loss of components)
- Operational constraints (e.g. ramp up/down rate, minimum load of electrolysers)
- Operational indicators (e.g. energy prices, carbon intensity of electricity)
- Decision variables (e.g. power to electricity export and hydrogen production, power to charge/discharge from storage)
- Objective function (e.g. revenue of the wind farm, carbon emissions reduction)

This module can evaluate the values of hybrid offshore wind systems, which could play an important role in the middle of the transition to the net-zero energy system. In the energy system that has a high share of wind power generation, the energy supply could be over the energy demand in a high-wind period but short of supply in a low-wind period. A hybrid electricity-hydrogen wind power system could use wind power effectively by changing electricity and hydrogen production, but the trade-off is adding additional capital costs to the system. This module could be used to investigate the suitable timing and conditions to build electricity-only systems, hybrid systems, or hydrogen-only systems.

4.2.2 Energy system simulation

The energy system simulation model simulates the integration of offshore wind farms and the energy system by considering the generation, transmission, and demand in the energy system. The model is built on an open-source Python environment for energy system modelling, Python for Power System Analysis (PyPSA, see Figure 4.3), which can simulate and optimise existing (if available) or customised energy systems by minimising the capital and operational costs. PyPSA is capable to simulate the energy system with multiple energy vectors (e.g. electricity, natural gas, and hydrogen) and sector coupling units (e.g. electrolyser, combined heat and power, carbon capture).

In the current version of the energy system simulation model in the assessment framework, the energy system integrated with the wind farm can be simulated based on the selected region and scenario. The required input parameters and data for the model can be divided into several parts:

- Energy vector to be simulated (e.g. electrical grid, gas network, oil for transport sector)
- Energy supply: capacity and costs of energy supply units (e.g. power plants for electricity generation, fuel imports); generation profiles of non-dispatchable energy sources (e.g. hourly wind and solar generation profile)
- Energy transmission and storage: capacity and costs of transmission systems (e.g. electricity or gas) and storage systems (e.g. pump hydro, battery, and hydrogen storage)
- Energy demand: time-series demand profiles for each energy vector (e.g. hourly electricity and gas demand)
- Carbon intensity of fuels (e.g. natural gas, coal, biomass)
- Operational limits (e.g. ramp up/down rate, minimum load)

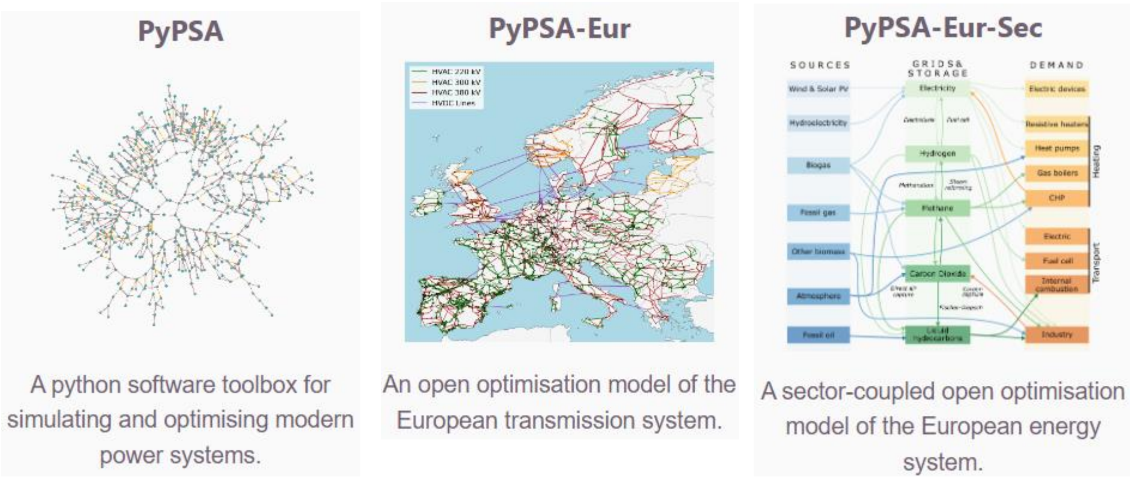


Figure 4.3 – The toolbox and models in the Python for Power System Analysis (PyPSA) package (*PyPSA Energy System Modelling Framework*, n.d.)

After the energy system is set up, the model can perform a power system optimisation which minimises the overall cost of the energy system (including capital costs and operational costs of all units in the system) by changing the selected variables (e.g. the energy supply of dispatchable energy sources, the capacity of design system) and considering all the constraints (e.g. generation and transmission capacities, ramp up/down rate of generation). For example, in an energy system with wind farms and gas-fired power plants, wind power has a higher priority in power generation due to the operational cost being lower than gas-fired power plants. The model can find the optimal capacity of a system (e.g. such as battery systems) if its capital cost per unit (e.g. £/MW) and the capacity range (e.g. upper and lower values) are provided.

This module can evaluate the impact of energy system parameters (e.g. the share of renewable energy, the capacity of transmission systems) on the design and the operation of the wind farm. This is crucial for long-term planning since the conditions of energy systems could change significantly during the transition toward the net-zero target.

5 Case studies

Three case studies are carried out in this section. Firstly, the capability of the base modules and advanced modules in the assessment framework is demonstrated. Secondly, the costs of floating offshore wind farms with different configurations are analysed using the base modules. Thirdly, the electricity required to decarbonise the wind farm service fleet is studied.

5.1 Demonstration: 500 MW example wind farm

A 500 MW floating offshore wind farm is selected to demonstrate the assessment framework. The wind farm has 34 of 15 MW turbines (actual power capacity is 510 MW) installed on 17,500 tonnes of stainless steel semi-submersible floating platforms. The floating platforms are connected to catenary mooring lines which have one end attached to the drag-embedded anchors on the seabed. The electrical power generated from each turbine is transferred to offshore substations via inter-array cables. Then the gathered power is transmitted to onshore substations via offshore export cables. The onshore substation is connected to the electrical grid via onshore export cables.

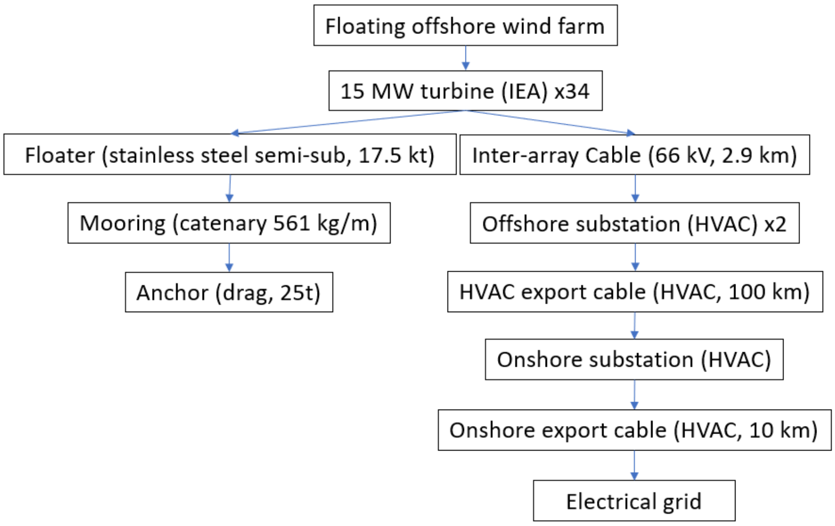


Figure 5.1 – The system configuration of a 500 MW floating offshore wind farm for demonstration

5.1.1 System configuration and input data

The system configuration of the example wind farm is shown in Figure 5.1. The key input data used in the example are:

- Wind farm system configuration (e.g. number of subsystems, type of subsystems)
- Specification of each subsystem/component (e.g. power capacity, efficiency)
- Costs, embodied carbon, and embodied energy of each subsystem/component
- Data for assembly, installation, O&M, and decommissioning activities (e.g. vessel cost and fuel consumption, failure rate, operation time)
- Environmental data (e.g. wind speed, wave height, water depth)
- Calculation/simulation parameters (e.g., discount rate, lifetime of the project)

The input data and parameters used in the example are summarised in Appendix B. These input data are collected from a wide range of sources (e.g. public reports, journal papers, and inputs from industrial experts) to demonstrate the capability of the framework. Technology-specific or site-specific data are required to provide the realistic figure of KPIs of a wind farm.

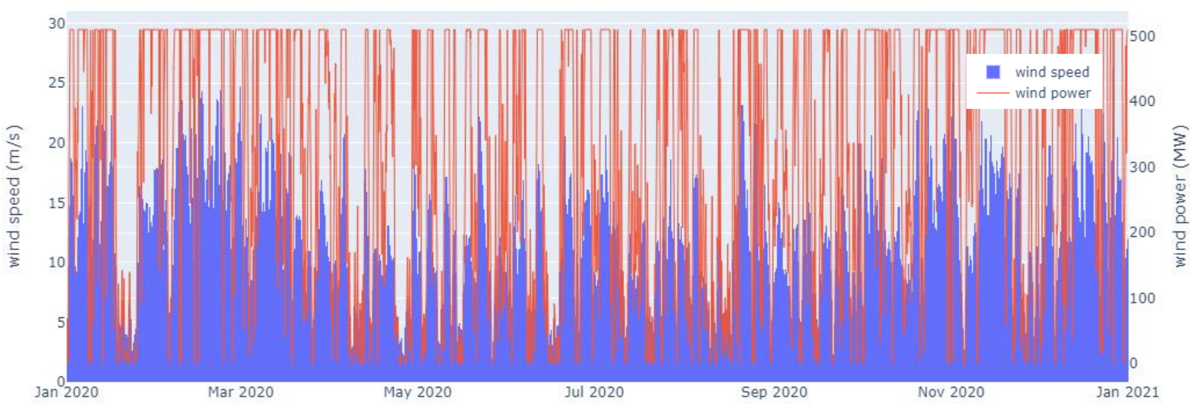


Figure 5.2 – Wind speed and wind power of a 500 MW example wind farm; based on 2020 metocean data

5.1.2 Base modules output

Energy generation is calculated based on the system configuration. In the example, the wind farm is producing electricity that is exported to the electrical grid. This can be changed to other types of energy such as hydrogen or ammonia if corresponding system configurations are defined. The time-series wind power generation data (see Figure 5.2) is normally calculated based on the wind speed data and the power curve of a turbine. The energy losses during the generation and transmission are considered if it is defined in the data of each subsystem.

The costs of each subsystem or each development phase (i.e. pre-development, manufacture, installation, operation, and decommissioning) are calculated based on either the input cost data (e.g. manufacture cost) or the output from the modules (e.g. installation costs calculated by installation module). In the end, the lifetime cost of the wind farm is calculated (see Figure 5.3). Then the net present value (NPV) of costs is calculated based on the duration of each development phase and a discount rate (see Figure 5.4).

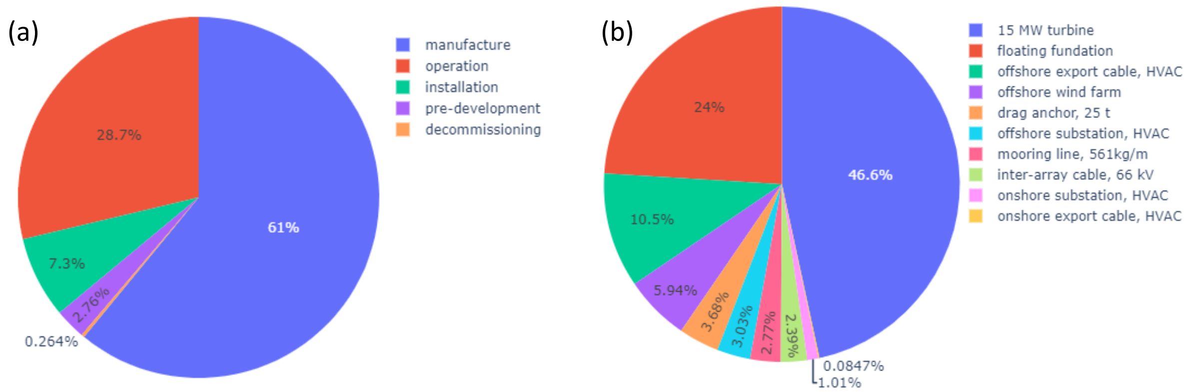


Figure 5.3 – The example of NPV cost breakdown by (a) development phase and (b) subsystem

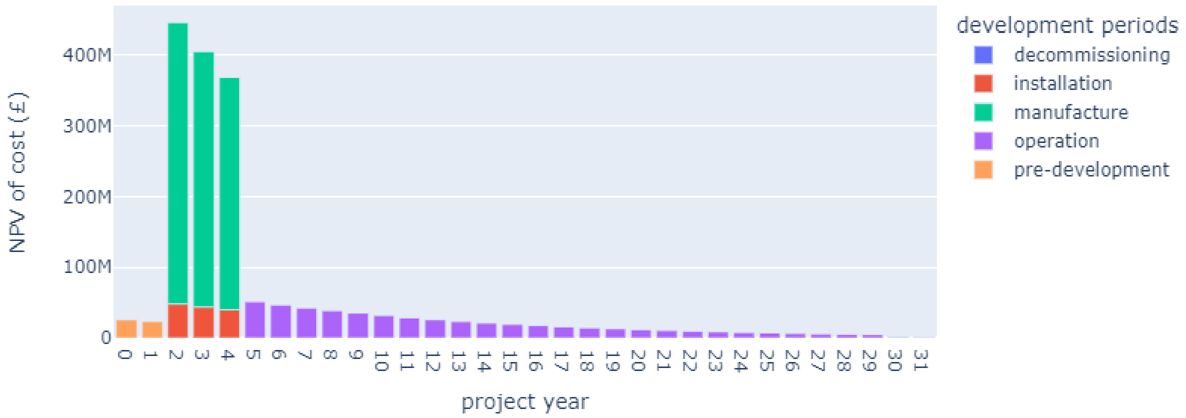


Figure 5.4 – Net present value of costs in the lifetime of the example wind farm (based on 2 years of pre-development, 3 years of installation, 25 years of operation, and 2 years of decommissioning)

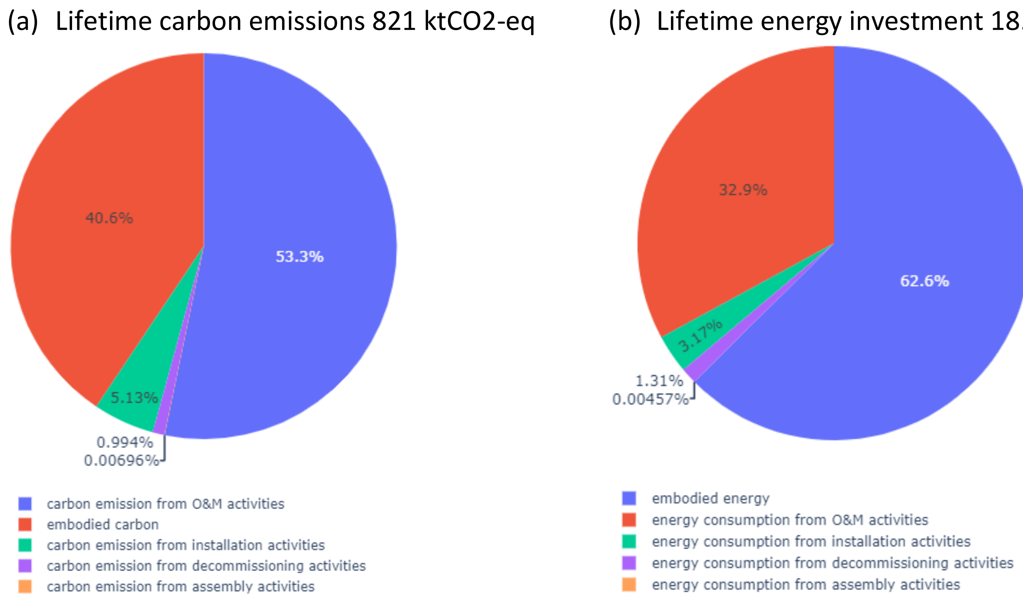


Figure 5.5 – Lifetime (a) carbon emissions and (b) energy investment of example wind farm

The lifetime carbon emissions and energy investment are mainly estimated based on two categories: the embodied carbon and energy of components, and carbon emissions and energy consumption from the activities. The former includes the carbon emissions and energy investment in the activities outside the scope of the wind farm development (which can vary depending on each project or scenario), such as the extraction of raw materials and the manufacturing of the components. Those can be obtained by the supplier of the components. The latter covers the activities within the scope of the wind farm project, such as survey in the pre-development phase, assembly at the port or shipyard, and installation at the offshore site. In the end, the lifetime carbon emissions and lifetime energy investment are calculated (see Figure 5.5). Then the carbon intensity and ERoEI can be calculated by dividing those numbers by the lifetime generation. Table 5.1 summarise the key outputs and KPIs of the example wind farm.

Table 5.1 – Summary table of the key assessment results of the example wind farm

Item	Unit	Value	Note
Annual wind power generation	MWh/year	2,792,397	
Annual electricity export	MWh/year	2,714,924	including energy loss
NPV of lifetime electricity export	MWh	16,831,829	discount rate 10%
Lifetime cost	£	3,829,056,270	
NPV of lifetime cost	£	1,788,314,854	discount rate 10%
Lifetime carbon emissions	kgCO2-eq	867,406,262	
Lifetime energy invested	MJ	18,685,495,485	
Key performance indicators			
Levelised cost of electricity	£/MWh	106.25	discount rate 10%
Carbon intensity of electricity	kgCO2-eq/MWh	12.43	
ERoEI for electricity generation	-	13.45	

5.1.3 Energy generation simulation output

A 500 MW electricity-hydrogen hybrid wind farm is used to demonstrate the capability of the energy generation simulation module. This hybrid system is based on the configuration of the 500 MW example wind farm (shown in Figure 5.1) and then integrated with an onshore hydrogen production system which has 430 MW electrolyser and 475 MW maximum electrical load (including energy losses and consumptions in other components such as AC/DC converters, desalination units, and compressors). Having a maximum electrical load slightly lower than the total power capacity of wind turbines can enhance the utilisation of the hydrogen production system and therefore reduce the cost of hydrogen per kilogram (ORE Catapult, 2020).

The key input data and simulation parameters in this exercise are:

- Energy source: 1-year hourly wind speed data
- Energy conversion: power curve of wind turbines, energy consumption for hydrogen production
- Operational constraint: minimum load of electrolysers
- Energy price: hourly electricity prices, fixed hydrogen price
- Decision variables: power to electricity export, power to hydrogen production
- Objective function: maximise the revenue of wind farms by selling electricity and hydrogen

In this exercise, the UK's historical hourly electricity prices in 2019 are used and the hydrogen price is assumed to be fixed in the simulation time horizon (see Appendix C: Input data for advanced modules). The impact of hydrogen prices is investigated by a sensitivity analysis.

Figure 5.6 shows the profiles of the hybrid wind farm in two weeks of operation. It can be found that wind power is used to generate electricity (blue bar) when the electricity price (green curve) is high. On the contrary, wind power is used for hydrogen production (red bar) when the electricity price is low.

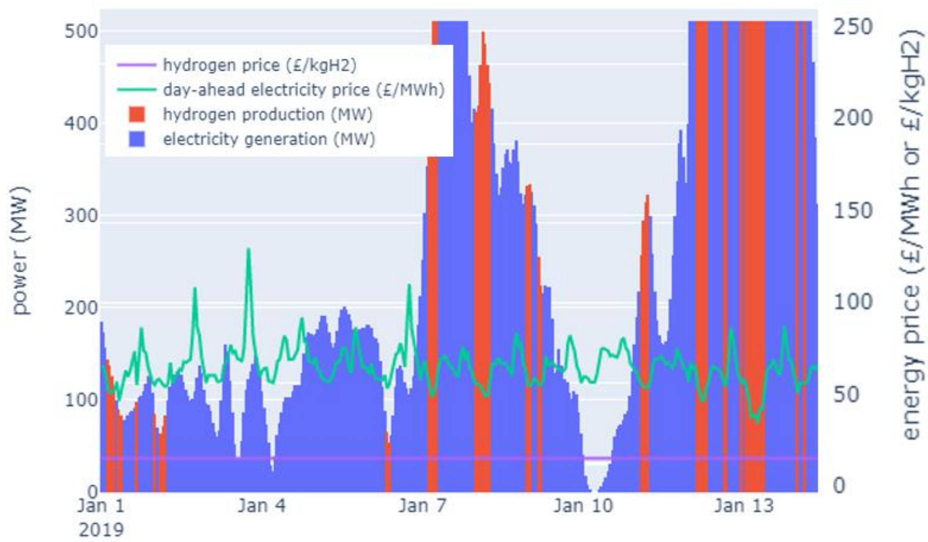


Figure 5.6 – The example of two-week energy generation profiles of an electricity-hydrogen hybrid system

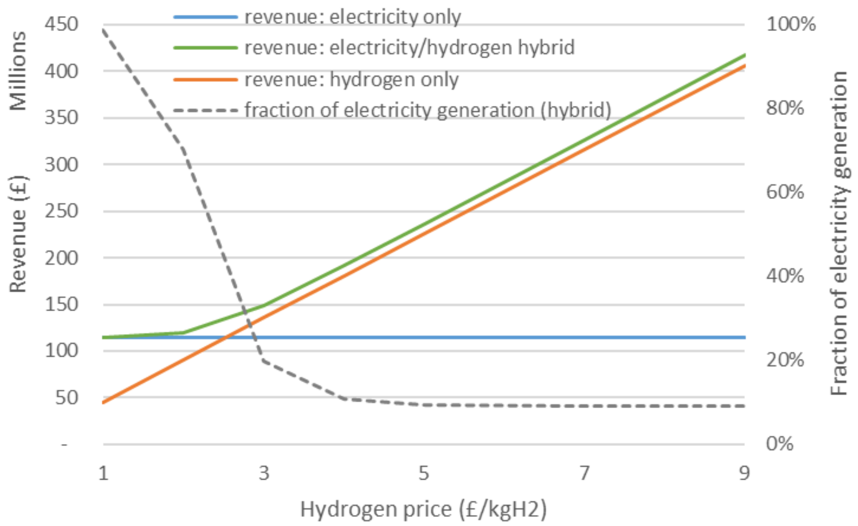


Figure 5.7 – The revenues and fraction of electricity generation of three wind farm configurations (i.e. electricity only, hydrogen only, hybrid) at different hydrogen prices

The results of the revenue of the hybrid system at different hydrogen prices are shown in Figure 5.7. The revenue curves of the electricity-only system (blue line) and the hydrogen-only system (amble line) are plotted on the diagram for comparison. It can be observed that the hybrid system tends to produce electricity when the hydrogen price is low and tends to produce hydrogen when the hydrogen price is high. The hybrid system has higher revenue than other systems when the hydrogen price is at a price of around £2.5-3/kgH_2 and about 30-50% of wind power is used to generate electricity. The hybrid system has a minimum electricity generation fraction of around 9% because the minimum load of electrolysers (e.g. 5%) is considered, and wind power generation could be over the maximum load of the hydrogen production system.

It is noteworthy that the analysis is based on revenue. The selection of the system configuration should also consider the cost of the system, which is higher for a hybrid system due to more components being needed (further analysis is carried out in section 6: Floating offshore wind system for different energy vectors).

In the future, the electricity prices or the carbon intensity of electricity could vary significantly with time. Therefore, it is important to have a system that can provide flexible generation, such as hybrid generation systems or systems integrated with energy storage. This module can be used to evaluate the impact of generation flexibility on revenues or carbon emissions reduction.

5.1.4 Energy system simulation output

The impact of integrating a 500 MW floating offshore wind farm on the carbon intensity of the electrical grid is selected to demonstrate the energy system simulation module. In this exercise, Great Britain's electricity system is simulated in two scenarios: 2020s and 2030. The 2020s scenario is based on the data of the GB's electricity system in 2021, and the 2030 scenario is based on the data from one of the National Grid's future energy scenarios – Leading the Way (National Grid ESO, 2022).

The input data and parameters of both energy systems are:

- generation capacity (e.g. power capacity of gas-fired power plants, wind, solar PV, nuclear, pump hydro)
- generation profile (e.g. onshore/offshore wind, solar PV)
- demand profile (e.g. electricity demand)

- transmission capacity (e.g. interconnector for electricity import/export)
- marginal cost of each generation unit
- operation limits (e.g. ramp up/down rate)

Detailed input data is summarised in Appendix C: Input data for advanced modules.

The operation of both energy systems to minimise the overall capital costs (fixed in this exercise) and operational costs is simulated by the energy system simulation module. The simulation results can be presented in several different diagrams. Detailed output data is summarised in Appendix D: Results from energy system simulation.

Figure 5.8 shows a stacked area chart of electricity generation in the national energy system in a winter month. At the demand site, it can be found that the electricity demand (equal to the total electricity generation) has significant variation within a day (lower at midnight and higher in the evening). At the generation site, it is obvious that wind power (purple area) has considerable variation over time, and combined cycle gas turbine (CCGT) power plants are adjusting the power to meet the demand. Other generation units (e.g. nuclear and biomass) have steady generation output. The time-series generation data can be converted into the carbon intensity of the electricity as shown in Figure 5.9.

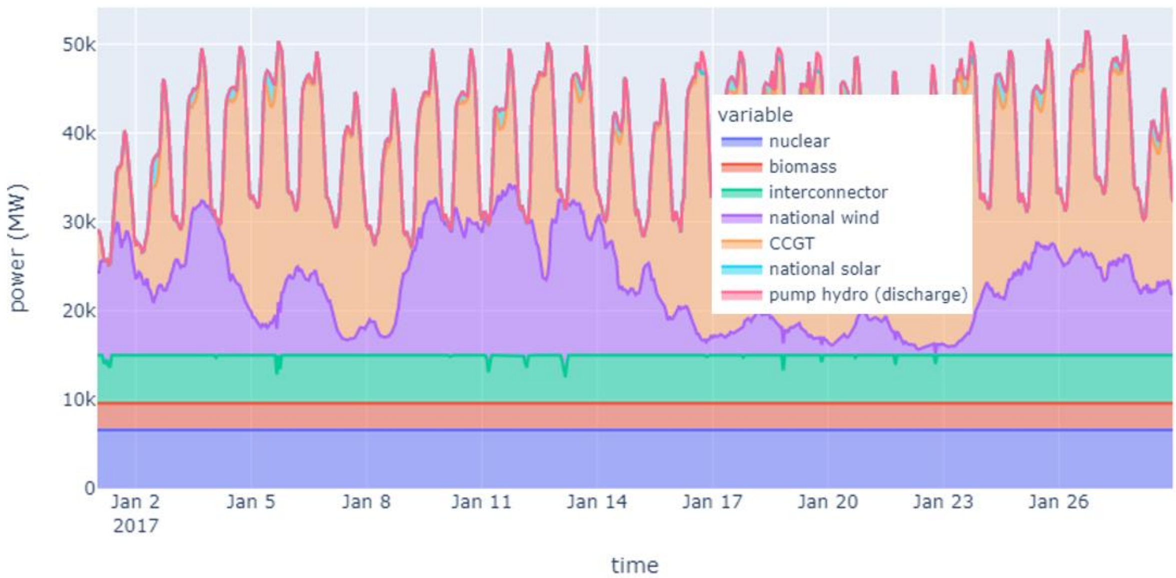


Figure 5.8 – The stacked area chart of electricity generation of national energy system in January in 2020s scenario; results from energy system simulation module

The electricity carbon intensity profile can be used to estimate the impact of integrating a 500 MW wind farm on the carbon emission of the energy system. Table 5.2 summarises the electricity carbon intensity and the carbon reduction by adding a 500 MW wind farm for electricity generation in the 2020s and 2030 scenarios. It can be found that carbon reduction is falling when the electricity grid is highly decarbonised low carbon energy sources. The alternative way to decarbonise the energy system is blending hydrogen produced from the wind farm into the natural gas grid to reduce the carbon emissions of the gas consumption. An approximate carbon reduction estimation based on the life cycle carbon emissions of natural gas (227 $kgCO_2/MWh_{\text{-thermal}}$) indicates that the hydrogen produced from a 500 MW wind farm can reduce 220 kt CO_2 carbon emissions in a year. This indicates that the condition in the energy systems can affect the effectiveness of selecting the type of energy to produce by the wind farm.

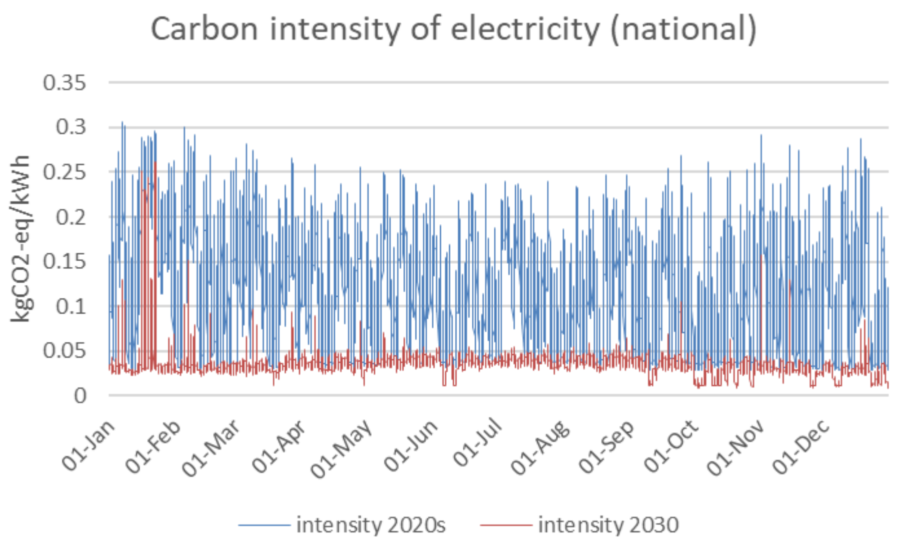


Figure 5.9 – Simulated carbon intensity of electricity in the national energy system in 2020s and 2030 scenarios

Table 5.2 – The carbon intensity and carbon emissions reduction by carbon emission

Parameter	2020s scenario	2030 scenario
Carbon intensity of electricity ($kgCO_2/kWh$)	0.134	0.035
Annual carbon emissions reduction by adding 500 MW wind farm for electricity generation ($ktCO_2$)	313	85

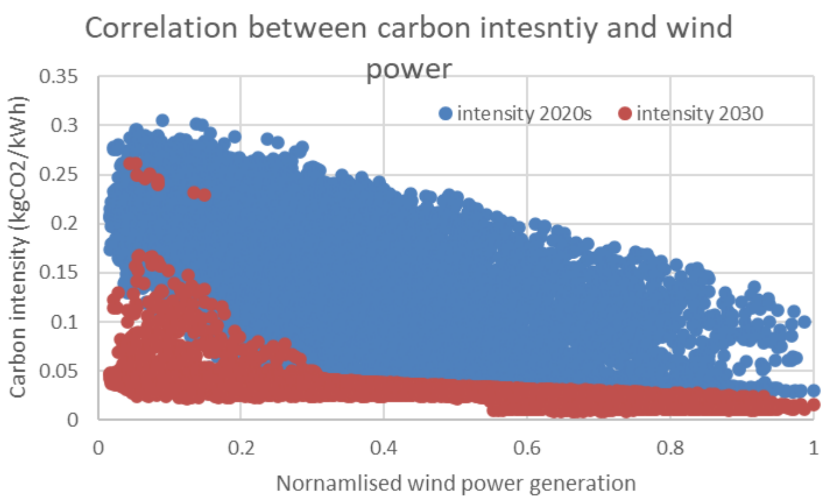


Figure 5.10 – The correlation between wind power and carbon intensity in 2020s and 2030 scenario

Figure 5.10 shows the correlation between wind power generation and the electricity carbon intensity in the 2020s and 2030 scenarios. It can be observed that the electricity carbon intensity is higher when wind power generation is lower. It is due to wind power has a significant share in the electricity generation, and dispatchable fossil fuel power plants such as CCGT have to produce more electricity to meet the demand at the low-wind period.

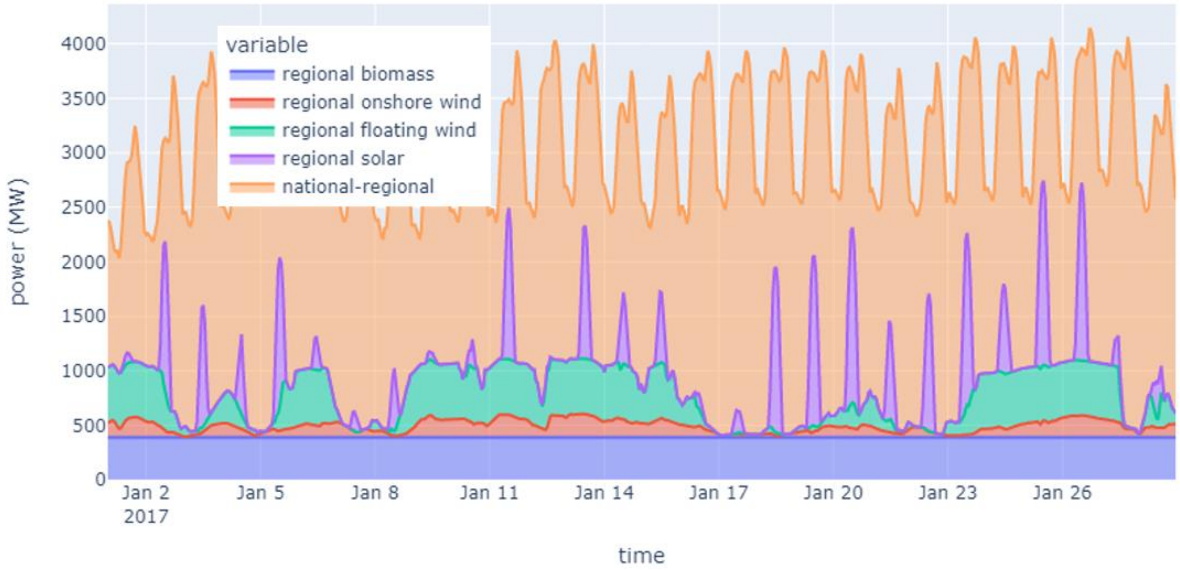


Figure 5.11 – The stacked area chart of electricity generation profile of South West England in January in 2020s scenario; results from energy system simulation module

The energy system simulation module can also simulate a regional energy system to investigate the impact of integrating wind farms on the local demand and power flow to the other regions. Figure 5.11 shows the simulated generation profile of the electricity system in South West England which has a 500 MW floating offshore wind farm integrated into the electrical grid. It can be found that the floating offshore wind generation (green area) has a positive correlation with the onshore wind generation (red area). This indicates that the power from the other regions or backup power is needed during a low-wind period, and energy storage can help to balance the supply and demand caused by the intermittency of wind power

5.2 System configurations for different energy vectors

This case study is to investigate the cost of the system configurations for different pathways discussed in section 2.2. Only three pathways (i.e. 1, 2 and 3) are selected to be studied in this report. Pathway 4 and 5 are not included in the analysis due to the availability of input data, especially in offshore liquid hydrogen and ammonia offloading and transport.

5.2.1 System configuration and input data

Three system configurations are selected to represent pathways 1, 2, and 3, respectively. The configurations and their key subsystems are shown in Table 5.3. The aim of this exercise is to investigate the impact of selecting different pathways. Therefore, the parameters that are not related to the pathway (e.g. wind power generators and inter-array transmission) are assumed to be the same across all configurations. The wind farm location and point of grid connection are also assumed to be the same. Table 5.3 summarises the major components of each subsystem.

The cost parameters of subsystems are summarised in Appendix B. The common parameters for the wind farm are:

- Power capacity of a wind turbine: 15 MW
- Distance between the manufacturing site and the installation port: 50 km
- Onshore transmission distance: 10 km
- Length of inter-array cable: 2,900 m
- Water depth: 100 m

Table 5.3 – The summary table of key components in four system configurations

<table>
<tr><th></th><th>Conf. 1
Electricity only</th><th>Conf. 2
Onshore hydrogen</th><th>Conf. 3
Offshore hydrogen and pipeline</th></tr>
<tr><td>Wind power generation</td><td colspan="3">Floating offshore wind generator</td></tr>
<tr><td>Inter-array transmission</td><td colspan="3">Inter-array cable</td></tr>
<tr><td>Offshore transformation / conversion</td><td colspan="2">Offshore substation</td><td>Offshore hydrogen production</td></tr>
<tr><td>Offshore transmission</td><td colspan="2">Offshore export cable</td><td>Offshore hydrogen pipeline</td></tr>
<tr><td rowspan="2">Onshore facility</td><td colspan="2">Onshore substation</td><td rowspan="2">-</td></tr>
<tr><td>-</td><td>Onshore hydrogen production</td></tr>
<tr><td>Onshore transmission</td><td>Onshore export cable</td><td colspan="2">Onshore hydrogen pipeline</td></tr>
<tr><td>Grid integration</td><td>Electrical grid</td><td colspan="2">Gas network</td></tr>
</table>

Table 5.4 – The list of major components of each subsystem

Subsystem	**Major component**
Floating offshore wind generator	wind turbine, floating platform, mooring line, anchor
Onshore substation	transformer, gas-insulated switchgear, converter (for HVDC)
Offshore substation	fixed/floating platform, onshore substation components
Onshore hydrogen production	AC/DC converter, desalination unit, electrolyser, compressor, backup battery
Offshore hydrogen production	fixed/floating platform, onshore hydrogen production components
Liquid hydrogen terminal	hydrogen liquefaction unit, liquid hydrogen storage, offloading unit
Onshore hydrogen terminal	loading unit, liquid hydrogen storage

In this example, the distance between the wind farm to the shore and wind farm power capacity are selected for the sensitivity analysis. It is because these two parameters have a significant impact on the cost of the transmission system. The range of these two parameters are:

- Offshore transmission distance: 100, 200, 300 km
- Power capacity of the wind farm: 500 MW and 2,000 MW

Noted that the change of distance to the shore will affects the distance to the O&M port. Therefore, the distance between the wind farm and the O&M port is assumed to be the distance of the transmission system plus 25 km, i.e. 75, 125, 225, and 325 km, respectively.

The power capacity of the wind farm not only affects the number of wind turbines but also the design of the transmission system. For configuration 1 and 2 (using electrical transmission), it is assumed that 500 MW wind farms have two offshore export cables and offshore substations, and 2 GW wind farms have six offshore export cables and offshore substations. This lower number per wind farm power capacity is based on the assumption that a higher voltage transmission can be used to increase the power capacity of each export cable and therefore reduce the number of cables and substations.

5.2.2 Results from the assessment framework

5.2.2.1 Lifetime cost comparison

The impact of distance to the shore and power capacity of wind farms are studied. Figure 5.12 shows the NPV cost of 500 MW wind farms with 100 km transmission distance in Configuration 1, 2, and 3. The NPV cost of Configuration 2 (onshore hydrogen) is about 18% higher than that of Configuration 1 (electricity only), which is attributed to the additional subsystem for hydrogen production. Compared to Configuration 2, Configuration 3 (offshore hydrogen) has a lower NPV cost (about 1%). It can be found that offshore hydrogen pipelines have a lower cost than offshore export cables, but the cost of offshore hydrogen production systems is much higher than the cost of the onshore hydrogen production system and offshore substations.

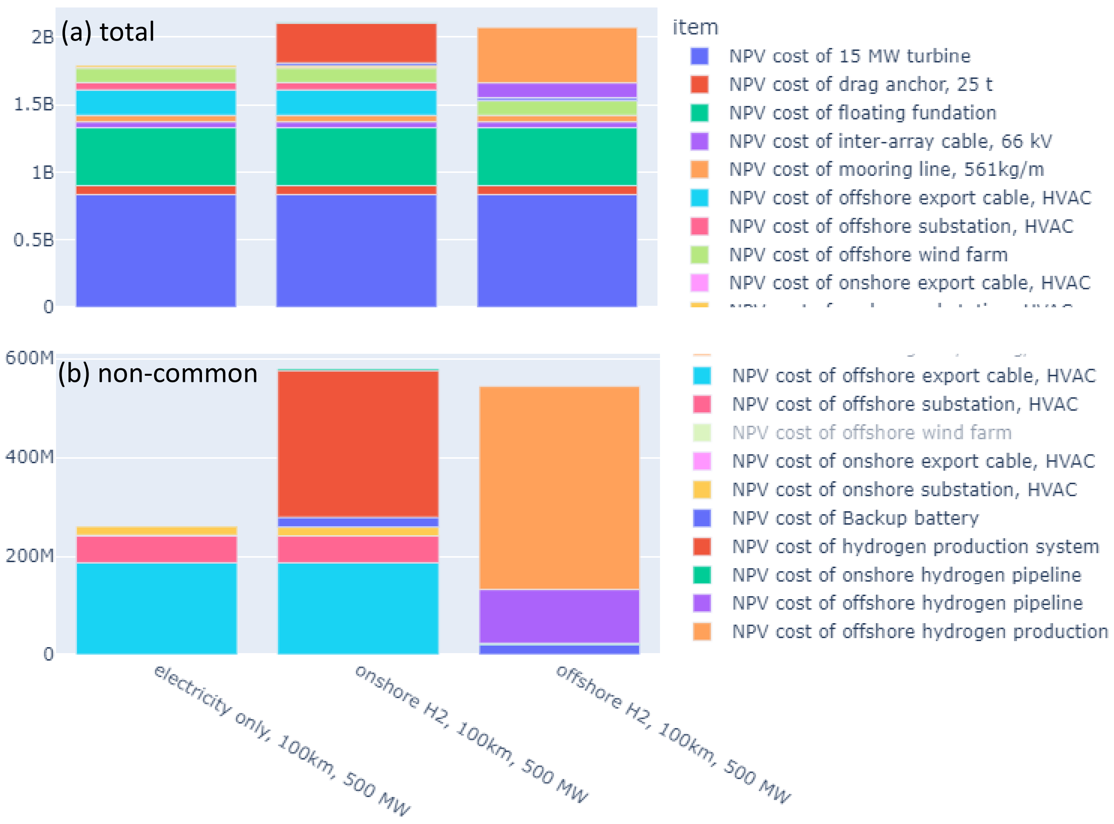


Figure 5.12 – NPV costs of configuration 1, 2, and 3 with 500 MW and 100 km transmission distance; (a) total NPV costs (b) NPV costs of non-common subsystem (exclude common subsystems such as wind turbines and floating platforms)

Figure 5.13 shows the NPV costs of 2 GW wind farms with 300 km transmission distance in Configuration 1, 2, and 3. Compared to the 500 MW wind farms with 100 km transmission distance, the cost of offshore export cable of 2 GW wind farms with 300 km transmission distance is 9 times much higher due to higher power capacity and longer transmission distance. However, the cost of offshore hydrogen pipelines is only 2.6-fold increase. It is because hydrogen can transport large amounts of energy in a single pipeline. Based on the formulation to estimate the hydrogen pipeline diameter (IEA, 2020), the inner diameter of pipelines to transport hydrogen produced from a 2 GW system is about 36 centimetres (or 14 inches), which is smaller than the pipelines used in the oil and gas industry (could up to 42 inches). This leads to a substantial cost reduction in installation and manufacture.

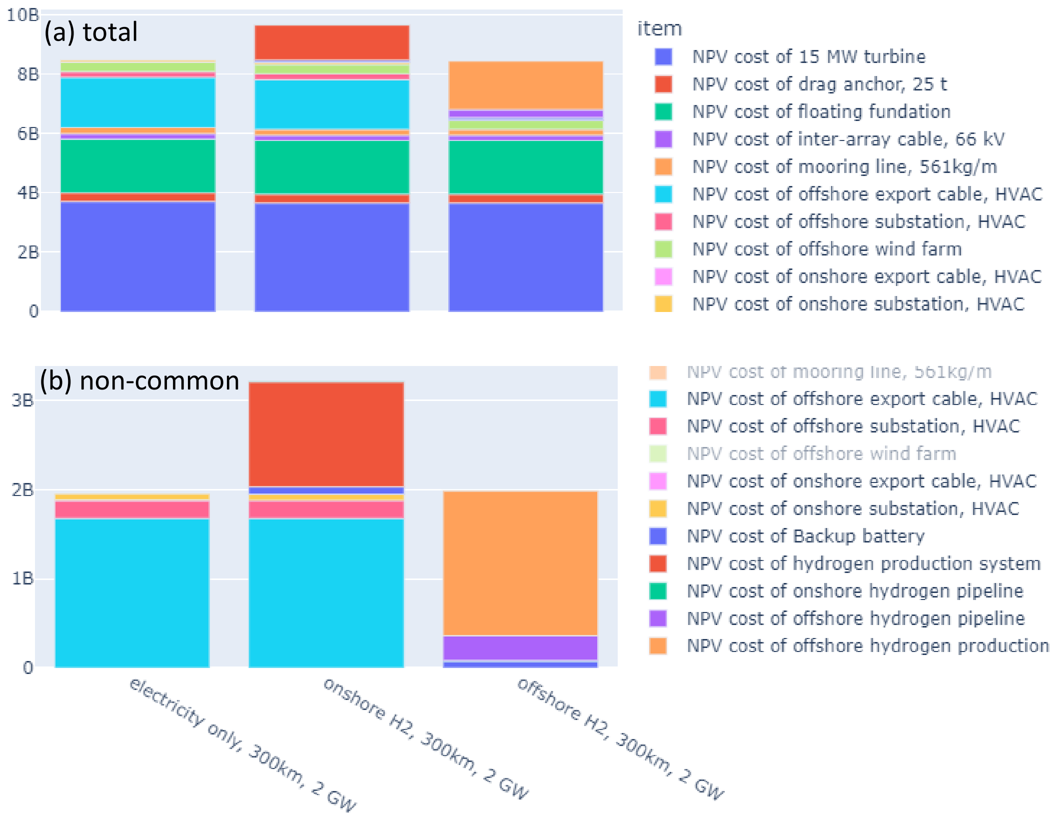


Figure 5.13 – NPV costs of configuration 1, 2, and 3 with 2 GW and 300 km transmission distance; (a) total NPV costs (b) NPV costs of non-common subsystem (exclude common subsystems such as wind turbines and floating platforms)

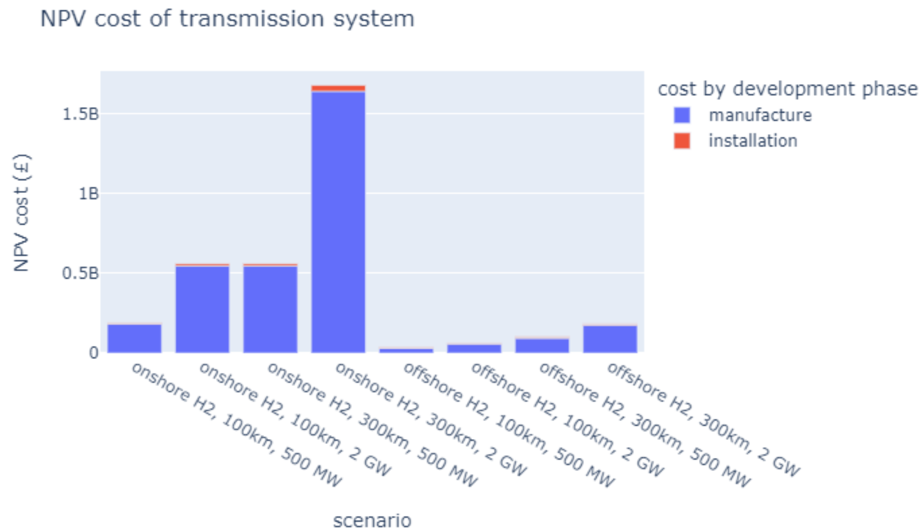


Figure 5.14 – NPV cost of transmission systems of onshore and offshore hydrogen systems at different conditions

Figure 5.14 shows the NPV cost of offshore transmission systems of onshore hydrogen (i.e. HVAC export cables) and offshore hydrogen (i.e. hydrogen pipelines) breakdown by development phases. The NPV cost of the transmission system in the onshore hydrogen system (offshore HVAC export cables) is much higher than the NPV cost of the offshore hydrogen system (hydrogen pipeline). It is worth noting that using HVDC instead of HVAC could reduce the cost of the electrical transmission system (see section 2.1.1) for long-distance transmission. Detailed costs and technical data are needed to consider HVDC in the analysis.

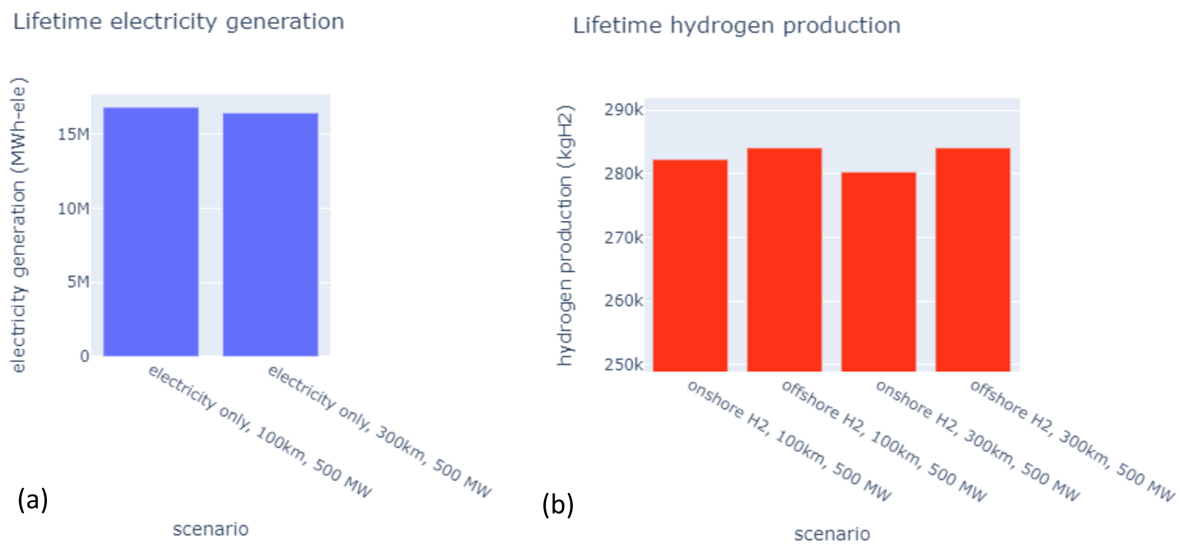


Figure 5.15 – Lifetime (a) electricity generation and (b) hydrogen production of different system configurations at 100 and 300 km of transmission distances

5.2.2.2 Energy production comparison

Figure 5.15 shows the lifetime electricity generation and hydrogen production of different system configurations and transmission distances. In electricity generation systems (see Figure 5.15a), the electricity generation is calculated based on the hourly wind speed data and the power curve of the selected wind turbine. The energy losses in the transmission (i.e. inter-array cables, substations, export cables) are also considered. Thus, the system with a 300 km transmission distance has 0.6% lower electricity export than the system with a 100 km transmission distance. For the hydrogen production systems (see Figure 5.15b), the wind power is first converted into electricity and is then used to power the hydrogen production systems. The electrical power losses in inter-array cables and AC/DC converters are considered. Hydrogen production is calculated based on the energy consumption in each component in the hydrogen production system, i.e. desalination units, electrolysers, and hydrogen compressors. Noted that the system downtime and energy losses during battery charging and discharging are not yet considered in this analysis.

5.2.2.3 LCOH comparison

Figure 5.16 shows the levelised cost of hydrogen (LCOH) in different configurations (i.e. onshore and offshore hydrogen production), wind farm power capacities (i.e. 500 MW and 2 GW), and transmission distances (i.e. 100 km and 300 km). At the same power capacity and transmission distance, the LCOH of offshore hydrogen systems is always lower than the LCOH of onshore hydrogen systems. With the same transmission distances, the LCOH reduces with the increase of the wind farm power capacity. The LCOH is higher with the increase of the transmission distance, but the LCOH increase in offshore hydrogen systems is less for the offshore hydrogen system.

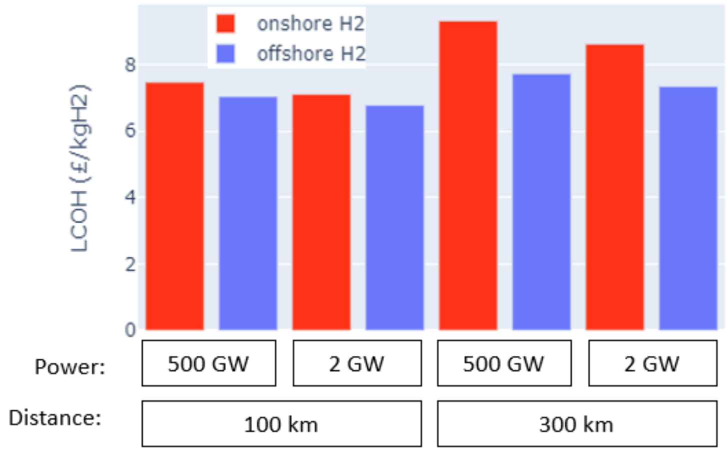


Figure 5.16 – Levelised cost of hydrogen in different system configurations (onshore vs. offshore hydrogen), wind farm power capacities (500 MW vs. 2 GW), and transmission distances (100 km vs. 300 km)

5.2.3 Summary of this case study

The preliminary results show that the cost of HVAC electrical transmission systems can increase significantly with the increase of the transmission distance and/or wind farm power capacity, and this cost increase is less for hydrogen pipeline systems due to they can carry high amounts of energy in a single pipeline with limited energy losses. The external factors (e.g. energy prices and parameters in the energy system) that affect the selection of system configurations are discussed but not investigated in the report due to the lack of data and the time limitation.

To have a comprehensive analysis of different system configurations of a wind farm, more site-specific data are required to provide a detailed cost and carbon emissions analysis. For example, the metocean data at the wind farm, and the costs and parameters of the transmission system by considering the environmental conditions. Since most of the offshore hydrogen technologies are not mature yet, the uncertainty in technology development and cost reduction needs to be considered in the analysis as well. Collaborations with stakeholders are needed to develop and validate the framework proposed in this report.

5.3 Deployment of low-carbon vessels for offshore wind operation

Offshore wind farms generate a significant amount of energy on the sea, and that energy can be used to power the shipping sector nearby. In previous sections, the potential alternative marine fuels to decarbonise the shipping sector (see section 3.2). The pathways to produce different types of low-carbon fuels from offshore wind power are reviewed and discussed in section 2.2.

In this case study, the energy efficiency of producing three low-carbon fuels (i.e. electricity, hydrogen, and ammonia) from offshore wind power is analysed. Firstly, the potential fuel production from a wind farm is estimated based on the energy efficiency of each conversion and transmission step. Secondly, the amount of required energy to decarbonise the installation and operational activities of a floating offshore wind farm is discussed.

5.3.1 Low-carbon marine fuels produced from wind power

Low-carbon marine fuels can be produced by wind power via different pathways. The wind farm system configurations and their cost to convert wind power into different types of fuels are studied in section 2.2.1. However, the energy efficiency of using those fuels in the vessels is not discussed, and this efficiency affects the amount of wind power required to decarbonise the shipping sector. Thus, similar to the well-to-wheel analysis for road vehicles, a well-to-propeller analysis is used to analyse the required conversion and transmission processes from the primary energy source to drive the propeller in a marine vessel.

Figure 5.17 shows the general figures of the energy efficiency in conversion and transmission steps in well-to-tank and tank-to-propeller processes for three types of fuels: fossil fuels, low-carbon fuels, and electricity. The vessel using low-carbon fuels has very similar tank-to-propeller efficiency as the vessel using fossil fuels, but its well-to-tank efficiency is much lower due to the energy losses in the fuel synthesis process. Compared to the vessels using low-carbon fuels, the electric vessel has both higher well-to-tank and tank-to-propeller efficiency. Therefore, electric vessels consume less primary energy (i.e. electricity) than vessels using low-carbon fuels.

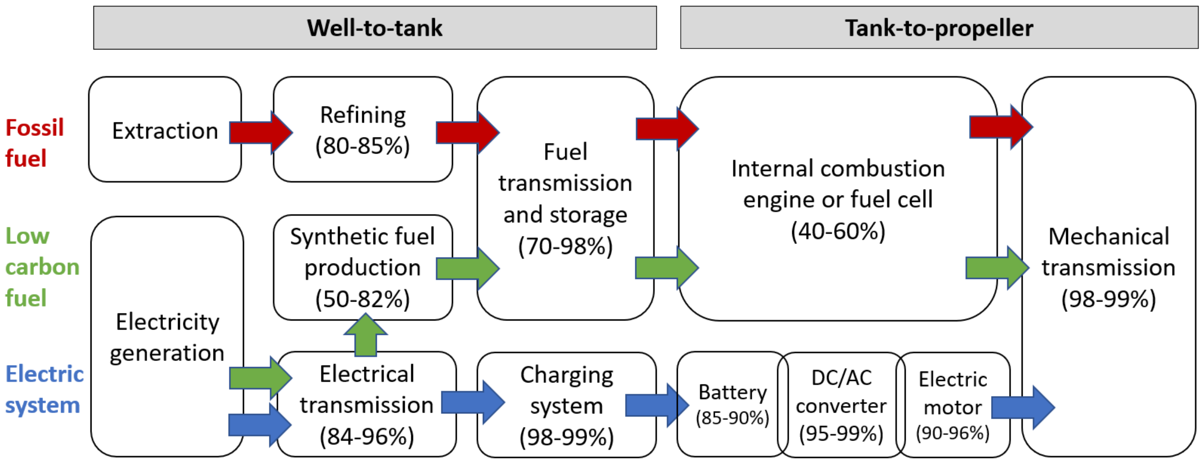


Figure 5.17 – Energy efficiency in well-to-tank and tank-to-propeller steps of fossil fuels, low-carbon fuels, and electric vessels

Table 5.5 – The well-to-tank and tank-to-propeller efficiency for marine diesel (baseline) and low-carbon alternatives

	Marine diesel	Renewable electricity	Green hydrogen	Green ammonia
Well-to-tank efficiency	-	95-98%	Compressed: 60-70% Liquid: 50-60%	45-55%
Tank-to-propeller efficiency	40-50%	73-86%	Fuel cell: 50-60% Engine: 40-50%	40-60%
Overall efficiency	-	69-84%	20-42%	18-33%

It is worth noting that, the energy consumption of fossil fuels is usually based on the energy content (also called heat value or calorific value) of the fuel. The upstream or well-to-tank processes (e.g. fuel extraction and refining) are not considered. This principle is applied in the lifetime framework introduced in section 4.

To estimate the amount of wind power required to produce the alternative fuels, the well-to-tank and tank-to-propeller efficiency of producing three alternative fuels (i.e. renewable electricity, green hydrogen, and green ammonia) from wind power are summarised in Table 5.5. The methods for hydrogen storage (i.e. compressed hydrogen or liquid hydrogen) and power generation technologies (i.e. fuel cells or combustion engines) have a considerable impact on energy conversion efficiency. Therefore, their efficiencies are listed in Table 5.5.

5.3.2 Vessel fuel consumptions in a floating wind farm

The 500 MW example wind farm presented in section 5 is selected to demonstrate the amount of wind power needed to produce the low-carbon fuels for the offshore wind farm operation vessels. Based on the results from the assessment framework, the lifetime fuel consumption of the vessels is about 158,000 cubic metres of marine gas oil. This is equivalent to 6,745 terajoules (or 1,873 GWh) of heat values. For reference, the electricity generation of the example wind farm in 25 years is about 67,500 GWh.

The required amounts of low-carbon fuels and wind power to decarbonise the fleet of the example wind farm are calculated based on the efficiency shown in Table 5.5, and the results are summarised in Table 5.6. Firstly, the lifetime energy consumption at the tank of each low-carbon fuel is calculated by the tank-to-propeller efficiency. It can be found that the energy consumption for electric vessels is lower than others due to their high tank-to-propeller efficiency. Secondly, the equivalent volume and weight of each fuel are calculated by the energy density and specific volumes shown in Table 3.1. The weight of hydrogen is only a sixth of the weight of ammonia, but the fuel volume is about 1.5 – 2.7 times higher. This does not include the volume and weight of high-pressure or cryogenic tanks. Lastly, the electricity consumption to produce each low-carbon fuel is calculated based on the well-to-tank efficiency. It can be found that electricity needed for electric vessels is much lower than other fuels, and green ammonia needs higher electricity to produce than others. Noted that the above calculation is purely based on energy efficiency, and many factors (i.e. required space for fuel tank or battery systems) are not taken into account.

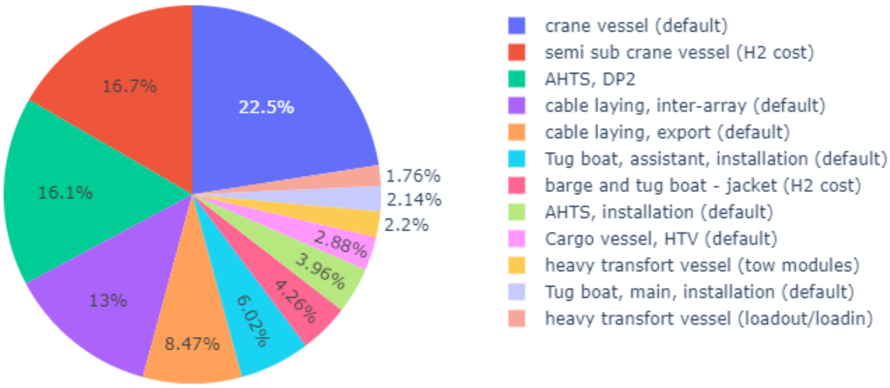
Table 5.6 – Estimated lifetime fuel consumptions for installation and O&M activities of a 500 MW example wind farm using different alternative fuels

	Marine diesel	Electricity	Green hydrogen	Green ammonia
Lifetime energy consumption at the tank (GWh)	1,874 (heat value)	1,061 (electricity)	1,533 – 1,874 (heat value)	1,686 (heat value)
Lifetime fuel consumption (tonne)	134,000	-	46,000 – 56,000	321,000
Lifetime fuel consumption (m^3)	158,000	-	Compressed: 1,263,000, Liquid: 711,000	472,000
Electricity consumption for fuel production (GWh)	-	1,099	2,594 – 3,066	3,373

The installation and operation tasks of offshore wind farms utilise different types of vessels. Figure 5.18 shows the lifetime fuel consumption of installation and O&M activities of the example wind farm. Each of the vessels can be more suitable to use a certain type of low-carbon fuel than the others. Thus, it is likely that multiple low-carbon fuels will be used to decarbonise the fleet for offshore wind farm services. For example, heavy lifting vessels and heavy transport vessels may be suitable to use ammonia as the fuel due to high energy consumption during the operation, and crew transfer vessels for a short distance with a daily operation pattern may be suitable to use electric systems. Further research considering detailed operational parameters and vessel design is required to identify the suitable low-carbon fuels for each vessel.

It is important to note that many factors could affect the type of vessels being used for the wind farm. For example, the results in Figure 5.18b are based on the O&M strategy that heavy lifting vessels are used for major component maintenance. The alternative for major maintenance is the tow-to-port strategy (i.e. towing the floating wind turbine generator to the port for maintenance by tugboats). Using unmanned vehicles could also replace the use of vessels for routine survey services.

(a) fuel consumption for installation by vessels



(b) fuel consumption for O&M by vessels

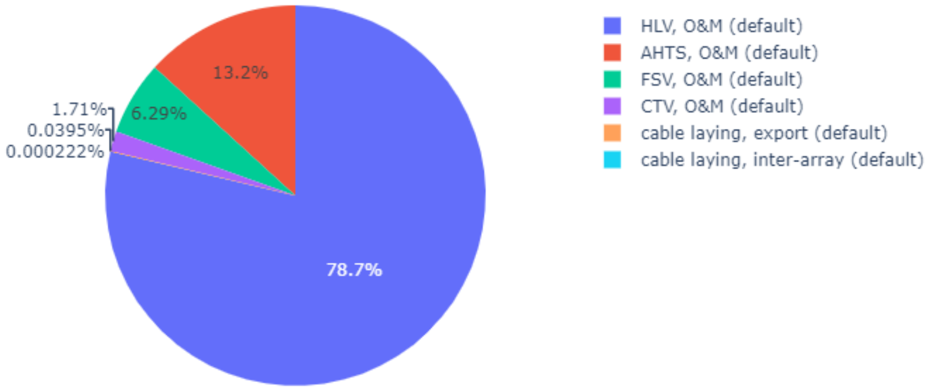


Figure 5.18 – The fuel consumption breakdown by vessel types for (a) installation tasks and (b) O&M tasks of the example wind farm

6 Summary

This report provides a high-level overview of the potential energy vectors that could be used in the low-carbon energy system and the shipping sector. The development of technologies that integrate floating offshore wind with different energy vectors and low carbon vessels is also reviewed. An assessment framework to evaluate the key performance indicators (i.e. cost, carbon emissions, and energy invested/return) of floating offshore wind systems is introduced to analyse the impact of integrating the system with energy vectors and low-carbon vessels. The capability of the calculation modules in the framework is demonstrated in the cost analysis of system configurations for different energy vectors (i.e. electricity and hydrogen) and energy efficiency analysis for various low-carbon fuels. Detailed data for the specific site and/or technology are needed to provide a comprehensive analysis of wind farms.

6.1 Key messages

Energy vector analysis:

- Offshore wind farms with corresponding configurations and components can generate power in various energy vectors that are needed to decarbonise the energy system and the shipping sector.
- Selecting suitable system configurations for an offshore wind farm is dependent on both internal (e.g. environmental conditions, system design and costs) and external factors (e.g. energy prices and the demand in the energy system) of a wind farm.
- The assessment framework introduced in this report can be used to investigate both the internal and external factors, but detailed data are needed for the comprehensive analysis.
- The preliminary cost analysis shows that cost of offshore hydrogen pipelines is lower than the cost of offshore HVAC export cables for the wind farm with a high power capacity and/or a long transmission distance.

Low-carbon vessels:

- The most promising low-carbon marine fuels are electricity, hydrogen, ammonia, and methanol. Each of them has its pros and cons and may be suitable for different applications.
    - The energy efficiency of electric vessels is 2 to 2 times higher than other fuels, but the energy density of batteries is 4 to 15 times lower than others.
    - Hydrogen has an energy density of 3 to 8 times higher than batteries but has harsh storage conditions (i.e. 700 bar or -253˚C).
    - Ammonia has an energy density 50% higher than hydrogen, less extreme storage conditions (i.e. 5 bar or -35 ˚C), and many existing infrastructures are available around the world. However, its capital cost and energy loss for production are higher than hydrogen.
    - Methanol has an energy density similar to ammonia however can be stored more easily. However, carbon dioxide is needed as feedstock, and burning methanol has local carbon emissions.
- Multiple low-carbon fuels are likely to be needed to decarbonise the fleet for offshore wind farm operations. Electric vessels are suitable for daily and short-distance operations. Other low-carbon fuels are more suitable for heavy and long-distance operations.
- The installation and O&M strategies of offshore wind farms affect the fleet combination and therefore the required low-carbon fuels for decarbonising.

6.2 Research challenges

Techno-economic assessment can provide quantitative evidence to the decision-making process, and an effective and accurate assessment can reduce the total spending time and cost in developing a solution. Since most of the technologies mentioned in this report are in the early stages of development, how to reduce the uncertainty in the assessment or properly reflect the uncertainty in the assessment is one of the key challenges in the project. Moreover, floating offshore wind systems are complex systems that involved the integration of different subsystems (e.g. floating platforms and mooring systems) and environmental parameters (e.g. metocean and geotechnical conditions). How to investigate the intercorrelation between different subsystems or research domains (e.g. ocean engineering and operations management) is another challenge. One of the scopes to develop the E^c simulator is to overcome the challenges mentioned above, and this requires collaboration between stakeholders in different fields such as research institutions, industrial partners, and policymakers.

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Appendix

A. LCOE calculation

Levelised cost of energy (or electricity) can be calculated in different ways. One of the common calculation is as follows (BIES, 2020):

Step 1: Gather Plant Data and Assumptions

Capital Expenditure (Capex) Costs:	Operating Expenditure (Opex) Costs:	Expected Generation Data:
• Pre-development costs • Construction costs* • Infrastructure costs* *adjusted over time for learning	• Fixed opex* • Variable opex • Insurance • Connection costs • Carbon transport and storage costs • Decommissioning fund costs • Heat revenues • Fuel prices • Carbon costs	• Capacity of plant • Expected availability • Expected efficiency • Expected Load Factor* (all assume baseload generation with no curtailment)

Step 2: Sum the net present value of total expected costs for each year

$$\text{NPV of Total Costs} = \Sigma_n \frac{\text{total capex and opex costs}_n}{(1+\text{discount rate})^n} \qquad n = \text{time period}$$

Step 3: Sum the net present value of expected generation for each year

$$\text{NPV of Electricity Generation} = \Sigma \frac{\text{net electricity generation}_n}{(1+\text{discount rate})^n} \qquad n = \text{time period}$$

Step 4: Divide total costs by net generation

$$\text{Levelised Cost of Electricity Generation Estimate} = \frac{\text{NPV of Total Costs}}{\text{NPV of Electricity Generation}}$$

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B. Input data for example wind farm

The key parameters and assumptions for the capital cost of each subsystem used in the report are summarised in Table B.1. The cost for assembly, installation, operations and maintenance, and decommissioning tasks are calculated by Task and Operation module and therefore not listed in the table.

Table B.1 – Cost parameters of subsystems used for the energy vector analysis

Subsystem	Specification	Development phase	Unit	Value	Note
wind farm	-	pre-development	£/MW	33,325	engineering & certification, development & consenting, environmental/geophysical surveys
		pre-development	£/project	34,615,000	development & consenting, environmental/geophysical surveys, Met station
		operation	£/MW/year	16,340	operating insurance, general operations costs
		operation	£/year	860,000	general operations costs
wind turbine	15 MW	manufacture	£/MW	1,061,025	turbine supply cost and premium
floating platform	15 MW semi-submersible	manufacture	£/kg	3.6	steel semi-submersible
anchor	25 tonne	manufacture	£/kg	5.5	
mooring line	steel; catenary	manufacture	£/kg	1.9	
inter-array cable	66 kV	manufacture	£/m	468	cable and accessories
offshore substation	HVAC	manufacture	£/MW	93,500	
export cable	HVAC	manufacture	£/m	1,210	
onshore substation	HVAC	capital	£/MW	46,750	manufacture and installation
onshore hydrogen production	85% of wind farm capacity	manufacture	£/MW	900,000	converter, electrolyser, desalination, compressor
offshore hydrogen production	85% of wind farm capacity	manufacture	£/MW	1,237,275	hydrogen production system, jacket, and piles
battery system	10% of wind farm capacity	manufacture	£/MW	529,000	
hydrogen pipeline	18 cm inner diameter	manufacture	£/km	411,873	
	36 cm inner diameter	manufacture	£/km	774,937	
	-	operation	% of CAPEX/year	0.00001%	

C. Input data for advanced modules

The hourly day-ahead electricity price in the UK market in 2019 is used to demonstrate the energy generation simulation module. Normalised electricity demand (by the maximum value) in the Great Britain and South West England are used in the energy system simulation module. The power capacity of each generation and storage units in the national (Great Britain except South West) and regional (South West England) are used for the energy system simulation.

The order of marginal cost of each power generation units are:

Coal > OCGT > CCGT > biomass > nuclear >

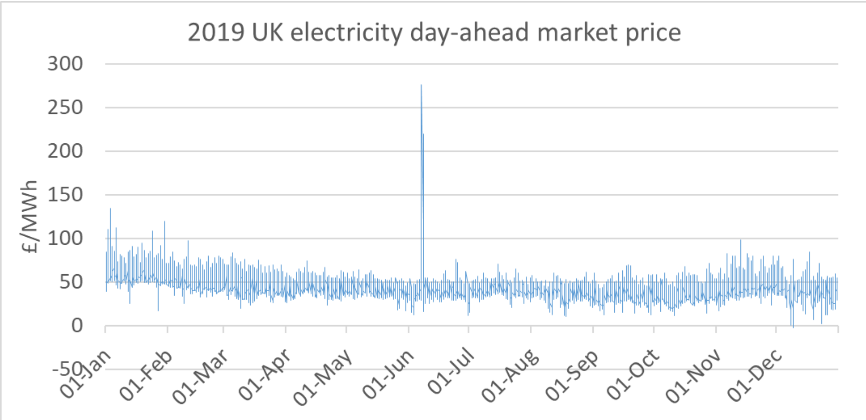

Figure C.1 – The UK's electricity day-ahead market prices in 2019

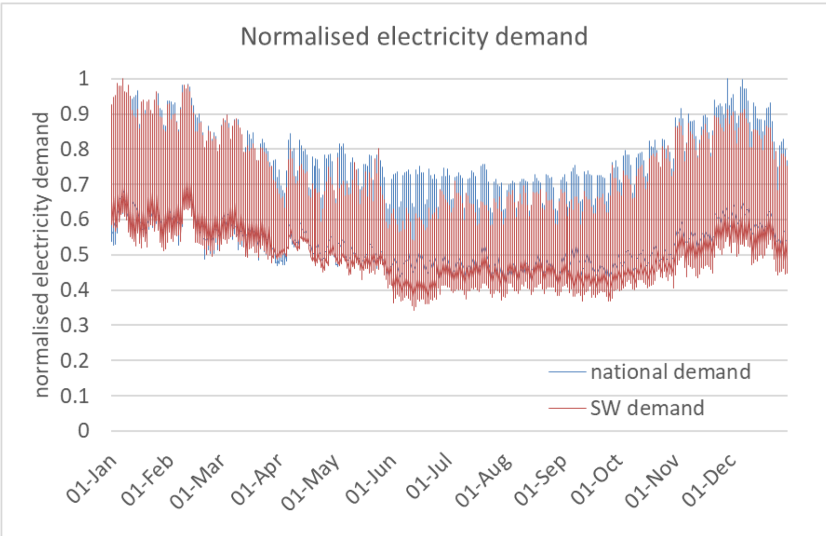

Figure C.2 – Normalised electricity demand in the Grate Britain and South West England in 2021

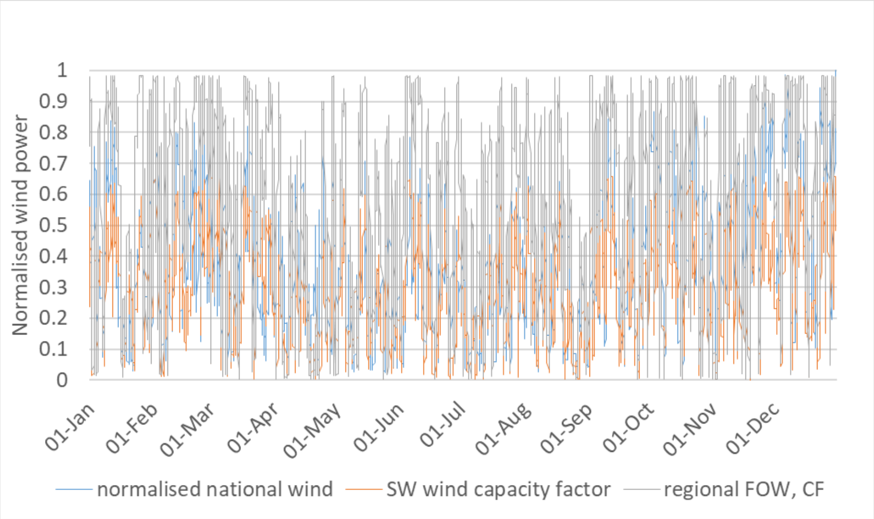

Figure C.3 – The normalised capacity of national wind power, regional wind power, and regional floating offshore wind

Table C.1 – The power capacity of geenration and storage units in national and regional energy systems in 2020s, 2030s, and 2050 (data source: National Grid Future Energy Scenrios; Leading the Way scenario)

Energy system	Generation / Demand	2020s	2030	2050
National	CCGT (GW)	30.0	28.0	15
	Coal (GW)	1.5	0.0	0
	OCGT (GW)	1.5	1.5	1.5
	Biomass (GW)	3	4.4	6.0
	Nuclear (GW)	6.6	5.6	5.0
	Interconnector (GW)	5.4	22.0	28.0
	Wind power (GW)	23.0	74.0	127.0
	Solar PV (GW)	9.8	32.3	89.0
	Pump hydro and storage (GW)	3.0	16.0	43.0
	Electricity demand (TWh)	299	319	449
Regional	Onshore wind	0.3	0.4	1.0
	Solar PV	3.2	7.7	15.7
	biomass	0.4	0.4	0.4
	Electricitiy demand (TWh)	24	27	38

Note: CCGT is combined cycle gas turbine; OCGT is open cycle gas turbine

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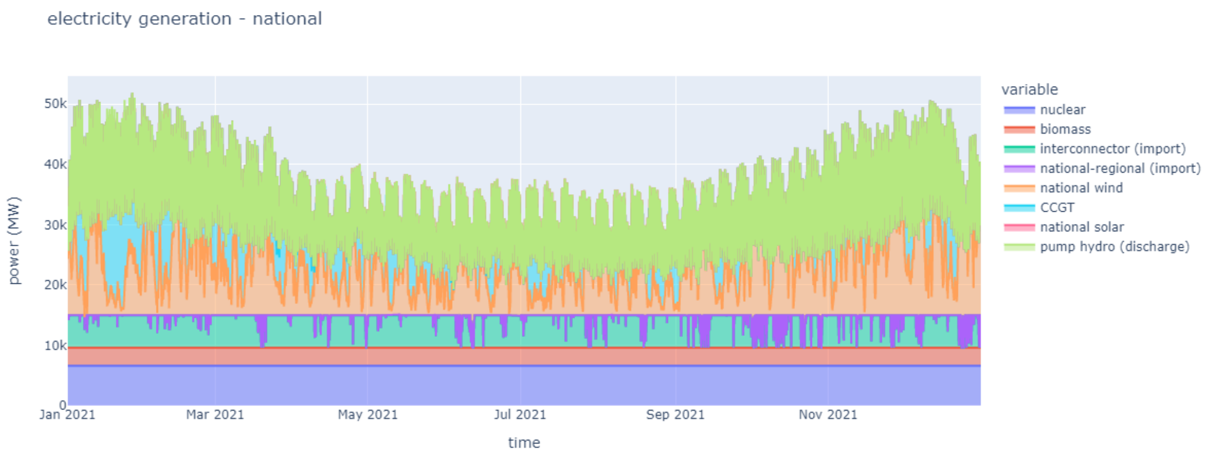
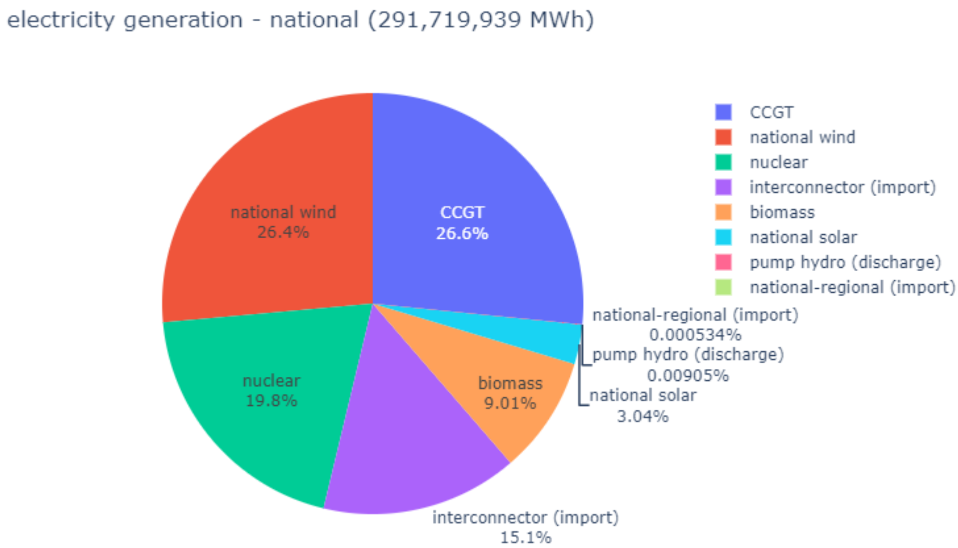
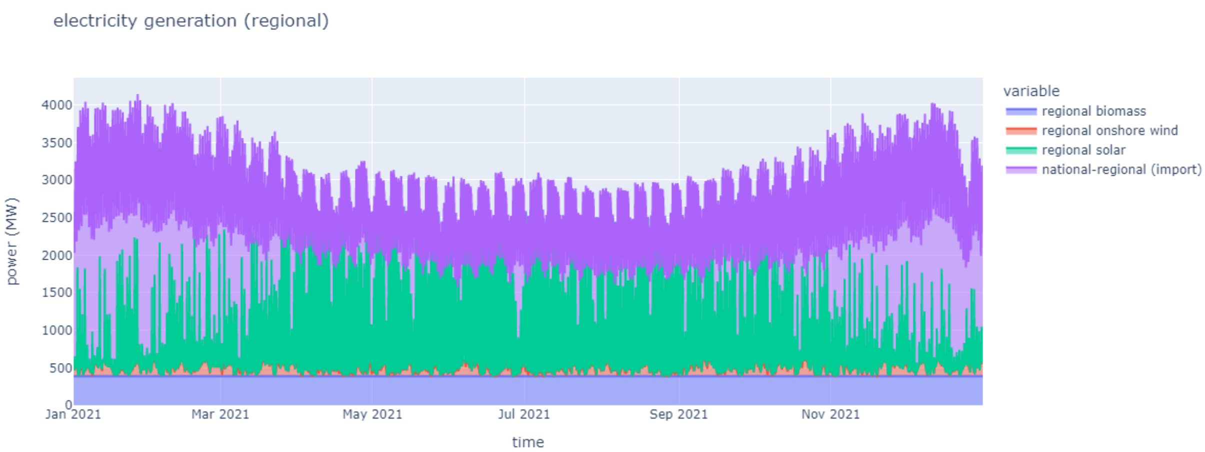
D. Results from energy system simulation







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