Department of Mechanical and Aerospace Engineering

Investigation into Electrification of Vessels for Offshore Wind Farm Service

Author: Brendan MacKinnon

Supervisor: Cameron Johnstone

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Abstract

This paper will explore the intrinsic link between the growth of offshore wind and the potential for alternatively fuelled fleets performing the costly operations and maintenance for the UK's wind farms. Offshore wind is set to grow even further as turbines' efficiency and size increase at the same time costs are being reduced in the industry. While offshore wind is maturing exponentially, alternatively fuelled vessels are only just beginning to develop. There are various sources of fuel and propulsion that can operate at lower costs and emissions to the traditional internal combustion engine (ICE) operating on marine gas oil. However, thus far, focus has been on large vessels that operate at low to moderate speeds. This paper identifies the most favourable technology for transitioning small and slightly larger new generation high speed vessels used for crew transfers to offshore wind farms both close and far from shore respectively. A full cost analysis reveals that for both vessels, GHG emissions can be reduced while long term profits are increased through the implementation of battery hybrid technology.

Acknowledgments

I would like to thank my academic supervisor Cameron Johnston for continual support and guidance throughout completing this individual project. I would also like to thank Jason Schofield from Green Marine for sharing his expertise on Wind Farm Support Vessel and allowing me to use their vessel in my case study. I would also like to the team at CMAL who provided guidance on marinized hybrid technology. Finally, I would like to thank Roberts Proskovics and his colleagues at ORE Catapult for aiding me with valuable information about the offshore wind industry and innovation.

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1.0 Introduction

1.1 Background

As a global civilisation, humans are coming to terms with the climactic consequences of the industrial revolution and beginning the mitigation process in order to stop the course of climate change, which is threatening our species very existence. In the UK, one of the most promising avenues of mitigation is the development of offshore wind as an industry. The UK has the most installed offshore wind capacity in the world and in the last decade, the industries share of UK generation increased from 0.2% to 10% (UK Governemnt, 2019a). As the industry both expands and matures the operations and maintenance (O&M) cycle of these wind farms will increase exponentially, leading to increased costs and emissions in operation.

Marine vessels contribute 3% of total human-kind CO_2 emissions. The International Maritime Industry (IMO), along with governmental bodies across the world are introducing stricter controls on emissions, which has paved the way for alternatively fuelled vessels (DNV GL, 2019). Although still in their infancy, these technologies offer a potential double benefit of reducing fuel consumption and replacing with something cheaper, while reducing exhaust emissions.

1.2 Problem Statement

The offshore wind industry must address the potentially hazardous rise in marine emissions related to its O&M strategies. Investment must be made in research and development of fleet infrastructure in order to minimize expenditure and emissions.

1.3 Aim & Objectives

1.3.1 Aim

Investigate the potential of hybrid vessels for offshore wind operations and maintenance, in relation to reducing emissions and costs for both short and long-distance vessels.

1.3.2 Objectives

- Provide forecast into both the rise of offshore wind and the nature of its operations and maintenance.
- Investigate the technology behind alternative marine propulsion and compare vessel technologies, suggesting most favourable for offshore wind maintenance.
- Investigate the feasibility of using wind power for charging at port.

- Perform case study for a 1GW wind farm comparing traditional vessel to alternatively fuelled one.
- Analyse the potential emissions/economic savings and relate this to IMO's 2050 target.

1.4 Scope

1.4.1 Targets Set in All Sectors

There is overwhelming support for governments to reduce greenhouse gas emissions (Directorate General for Communication, 2017). This has been increasingly reflected in policy throughout Europe as 2050 draws closer (European Comission, 2019), which has become the conventional date for major change. Two sectors that are set for a radical transition are both energy and transport.

Energy

Scotland has legislated for a CO_2 reduction of 90% in relation to 1990 levels by 2050, and a 66% reduction by 2032 (Scottish Government, 2018b). The Scottish Government aims to have parity between renewable energy generation and gross electricity consumption by 2020 and to be 100% renewably powered by 2045 (Scottish Government, 2018a).

Transport

Transport is responsible for close to a quarter of Europe's CO_2 emissions and contributes greatly to air pollution in urban areas (European Commission, 2019). The European Union has made a large amount of funding available for local council areas to implement infrastructure for electric vehicles and the transition is well under way. Scotland has set a target to phase out new petrol and diesel cars by 2032 in line with this European transition. (Scottish Government, 2018b)

The EU have faced difficulty addressing the full extent of their transport emissions as 13% of the total emissions are made up of maritime sector (European Commission, 2019). UN based IMO is the primary legislator for maritime targets. Some key actions taken by the IMO include:

- Set a target for 50% cut in all emissions by 2050. (IMO, 2018)
- Introduced a tax for bunker fuels that are high in dangerous pollutants such as Sulphur Oxides (SOx). (IMO, 2019a)
- Vessels in busy ports, such as those in the English Channel must connect to shore power, rather than run generators overnight at port. (Global Maritime Energy Efficiency Partnerships, 2018)

- From 2021 Tier III limits on SO_X and Nitrous Oxides (NO_X) emissions will force most new traditional vessels to invest in potentially expensive exhaust cleaning apparatus and switch to low sulphur fuels (IMO, 2019b)

The IMO Tier regulations are best described in Figure 1:

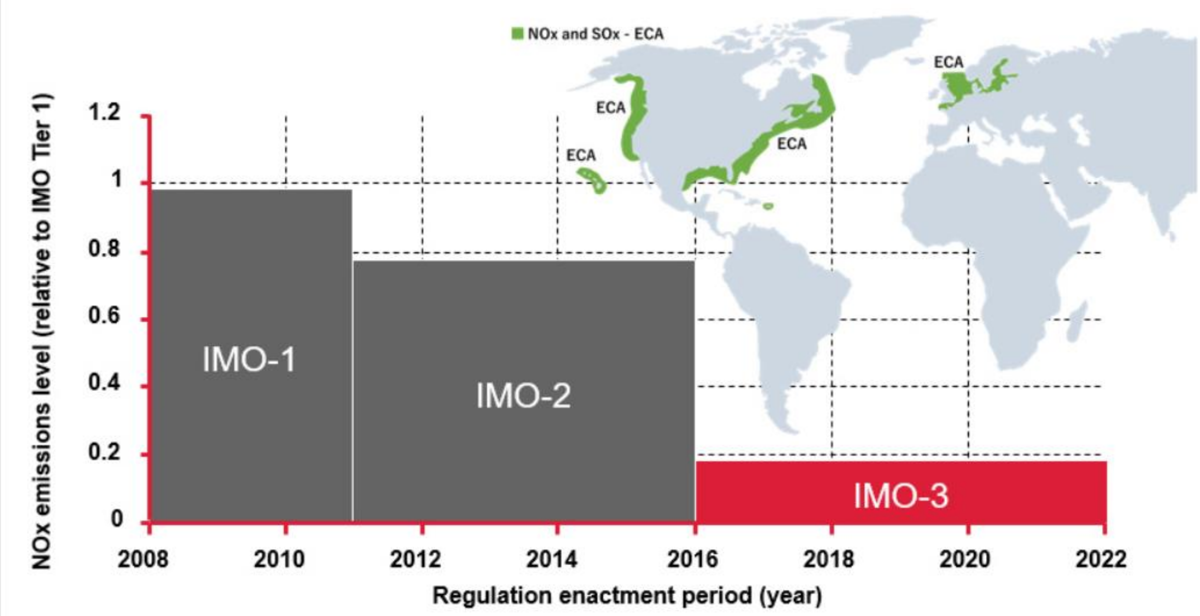


Figure 1 - IMO NO_X Tier Regulations (Yanmar, 2018)

1.4.2 Targets Have Led to Innovations

Legislating for change and funding research has brought about innovative technologic advancements for each sector. The UK’s renewables accounted for 33% of the total energy mix in the fourth quarter of 2018 at 44GW (UK Government, 2019b). This has been largely due to the growth of offshore wind as a technology, allowing for larger turbines further out to sea.

Furthermore, the 2019 sector deal negotiated by the industry with the UK government ensures £557 million of investment and has prospected for installed capacity reaching 30GW by 2030. Further forward to 2050 and the deal prohibits 75GW and 7500 turbines making up 56% of today’s electrical demand. (UK Governemnt, 2019a).

However, as can be seen by Figure 2, this 75GW is clearly not ambitious enough and offshore wind as well as other renewables will have to increase their output. Therefore, this figure may well be a cautious estimation.

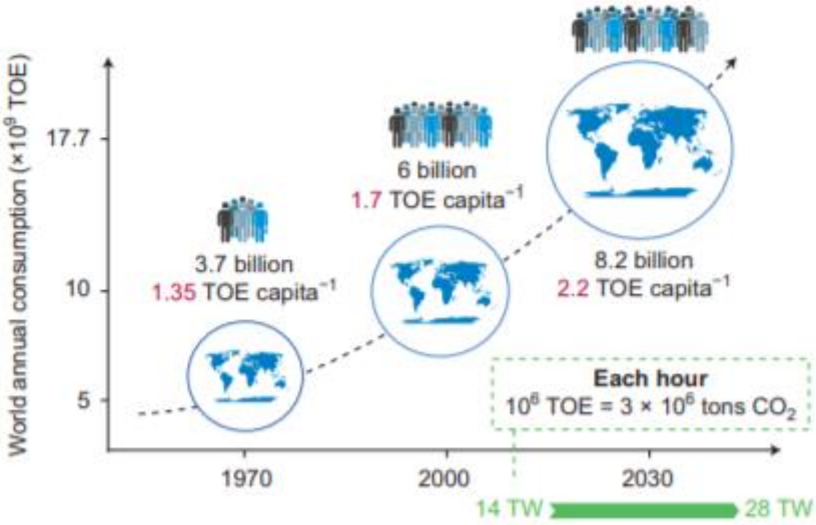


Figure 2- Growth of World Annual Consumption

(D. Larcher, 2014)

The second biggest change to the UK, which is likely to change even more drastically in the coming decade, is the transition to electric vehicles. The UK Government is predicting that parity in price between EV's and standard combustions engine vehicles will occur in the next decade and by the end of the 2030's EV's sales will outstrip the traditional vehicle (UK Governemnt , 2018). This will undoubtedly aid in reducing deaths from air pollution from transport which the World Health Organisation (WHO) estimated led to the deaths of over 12 million people in 2012 (World Health Organisation, 2014).

However, the transition for the UK will have the same hinderance that the EU faces when approaching transport, how do they deal with maritime emissions? The technology for electrification of vessels has developed much slower than its on-land counterpart and shipping is something that the government struggle to enact change in. Therefore, the government must take proactive action in the maritime transport sector in order to enact some improvements.

In the last decade, uptake and development of battery-operated marine vessels has been slow but recent advances in battery power and ship design have opened a new chapter for marine transport vessels. The world leader in this field is clearly Norway, who have invested heavily in renewables and electrification of transport with the money from their oil fund. A study performed by Bellona and Siemens concluded that, based on data from current battery powered propulsion vessels, 70% of Norway's ferry fleet of 180 vessels could be electrified and would indeed be more profitable after the transition due to a fuel saving and less maintenance costs (Siemens , 2016).

While other countries do not have the luxury of an oil fund, the transition has been understandably slower. However, as previously stated the EU are supporting research and development in this field and in Scotland, Caledonian Maritime Assets Limited (CMAL) have built three hybrid ferries and are currently building two large LNG dual fuel ferries (CMAL, 2015) (CMAL, 2018)

However, there is little evidence of Scotland following suit on different variations of the transport vessels, specifically crew transfer vessels; considering the Offshore Support Vessel (OSV) Viking Princess in operation and boasting 30% reduction in emissions in Norway (Norwegien Solutions, 2018). Therefore, it seems there is an opportunity for research and development into this field.

1.4.3 Investment into Offshore Wind Research & Innovation

As stated earlier, the offshore wind sector deal means by 2050 the backbone of the UK electrical grid may be offshore wind. Meeting 30GW by 2030 would see an £80bn investment in infrastructure and UK Research & Development spending to increase to £7bn by 2022 (UK Governemnt, 2019a). Based on this, it would seem a wise choice to develop an electrification-based transition of WFSV's

The offshore wind O&M sector will likely rise along with the industry as a whole, which account for 20-35% of lifetime costs of a wind farm (R Camilla Thompson, 2015). If the innovation can rise to the challenge of the targets being set, then more efficient vessels offer a cost-effective avenue for the industry to meet its emissions targets.

The UK has recently expressed ambition to be a leader in the transition to cleaner maritime vessels with two major action plans by the Department of Transport. Firstly, Maritime 2050 puts into effect a long-term plan for zero-emissions in the maritime sector by 2050, highlighting the potential environmental, health and economic benefits. The maritime energy efficiency sector is prospected to reach $15 billion a year by 2050 in this report, and the UK has an ambition to stake a foothold in this sector to maximise benefits. One of the first actions of this policy is to fund £400,000 to a competition by the Carbon Trust Offshore Wind Accelerator, hoping to find the best design for energy efficient offshore wind Crew Transfer Vessels (Department for Transport, 2019).

Following on from Maritime 2050, in July 2019 the Department for Transport released the Clean Maritime Plan which sets more targets in the coming decades. Principle of which is that every vessel should optimise its energy efficiency by 2025 and every new vessel should have zero-emissions capabilities (Department for Transport, 2019). These two statements of intent from the UK Government highlight the relevance of this field of research.

1.5 Sample Methodology

1.5.1 Critical Literature Review to Appraise Hybrid Propulsion and O&M Logistics

Offshore Wind

The development and prospected rise of offshore wind farms are key to providing scope for this research. The economics of offshore wind are crucial to its recent success and confidence in the industry will be dependent on the continuation of this economic parity with fossil fuels. Therefore, in order to propose a change in O&M strategy, O&M as a component of the economics of offshore wind must be established for a robust comparison.

Alternative Propulsion for Vessels

An indication into the progress that propulsion technologies have had in replacing the ICE must be made, with a suggestion of the extent to which a supply chain, and so the usability has advanced. The benefits and weaknesses of each technology in a workboat profile must be analysed to ascertain which technology would be best suited for a WFSV transition.

Fuel & Emissions

The logistical feasibility of charging at port for a secure operational profile must be examined, with an indication of the costs and emissions involved. Upon doing so, hybrid transition costs & savings can be established and pitted against potential emissions savings of ICE's and other, more expensive technologies.

1.5.2 Case Study & Discussion

A reference WFSV profile, costs and emissions for a specific port/farm must be established and then compared to the hybrid technology. The costs to the owner and client over the course of a 25-year lifespan, with respect to changes in energy prices, will inform the potential of this technology to transform the sector and meet targets.

2.0 Literature Review

2.1 Development of the Offshore Wind Sector

The offshore wind sector has undergone some striking changes in the last decade, leading many to think it will be the backbone of our electrical grid (R Camilla Thompson, 2015). What has caused this marked rise in production from the sector can be attributed to two factors that are indeed linked. The price of building offshore windfarms has decreased due to better construction techniques, mass production and lower investment costs. Furthermore, the power generated from offshore wind has increased, leading to a greater return of investment. The growth in output can be seen in the UK's operational report for 2018 by the Crown Estate in Figure 3 comparing capacity factor (efficiency) to power output.

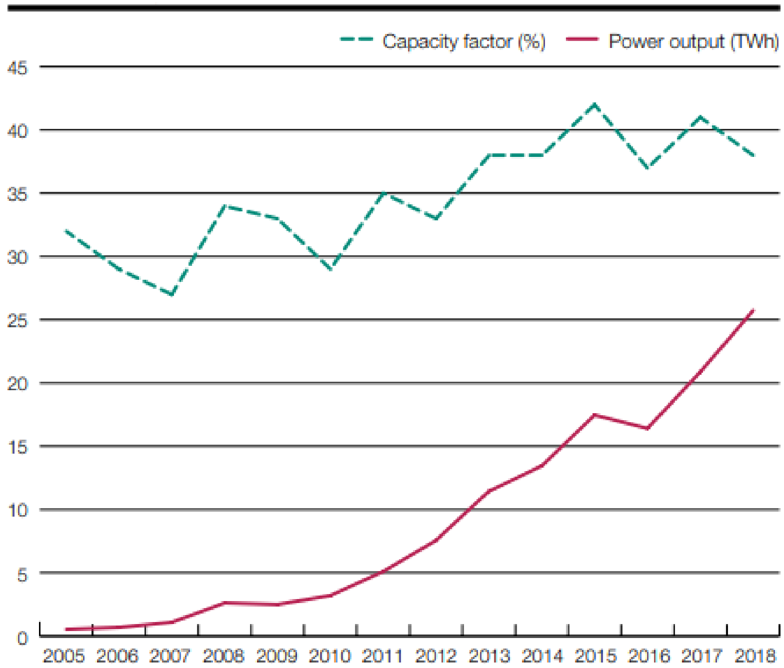


Figure 3 - Capacity Factor vs Power Output for UK Offshore Wind

(The Crown Estate, 2019c)

The main driver for this uptake is larger rotor blades and turbines, increasing the range of wind speeds that energy can be produced. In terms of lowering investment costs, the main driver is the contracts for difference (CfD) auctions which set the price that companies can bid for projects, based on the MWh value of production. The lower the clearing price, the cheaper the capital cost for the company and so the greater the investment in the technology. A relationship that is best described by the International Renewable Energy Agency in Figure

4 which shows the capacity factor increasing while the installed cost for a wind farm is decreasing.

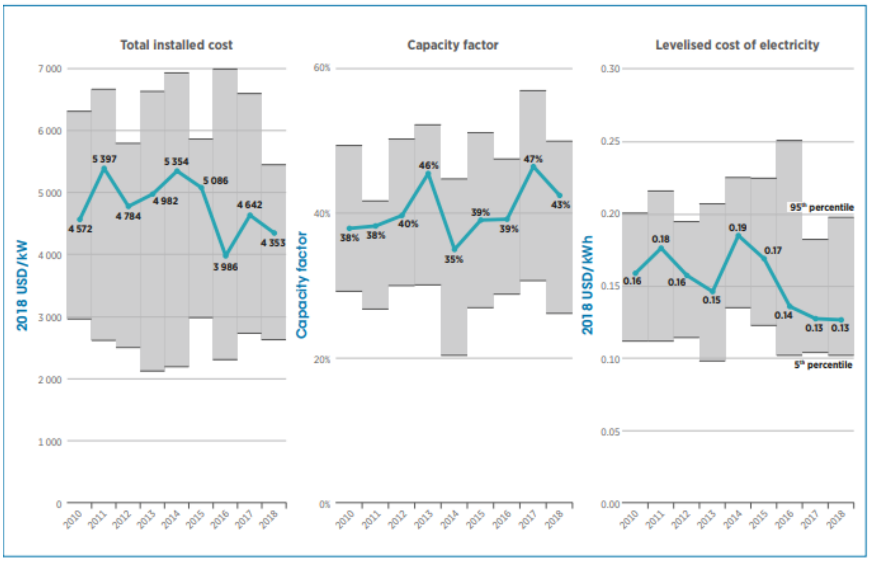


Figure 4- Levelised cost of Electricity of UK Wind Farms

(International Renewable Energy Agency, 2019)

However, clearing price and increased power output focus only on the capital cost of wind farms. The O&M phase of a wind farm can have a substantial impact on the overall cost. Leading energy research firm Aurora released a 2018 study (Aurora, 2018) which highlights that the clearing price for CfD's dropped from £117 per MWh in 2015 to £62 per MWh in 2017. Furthermore, the study indicated the CfD auctions are one of two key developments to make offshore wind cheaper, the second being optimised O&M strategies.

However, the key drivers are conflicted by differing sources. The 2019 Sector Deal (UK Governemnt, 2019a) attributes the increased power capture by 60% in recent years and development of deep-sea sites as far as 100km out to sea as the two most important technological advances in the rise of offshore wind. Looking forward, the Sector Deal report indicates the technology is likely to improve further by the early 2020's and turbines over 250m above sea level generating 15-20MW each will be the new standard. This is likely to lead to an exponential increase in investment in offshore wind.

There is still room for improvement on the whole picture of offshore wind as the O&M phase becomes larger the longer turbines are operating. Aurora states that, although optimising strategies have led to a decrease in O&M costs, they still account for a large proportion of lifetime costs. Leading energy analytics firms put the proportion at 16-35% with an average value of 25%. (Poyry, 2013) (Aurora, 2018) (European Boat Design Innovation Group, 2016) (ORE Catapul, 2016).

2.2 Operation & Maintenance of Offshore Wind

In order to review a change of O&M vessels, and the effect that would have on overall O&M costs, the position of O&M within the offshore wind lifecycle must be understood.

2.2.1 Annual Maintenance Profile

The two principle types of maintenance for offshore wind are preventative and corrective. The two are well described in Scottish Power's comprehensive guide to offshore wind O&M in the UK:

> - ***"Preventative maintenance** includes proactive repair to, or replacement of, known wear components based on routine inspections or information from condition monitoring systems. It also includes routine surveys and inspections.*
>
> - ***Corrective maintenance** includes the reactive repair or replacement of failed or damaged components. It may also be performed batch-wise when serial defects or other problems that affect a large number of wind turbines need to be corrected. For planning purposes, the distinction is usually made between scheduled or proactive maintenance and unscheduled or reactive maintenance"*
>
> (Hassan, 2013)

The annual profile of maintenance is case sensitive to wind farms and turbines. However, although corrective maintenance cannot be forecasted with great accuracy, preventative maintenance has a more predictable profile. Generally, preventative maintenance takes place in the summer months when the wave heights and weather conditions are more favourable, every turbine can be assumed to have one service a year and is visited for inspections periodically (Hassan, 2013). Wind Power Offshore claimed in 2013 that every turbine in the UK would require 6 visits per year (Wind Power Offshore , 2013) and green port hull estimated 2 visits per turbine each year (Green Port Hull, 2017). However, O&M costs and so visits will increase with the lifetime of the windfarm and as the turbines in our waters age, these figures are likely to rise.

2.2.2 *Operation & Maintenance Spending Prospectus*

As mentioned before, with the expansion of the offshore wind sector comes larger O&M procedures for new and existing turbines. The older the turbines, the more surveying and maintenance are required. Figure 5 depicts the rise in O&M spending, which is expected to be exponential, and so cutting costs in this sector will become extremely important to investors.

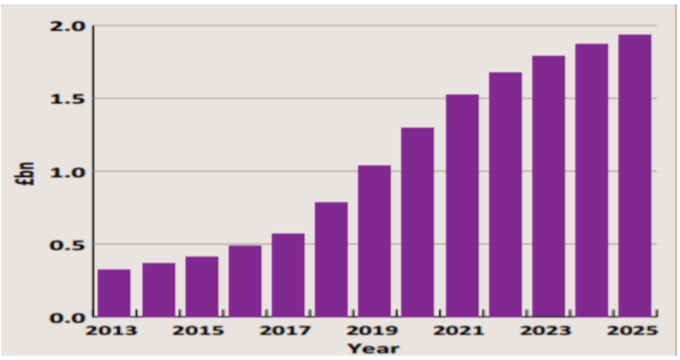


Figure 5- O&M Spending Prospectus (UK)

(Hassan, 2013)

2.3 Maintenance Vessel Types for Offshore Wind O&M

There are various types of O&M vessels that have unique operational profiles. Generally, the vessels involved with constructing the wind farm are very large and require very powerful propulsion methods to carry heavy equipment. They are also prone to stay out at sea for days at a time and so for the purposes of this research, they will be discounted on the grounds that they would require too much investment to apply real change. The O&M vessels have varying operational profiles and power requirements and therefore, may be more suitable for electrification.

2.3.1 Vessel Power & Operational Profile

The most important parameters to contemplate when considering using alternative propulsion methods would be the power requirements and operational profile. If all, or a significant proportion of the power, where to be replaced by a clean energy source; then the power requirements of the vessel must be within the capabilities of current technology. The vessel will also likely have to be docked overnight for recharging/refuelling as to minimize the size of the alternative fuel to cut costs.

<u>Wind Farm Support Vessel (WFSV)</u>

Figure 6- Wind Farm Support Vessel

(Green Marine, 2019)

WFSV's are the smallest of the primary maintenance vessels for offshore wind, typically carrying 12 technicians to and from a wind farm at a high speed to work bases up to 12NM and swells up to 1.5m (European Boat Design Innovation Group, 2016). The WFSV is required to offset the motion of the waves in order to allow the technicians safe offloading onto the base of the turbine to carry out their work. The rated power of a WFSV this size is supplied by something similar to the Green Quest (pictured) at 2 x 650kW engines (Green Marine, 2019).

At higher wave heights, the smaller WFSV's struggle to safely transfer crew and so a larger generation of WFSV's with space up to 24 passengers are also in operation such as the Seacat Courageous (2x1080kW) (Seacat Services, 2019) and the Northern Offshore Services M/V Sea Supplier (2x1440kW) (NOS, 2019a). These types of vessels could work on windfarms up to 40NM, work in significant wave weight of up to 2.5m and are commonly fitted with buoyancy increasing systems that help with dynamic positioning and speed but have a negative effect on fuel consumption (European Boat Design Innovation Group, 2016). Typical fuel consumption rates for the two sizes of vessels are 200l/h and 384l/h respectively for small and large (Yalcin Dalgic, 2014).

Service Operations Vessel (SOV)

Figure 7 - Service Operation's Vessel

(Damen, 2019)

SOV's are generally used to transfer and accommodate maintenance engineers for extended trips to wind farms and have an operational speed of up to 15kt (The Crown Estate, 2019a). The vessels are built to accommodate up to 45 passengers and can stay at sea for up to a month. One such vessel is the Acta Auriga (4920kW) (Acta Marine, 2019). They have much bigger propulsion and hotel loads than WFSV's and are more suited for larger maintenance operations that are far out to sea. (Hassan, 2013)

The operations of the two principle vessels and helicopters are conveyed well in Figure 8 taken from the Scottish Power O&M study in 2013, from left to right are WFSV's/Helicopter Support/SOV's. Helicopters are only considered for jobs where the sea state will not allow CTV's of SOV's as they are extremely expensive (The Crown Estate, 2019a).

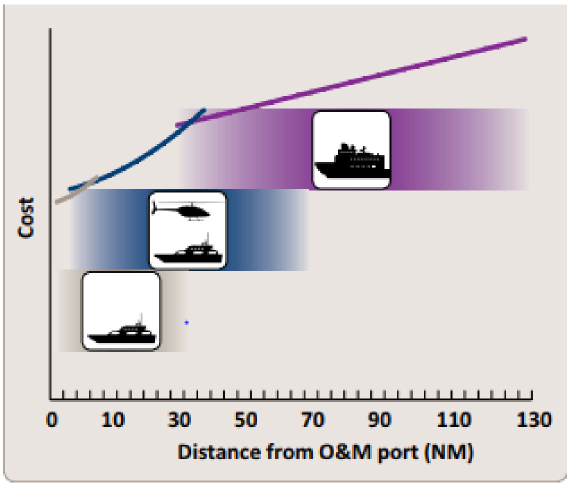


Figure 8 - O&M Vessel Operations

(Hassan, 2013)

2.3.2 Favourability for transition

Of the primary offshore wind O&M vessels, due to technological constraints and costs, it would be most favourable to consider the WFSV for an alternative fuel study. The small size of the engine along with operating short trips and docking overnight, connected to the grid, makes it an ideal candidate. However, it must be noted the small size may prove a problem when considering adding heavy machinery to replace an ICE. Furthermore, as wind farms progress further out to sea the industry may rely more on the new generation, therefore both large and small vessels must be modelled.

2.3.3 Key Price Components

The key price components when considering O&M would be the fuel and charter costs for the vessels used, technician's wages and parts. For sites <100km from the shore both lost production and transport account for 45% of costs each, while repair and staff cover the remaining 5% (Carroll, 2016). Of the total O&M schedule, inspection maintenance accounts for 4% of the total costs (Christine Rockmann, 2017).

The overall planned O&M spending on turbines for a 1GW Wind Farm is £33m per annum. Charter rates vary but average at around £2500 while fuel accounts for 30% of vessel costs (The Crown Estate, 2019a). The current industry standard is a 7MW turbine (UK Governemnt, 2019a) and so the number of turbines in a 1GW wind farm would be:

$$No. of\ Turbines\ in\ a\ 1\ GW\ Wind\ Farm = \frac{1000}{7} = 143\ turbines$$

Therefore, an estimation of the annual fuel costs for annual service for WFSV's can be made from these figures:

WFSV fuel costs for a 1GW wind farm inspection maintenance

$$WFSV\ cost = \frac{(33{,}000{,}000\ x\ 0.04)\ x\ 0.45}{143} = \text{£}4153.8 \text{ per turbine}$$

$$WFSV\ Fuel\ Costs = \text{£}4153.8\ x\ 0.3 = \textbf{£1246 per turbine}$$

WFSV charter costs for a 1GW wind farm inspection maintenance

As both the cost of charter and fuel are the two price components for client vessel costs, the charter cost for this scenario can be assumed to be:

$$WFSV\ Charter\ Cost = 4153.8 - 1246 = \text{£}2907.8/day$$

An ideal solution would not have any negative effects on the vessel owner profit margins and so the alternative fuel technologies effect on capital costs and maintenance must be compared to a reference case for a WFSV.

WFSV Maintenance Costs

In order to ascertain a figure for maintenance, a derivation must be made from the budget for vessels of a 1 GW wind farm, knowing that 3% of operational costs are on planned maintenance (Basman, 2009). This derivation assumes that the budget for a 1GW wind farm encompasses owning a vessel rather than chartering, for the purpose of obtaining a value for maintenance. Furthermore, in order to break the value down for one vessel, the time period of work is set for months with significant wave height below 1.5m; these are shown in Figure 9.

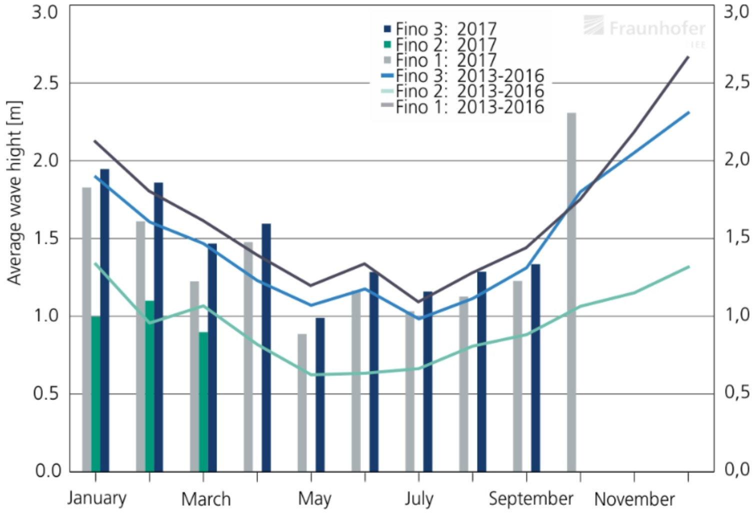


Figure 9 - Significant Wave Height in North Sea & Baltic Sea

(Windmonitor, 2018)

Figure 9 displays that 143 trips could be made by one WFSV between May and September and so for the ease of comparison the number of vessels to be considered will be one. In-Situ, circumstances such as wind speed and visibility will impair this from becoming a reality, and large wind farms will have up to 10 spaces for WFSV's at port (The Crown Estate, 2019a).

$$WFSV\ Maintenance\ Cost = ((33{,}000{,}000\ x\ 0.04)\ 0.45))\ x\ 0.03 = £\mathbf{17,820/y}$$

2.4 Development of Alternatively Fuelled Vessels

2.4.1 Power & Propulsion in Marine Vessels

The general power train of a marine vessel is simple; a chemical reaction produces kinetic energy through an ICE which is connected to a propeller system. The propeller then propels a mass of water away from the vessel, generating a reactive force to produce motion. This is sometimes likened to the turning of a screw to induce motion into wood.

In an idealised environment, if a ship is travelling at uniform speed then the thrust from the propellers should equal the resistance on the ship. However, for a vessel in the ocean there are a great number of resistances that results in a relationship of horse power varying as a cube of the speed (Hardy, 1948). Furthermore, the complex variety of resistances acting against the thrust of the propellers will have varying effects at different speeds. The relationship between speed and horsepower in marine vessels is shown in Figure 10.

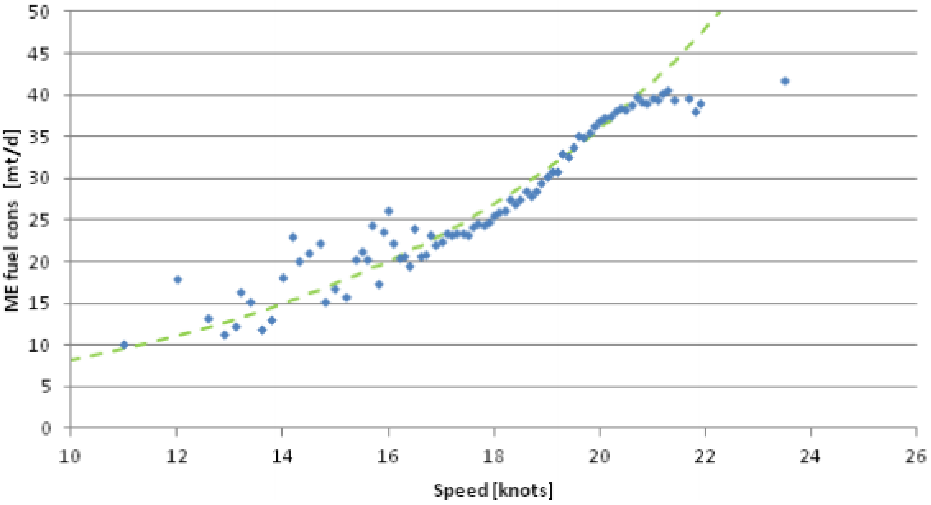


Figure 10 - Fuel Consumption vs Speed (Knots)

(Melén Eriksson, 2012)

The main resistance to consider is the frictional resistance which occurs between the hull of the vessel and the surface of the water and can be offset by careful naval architecture. The frictional resistance at high speeds can account for 50% of resistance (Hardy, 1948). The naval architecture techniques to avoid this would be to limit the proportion of the ship underwater i.e. the wake of the ship, using friction reducing materials, finishing on the hull and limiting speed. WFSV's operate close to shore and at high speeds and predominantly have a catamaran hull in order to limit resistance. (Tavner, 2012).

Due to this horsepower vs speed cubed relationship, vessels require a propulsion system that can deliver high amounts of power for prolonged periods of time; hence, the standard has been ICE's operating on energy dense Marine Gas Oil (MGO).

2.4.2 Fuel Power Density

For all the technologies intending to replicate electrical energy production given by a traditional gasoline combustion engine, there is one key characteristic they need to consider, which is energy density. Shown in Figure 11 are the main challengers to ICE's, measured in terms of specific power and specific energy. Figure 11 shows that, although the potential energy produced by batteries and fuel cells can be in the same region as combustion engines, their specific power has room for improvement.

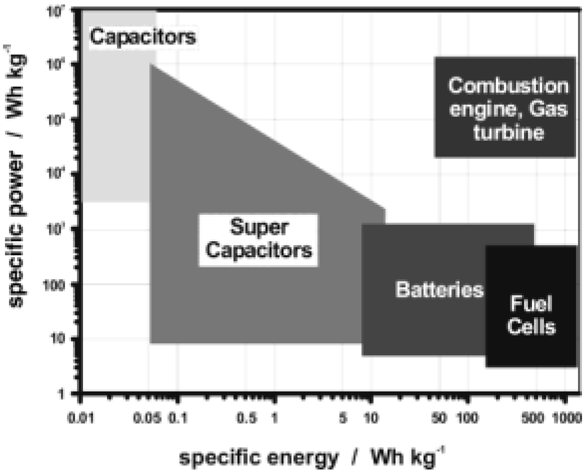


Figure 11 - Specific Power vs Specific Energy of Primary Engine Types

(Dr. Martin Winter, 2004)

In an engine it is healthy to have a good mix of these but primarily to deliver power, and so to match the same power as an ICE, batteries and fuel cells need to be much larger to match the amount of power created.

Furthermore, the fuel that can be used in these technologies has a similar scale to consider. Figure 12 shows the main fuel types across the technologies in terms of energy by terms of mass and then volume.

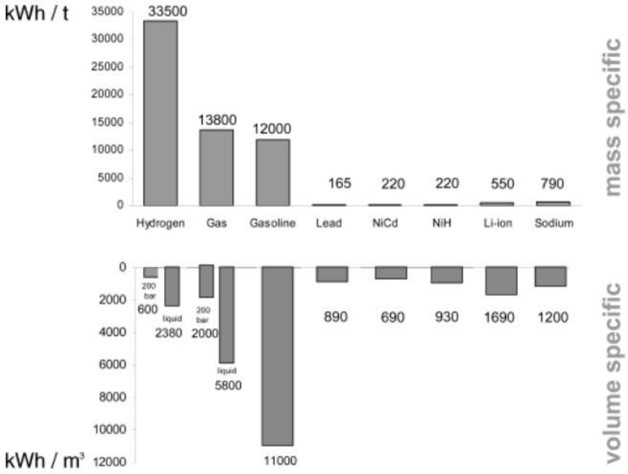


Figure 12 - Energy by Mass & Volume of Major Fuel Types

(Dr. Martin Winter, 2004)

The fuels to note when concerned with specific energy by mass are Hydrogen, Gas and Gasoline. Hydrogen has clearly the most specific energy per tonne of any of the fuels. When it comes to specific energy by volume there is a very interesting shift that explains why gasoline is the prominent fuel for engines. Gasoline can deliver far greater energy over a metre cubed than any other fuel, making it ideal for a small and lightweight engine. Matching gasoline energy with hydrogen would require the H_2 tank to be larger than a comparable MGO tank. An important note is that both Hydrogen and Natural Gas have a much greater energy density as a liquid than as a gas, although Natural Gas has roughly double the calorific value.

Finally, Lithium-Ion is the most powerful of the battery metals and in terms of volume, can hold more energy per m^3 than Hydrogen gas, but not Liquid Hydrogen. Since 2004 there has been a massive development in Lithium-Ion energy densities driven by the electric vehicle market. Energy density parity between Lithium-Ion and Gasoline is predicted for around the year 2045 (Vijayagopal, 2016). The potential for parity is shown well in Figure 13, in which researchers from University College London have performed a case study of a vessel comparing present and future battery densities to an ICE engine.

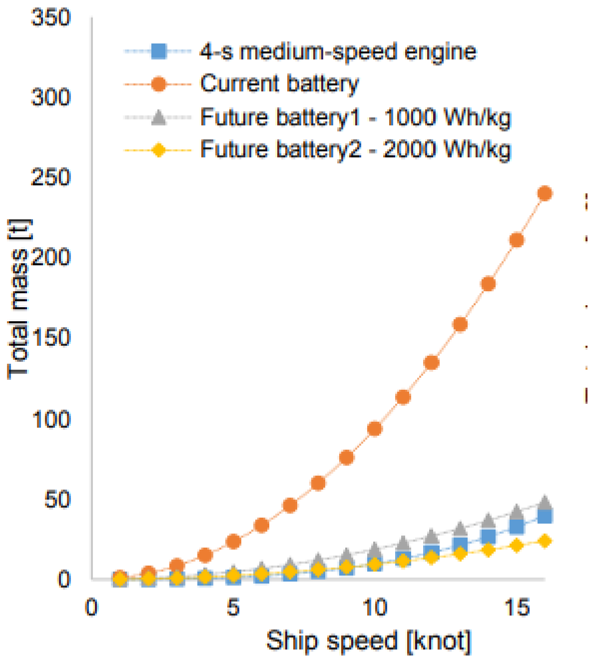


Figure 13 - Energy Density of Future Batteries vs Oil

(Peng Wu, 2016)

Considering the characteristics of the fuel and propulsion systems discussed above, some alternative fuels have been implemented into maritime engines, namely fuel cells, gas/MGO engines and batteries. Both fuel cells and batteries can be supported along with combustion engines or as a complete replacement, although the latter requires considerable cost and system size due to the power capabilities. Adding an alternative technology will also depend greatly on the function of the vessel and power requirements. Certainly, passenger ferries with large 1MW Lithium-Ion batteries are already in production (Hockenos, 2018). However, the technology has not yet developed into more power intensive fields, although it has emerged as the most effective battery type for cyclical applications (Christian Julien, 2016).

2.5 Traditional Maritime Engine

The most common vessel engine would be the ICE, which has been widely taken on board by the maritime industry. Reciprocating diesel ICE’s are used in three categories; low-speed, medium-speed and high speed. For the operation of a WFSV, it is important to reach high speeds for the workforce to reach the windfarm as soon as possible if there is a fault that needs attention. High speed engines typically operate at more than 1000rpm, in order to achieve this the complexity and size of the engine is increased, and so installation and maintenance becomes more expensive. (Townsend, 2008)

2.5.1 Power Train

In ICE's, the engine is connected straight to the propeller(s) by means of a reduction gearbox and electric motors; this garners a high efficiency by limiting moving parts and so energy conversions. As shown in Figure 14, this is achieved through a traditional combustion engine, where the burning of fuel and air inside a combustion chamber creates steam to move pistons that produce linear motion that is transformed to rotational movement in the propeller. An alternator will generate the electrical power required for the vessel, either alone or with additional diesel generators. This is reliant on a constant flow of fuel for combustion.

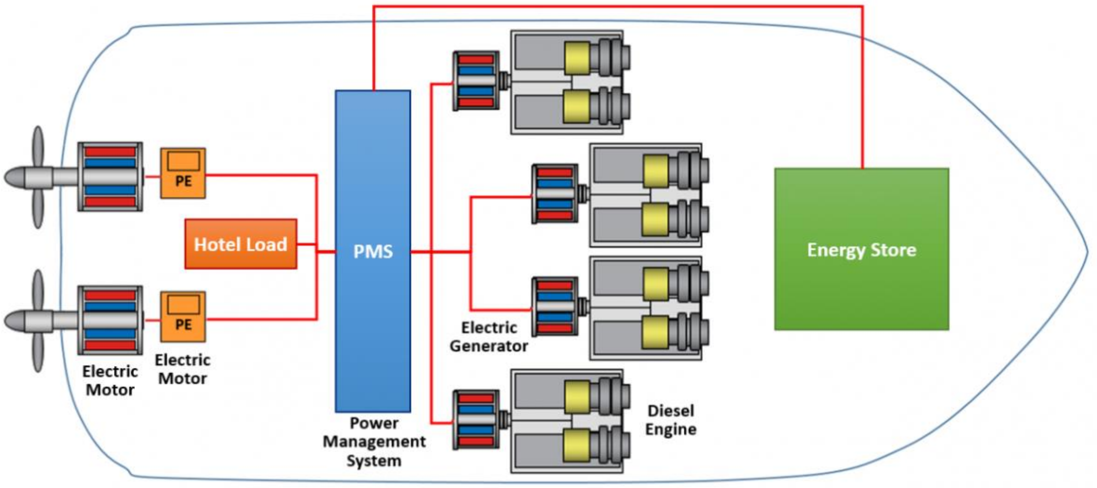


Figure 14 - Power Train Schematic of ICE Vessel

(Jonathan Brown, 2016)

2.5.2 Fuels

The potential for types of fuel for the combustion is quite varied, from biofuels to crude oil, as long as it has the correct properties to work in a combustion chamber it can be used. Overwhelmingly, due to the quantities needed for maritime vessels, the cheapest and 'dirtiest' of engine oil is used. These are at the bottom of the chain in the distillation of crude oil, broadly termed to be Heavy Fuel Oil (HFO) and Marine Fuel Oil (MFO). The most commonly used of these is HFO in large ships, as it requires a larger engine for the combustion. However, in terms of transfer vessels the most common scenario is a mixture of the two, leaning heavier on the MFO side that is MGO according to Marquard & Bahls which is a principle tankard fuel trader in Northwestern Europe (Marquard & Bahls, 2015).

2.5.3 Emissions

Aside from CO_2, there are two main pollutants that the IMO has legislated limits for, Sulphur Oxides (SO_X) and Nitrous Oxides (NO_X). MGO with a SO_X content below 0.1% will become mandatory in all ECA's by 2020 and a 75% reduction in NO_X emissions will become mandatory in 2021 (DNV GL, 2019).

All the major bunkering sites will facilitate the shift to MGO 0.1% and so this will not present a great challenge for vessel operators. However, a similar alteration of fuel is not possible for NO_X emissions and so most vessels must consider costly exhaust cleaning technologies or alternative fuels, the most popular of which is a Selective Catalytic Redactor (SCR) (DNV GL, 2019).

CO_2 emissions are only reduced by <5% in switching from HFO to MGO an so in time, measures will be taken to increase this figure to >50%. However, on MGO this sort of engine would be in compliance with Tier II regulations on SO_X but not on Tier III regulations on NO_X.

2.5.4 Cost

The cost of MGO is $600/mt (DNV GL, 2019) and as shown in Figure 15, it follows the price trend of crude oil. The price of MGO may fluctuate in the future however, the price of MGO is set to rise to near $900/mt in the next decade (BunkerEx, 2018). This is likely to drive accelerate a transition to more fuel-efficient technologies for vessels.

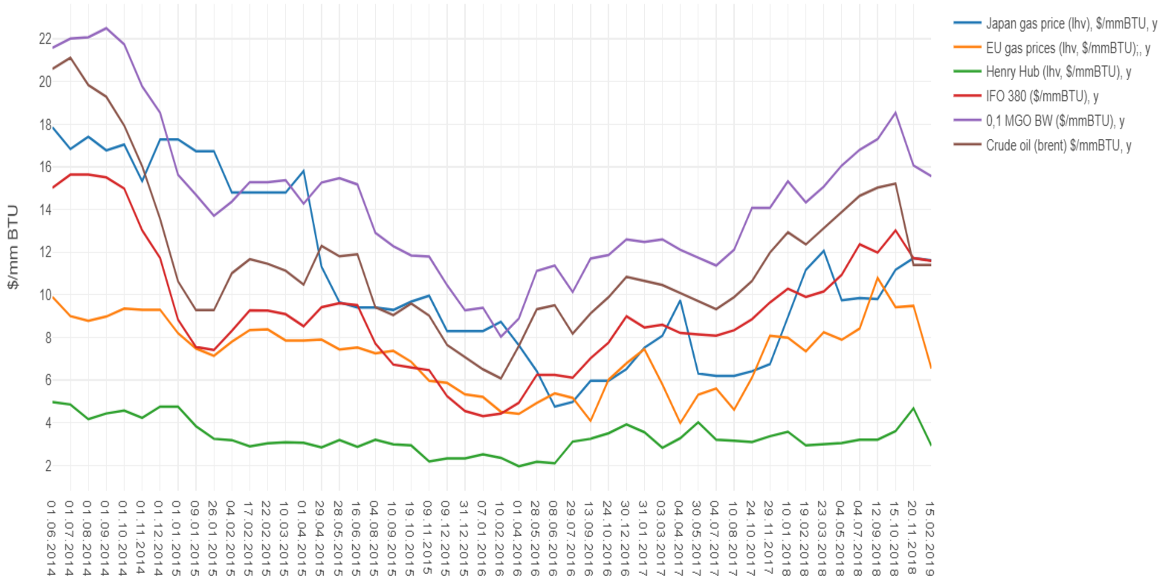


Figure 15 - Gas/Oil Price Trends 2014/19

2.6 Favourability of Alternative Fuel/Propulsion for WFSV

The principle of operation for marine technologies will encompass all the necessary components in the system that allows the vessel to be fit for purpose and operate safely, particularly when there are human lives on board. Different vessels have diverse operations and so, place higher significance on certain aspects, such as comfort, speed and fuel economy. These parameters become design criteria for vessels and must be given significant consideration when suggesting a substantial change in design, such as implementing battery powered propulsion.

LNG Dual Fuel

Natural Gas has been mined for decades and consists mostly of Methane, which has been super-cooled and liquified in order to transport and then re-gasified for sale and operation. In a maritime engine LNG can either work in a gas only otto-cycle engine or a dual fuel diesel cycle engine. Although, when an engine has been converted to dual fuel operation, it is limited to diesel cycle with a maximum gas concentration of 70% (DNV GL, 2019). LNG has so far been utilized in large vessels that operate at moderate speeds (DNV GL , 2015). The gas is usually stored on deck and requires a considerable amount of space.

Of all the alternative fuels, LNG is considered to have matured the most and prices for LNG are roughly half that of MGO (DNV GL, 2019). The benefits of using LNG are a vast reduction in fuel consumption and emissions. The emissions created from LNG burning are less than MGO. A vessel equipped with 70% of this fuel instead of 100% MGO will operate at a reduced cost of fuel, but access to this fuel is not as secure as MGO. Most major ports in the North and Baltic Sea’s either have or will have LNG bunkering (DNV GL , 2015) therefore it is likely only rural ports that may incur higher transportation costs.

Considering WFSV’s, the average hull length is 20m (Appendix B) and so there is not a great deal of space for LNG storage. Furthermore, leading dual fuel engine supplier Wartsilla do not sell engines the size of one of those engines commonly found in WFSV’s such as the Green Quest at 650kW (Wartsilla, 2019). Therefore, the likely course of action would be to convert either one or both engines and so limit operations to diesel cycle. While this would incur fuel savings, the capital cost and lack of significant emissions reduction limit the usefulness of this technology.

The potential for LNG increases with this size of the vessel. The new generation for WFSV’s may well have space to accommodate the storage and engines large enough to warrant an

Otto-cycle DF engine. The benefits for such a transition are potentially significant, considering the incoming SCR costs that would be avoided. However, the technology would need to mature even further before large scale uptake in small high-speed vessels can be seriously considered. Figure 16 shows a list of LNG vessels in operation and on order in 2017 and the vast majority are large vessels.

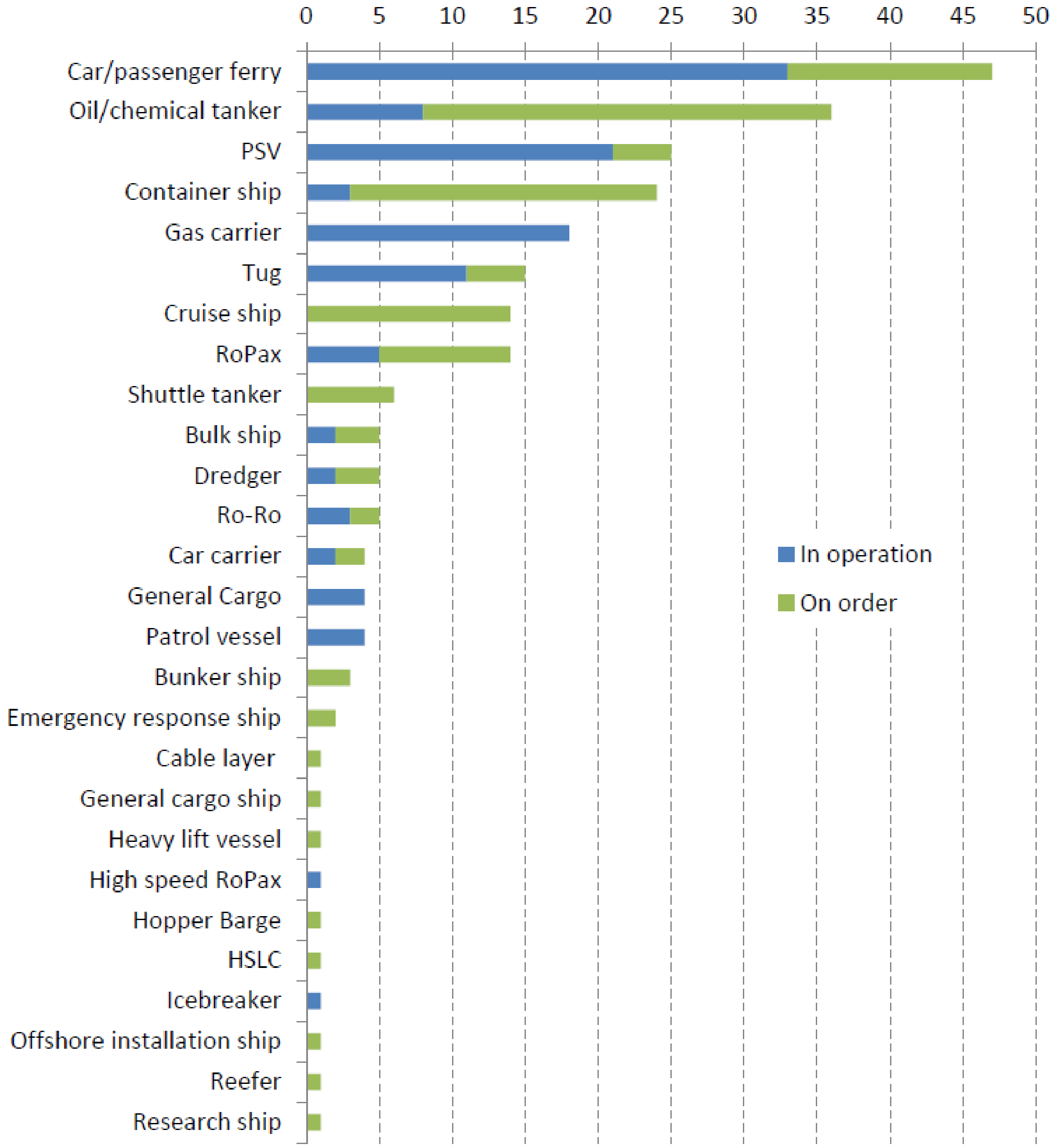


Figure 16- LNG Fleet (2018)

(International Transport Forum, 2018)

Hydrogen Fuel Cell

Although Hydrogen is also a gas, it is more versatile than LNG. Liquid Hydrogen can be used much in the same way as LNG and under the same guidelines, just operating under higher pressures and safety measures (L.E Klebanoff, 2017) (International Maritime Organisation, 2015). However, unless there is ease of access to Liquid Hydrogen it is less applicable than LNG.

The most promising source of propulsion from Hydrogen is through a Proton Exchange Membrane Fuel Cell (PEMFC), for which pure hydrogen, made from extremely fresh water is the perfect fuel (Lemoos, 2011). The PEMFC creates electricity for motors in a vessel by pushing H_2 atoms through an anode, and by means of a chemical reaction, ionizing the now positively charged atom for applications. The main by-products of this reaction are oxygen and water.

PEMFC's can replace engines but require large amounts of Hydrogen which is an expensive fuel if there is not an electrolyser at site. For maximum emissions reductions, the electrolysis that creates hydrogen will be supplied by a renewable electrical current.

A comprehensive feasibility study into converting a 35 knot 100+ passenger ICE ferry into a hydrogen one was carried out for a Lockheed company, Sandia, with cooperation from the U.S Department of Energy (Joseph W. Pratt, 2016). The main findings are:

- That for a high-speed vessel, Liquid Nitrogen (LH_2) is the preferred fuel for storage and energy density purposes.
- Capital cost of transporting or electrolysing, then liquefying hydrogen are extremely high, so too is refuelling equipment.
- Operating costs of electricity from grid is 2-3 times more expensive than ICE fuel, and from renewable sources costs would be significantly higher.

As this technology is still in the early stages of development, it should not be considered for small high-speed vessels until the technology has been tried and tested on larger vessels and appropriately scaled down.

2.7 Hybrid Maritime Engine

The hybrid maritime engine uses two sources of power for propulsion, which can alternate in reliance on either. The IMO engine run on MGO, coupled with large Lithium-Ion battery banks to power propulsion units, and so decrease work done by the engine to save on fuel.

The hybrid system lends itself towards CTV/WFSV operations as when the vessel is at the destination and in idle mode while the technician works, the potential for running solely on batteries is high, and so severely cutting emissions and fuel. This is cutting edge technology and as of yet, not utilized in the industry. However, in June 2019 Northern Offshore Services announced the first of their E-Class CTV's which will operate in exactly this way and they hope to revolutionise the industry (NOS, 2019). This gives a clear mandate towards hybrid technology propulsion for WFSV.

2.7.1 Power Train

The operation of a typical hybrid vessel is shown in Figure 17 which depicts the operational components of the MV Hallaig, a hybrid ro-ro ferry operated on the Isle of Skye.

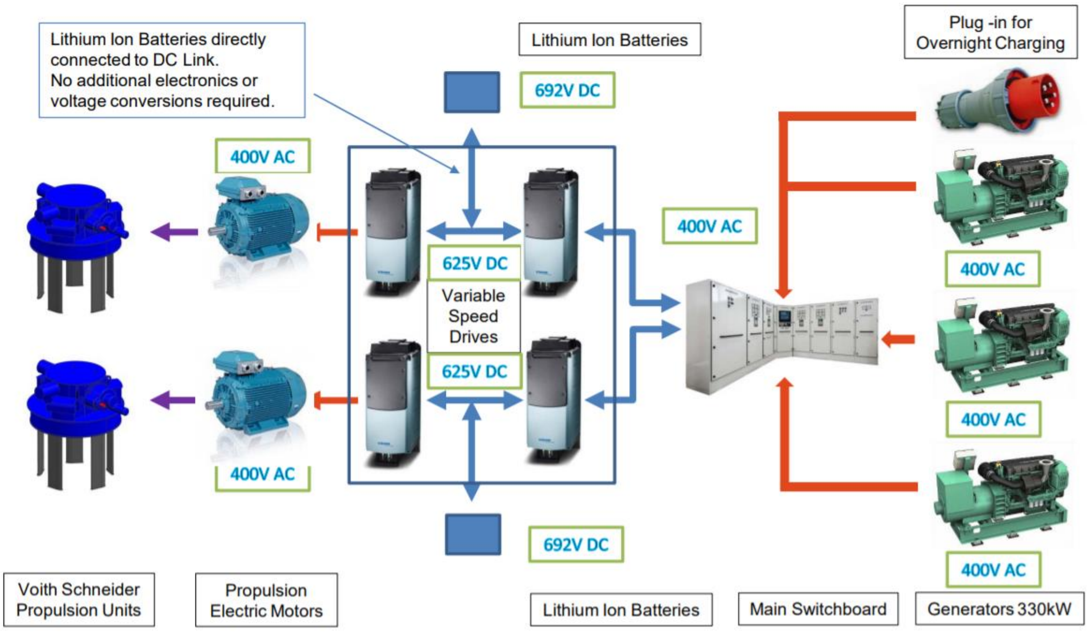


Figure 17 - Power Train Schematic of Hybrid Vessel

(Anderson, 2012)

There are three diesel generators that offer a primary charge to the variable speed drivers. The two Lithium-Ion banks offer a compensatory power source that can cover the entire capacity if possible, operating in parallel to the speed drivers. The batteries can also be configured in series, where the motors can be supplied by either the battery packs or speed generators, however, it is widely accepted that parallel configuration is the most suited to high power vessels (Nova Scotia Boatbuilders Association, 2015).

2.7.2 Emissions

Emissions will be reduced in total by a percentage, while not eliminating any specific pollutants. The reduction is highly sensitive towards the duty-cycle of the vessel. An offshore support vessel, the Viking Lady, in operation in Norway servicing oil platforms has a hybrid propulsion technology engine. The designers of the hybrid system on the Viking Lady claim offshore workboats can typically achieve a 30% reduction in GHG emissions and a 25% reduction in NO_X (DNV GL, 2015).

2.7.3 Charging

Charging the batteries for a WFSV would generally require a slow, overnight charge in order to preserve the health of the batteries or a rapid charge for faster turnaround. The connection to achieve slow rate of charge would be directly available from the local network and a charging station would not be necessary. However, for the case of rapid charging the most advanced technology in the field must be modelled for vessels. The Tesla supercharger version 3, with a charging capacity of 250kW can be delivered to each car on the station from a 1MW power cabinet (Tesla, 2019). This means that for a battery bank the size of the one in the MV Hallaig (750kWh), but built to accommodate this type of fast charging, the battery would fully charge in 3 hours. With an operating system at port the charging time could be varied to slow overnight charging to cut costs and extend battery life or rapid charging if unplanned maintenance is required.

2.7.4 Cost

Cost for the Vessel Owner

Capital

The DNV have conveyed the price of maritime Lithium-Ion hybrid installations in Figure 18 which depicts both the initial system cost and the cell replacement cost.

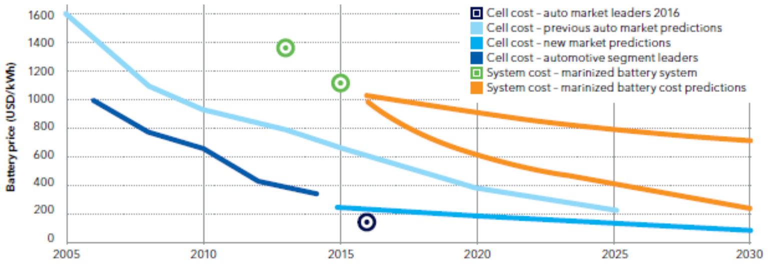


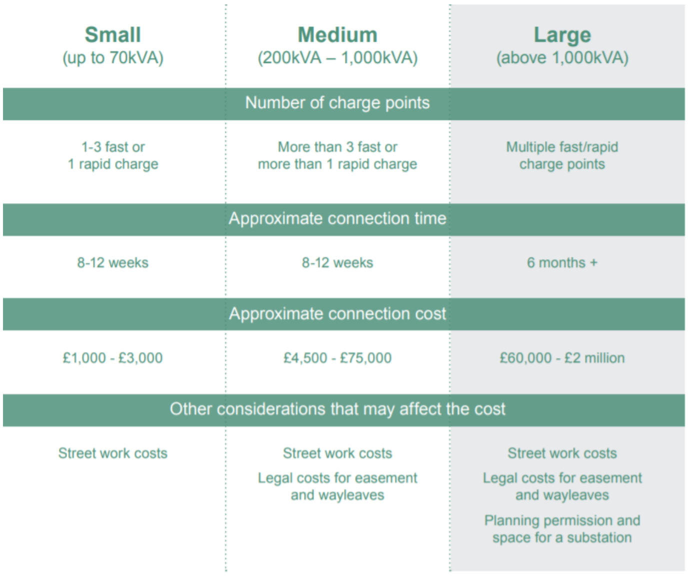
Figure 18 - Price Projections of Marinized Lithium-Ion Systems

(DNV GL, 2019)

Batteries in maritime applications have been used to back-up installed power and improve efficiency rather than replace specific engines such as in the offshore supply vessel Edda Ferd (Corvus Energy, 2015). Therefore, it would be more beneficial to design a similar configuration of an additional 30% of engine power system as parallel batteries.

$$\boldsymbol{Capital\ Cost\ (Hybrid) = (0.3\ x\ kW)\ x\ 600}$$

The capital cost of a rapid charger can be assumed to be £2000 according to Western Power Distribution.



Small (up to 70kVA)	**Medium** (200kVA – 1,000kVA)	**Large** (above 1,000kVA)
Number of charge points		
1-3 fast or 1 rapid charge	More than 3 fast or more than 1 rapid charge	Multiple fast/rapid charge points
Approximate connection time		
8-12 weeks	8-12 weeks	6 months +
Approximate connection cost		
£1,000 - £3,000	£4,500 - £75,000	£60,000 - £2 million
Other considerations that may affect the cost		
Street work costs	Street work costs Legal costs for easement and wayleaves	Street work costs Legal costs for easement and wayleaves Planning permission and space for a substation

Figure 19 - Connectivity Price for Charging Technologies

(Western Power Distribution, 2019)

The capital cost for a Tesla Supercharging station is considered to be $250,000 (DeBord, 2017) which would have 4 x 250kW connections. For a prototype simulation with a single connection the capital cost for a rapid charger can be assumed to be $62,500 which would convert to £49761.88 at USD0.8 = 1Sterling.

Therefore, the capital cost of the Green Quest with Lithium-Ion technology has two scenarios:

390kWh Standard Charge	390kWh Rapid Charge
£187,200	187,200 + 49,762 = **£236,962**

Maintenance

Over the operational life of a system, Tesla batteries are designed to last 1500 cycles (Alvarez, 2019), therefore if completely discharged to 20% each day, operating 2 annual trips per year (Hull) in the Baltic Sea where the significant wave height rarely rises above 1.5 metres:

$$Battery\ Life = \frac{1500}{(146\ x\ 2)} = 5.2\ years$$

The days of <1.5m significant wave height in the North Sea would be considerably less however, due to the uncertainty of annual profiles, it is preferable to over-estimate the value for battery replacement.

The price of the cell to be replaced is falling and is represented in the same graph from which capital costs of hybrid maritime system has been derived in Figure 17. With a USD – Pound Sterling rate of 1:0.8 and a lifespan until 2045, assuming the 2030 level stabilises the replacement cell costs can be calculated by:

$$Replacement\ Cell = (0.8\ x\ DNV\ battery\ price)\ x\ (0.3\ x\ kW)$$

Therefore, the four replacement prices are:

- 2025 - £120/kW
- 2030 - £80/kW
- 2035 - £80/kW
- 2040 - £80/kW

Where the hybrid systems improves on an ICE is in its value in the overall mechanical maintenance for the lifespan of a vessel, which along with reduced fuel consumption is attributed to be a key component in the case for 43 long route ferries in Norway being more profitable as hybrids (Siemens , 2016). The overall reduction to maintenance is case sensitive, however, a common figure in literature is a 50% reduction (Hybrid Marine Solutions, 2019) (Danfoss, 2019). Although CMAL estimate overall reduction in mechanical maintenance for their hybrid ferries to be 30% ‘personal communication’ (CMAL, Assistant Technical Superintendent, 2019). Therefore, once again the conservative estimate should be followed due to uncertainty.

Considering there is an added cost to maintenance with a replacement battery every 5 years, the overall reduction becomes more profitable for the vessel owner with the fall in price of cell cost in maritime Lithium-Ion systems.

Cost for Client

For a battery designed to 30% of the total power output, a fuel consumption reduction of 19% is likely (MAN, 2019) (Siemens , 2015). Therefore, the total fuel costs of MGO can be reduced by 19% + the overnight cost of electricity.

In order to calculate a reliable figure for overnight electricity, the percentage decrease from 15:00 and 03:00 for the last week in June 2019 is recorded from the Drax figures in Table 1 (Drax, 2019), this decrease can then be applied to the quarterly average.

Table 1 - UK Day/Night Electricity Price 25/06/19 - 01/07/19

Date	Day (MW/h) 15:00	Morning (MW/h) 03:00
25/06	48.8	37
26/06	72	61
27/06	42	51
28/06	56	42
29/06	41	42
30/06	59	38
01/07	62	60
Average	**54.4**	**47.3**

$$Percentage\ Decrease = \left(1 - \frac{47.3}{54.4}\right) x\ 100 = 13\%$$

The average price decrease in a week for the five available months in 2019 from April – August is 9.8% due to there being several weeks where there is a price increase overnight. The results for the week in June are the closest to the average and so the value of -13% is an acceptable value to carry through. The results from the electricity price analysis are represented in Appendix B.

Therefore, for the first quarter in 2019, for which the average price for electricity was £52/MWh (Drax, 2019), an estimate figure for the price of electricity overnight is:

$$Price\left(\frac{£}{MWh}\right) = 52\ x\ 0.87 = £45.24/MWh$$

2.7.5 Health & Safety

The main difference from traditional maritime vessels in terms of health and safety would be the operation of the battery packs as to not risk electric shock/fire and working next to high voltages for the engineers on board and operating the charging. To allow fast charging the voltages must be high and therefore there is a greater risk to human life; although this risk is significantly decreased with induction charging. There are predefined guidelines to working with large batteries at work from the Health & Safety Executive which sets out best practice to avoid danger to human health (Health & Safety Executive, 2006).

2.8 Analysis of Onshore Cabling and Grid Connection

2.8.1 Transmission from Turbine to Grid

For typical offshore wind farms, the turbines are all connected via subsea cables which interconnect to an offshore substation where the currents and voltages are transferred into transmission cables via transformers. Depending on the size of the wind farm there will be varying amounts of cables at different voltages. The cable(s) will connect to the mainland through an onshore substation of a similar nature, which conditions the power for either small-scale local connections or large-scale grid transmissions/industries. This is an extremely high voltage and does not have many uses other than transmission of electricity with very little losses due to the V=IR relationship. The ownership of this power now transfers to the Distribution Network Operator (DNO) for local or national distribution (The Crown Estate, 2019a).

2.8.2 Viability of Using Onshore Connection to Feed CTV's at Port

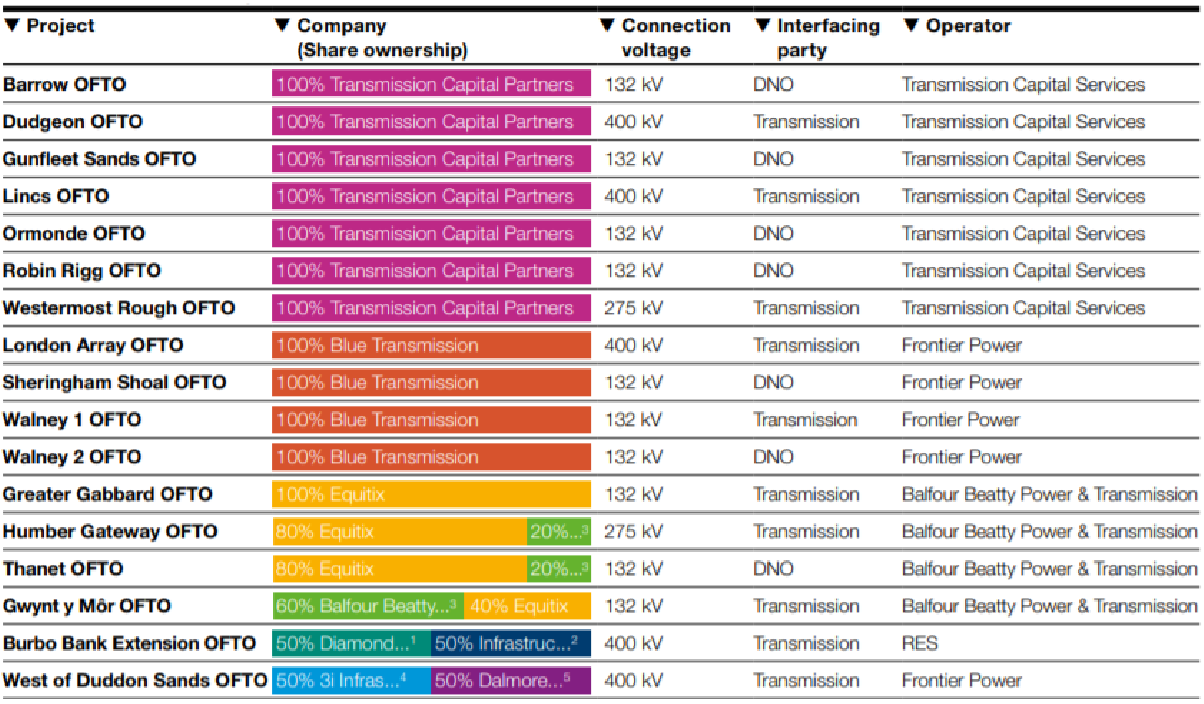
It would be beneficial to use power generated by wind farms to charge the vessels that service them. This could provide a very large load at port for the power to charge and reduce wasted power from transmission losses and scenarios where wind farms are paid to stop producing as to not overload the grid. Such constraint payments have recently been estimated at £173 million a year, paid by the taxpayer (Steve Bird, 2019).

The feasibility of this is difficult to predict, but while the positives are clearly defined, the technical difficulties are not so clear. Mainly the ownership, conditioning and wiring of the power from substation to vessel would be problematic. For this to be feasible, it would have to represent a cost-effective option that would be worth the capital cost of implementation. However, the vessel in production for 2020 by NOS will have capability to charge both from the grid and from wind power therefore, it is indeed feasible (NOS, 2019).

2.8.2.1 *Wiring*

In an ideal world, it would be possible to run a wire straight from the underground cable at the closest vicinity to the port and hook up to the vessels. However, these wires are not simply split up and fed off to loads at whatever point fits best.

Figure 20 describes ownership of transmission from turbine to grid for the major projects in the UK. The differing ownerships of power and the types of voltages/transmission are conveyed well here.



▼ **Project**	▼ **Company (Share ownership)**	▼ **Connection voltage**	▼ **Interfacing party**	▼ **Operator**
Barrow OFTO	100% Transmission Capital Partners	132 kV	DNO	Transmission Capital Services
Dudgeon OFTO	100% Transmission Capital Partners	400 kV	Transmission	Transmission Capital Services
Gunfleet Sands OFTO	100% Transmission Capital Partners	132 kV	DNO	Transmission Capital Services
Lincs OFTO	100% Transmission Capital Partners	400 kV	Transmission	Transmission Capital Services
Ormonde OFTO	100% Transmission Capital Partners	132 kV	DNO	Transmission Capital Services
Robin Rigg OFTO	100% Transmission Capital Partners	132 kV	DNO	Transmission Capital Services
Westermost Rough OFTO	100% Transmission Capital Partners	275 kV	Transmission	Transmission Capital Services
London Array OFTO	100% Blue Transmission	400 kV	Transmission	Frontier Power
Sheringham Shoal OFTO	100% Blue Transmission	132 kV	DNO	Frontier Power
Walney 1 OFTO	100% Blue Transmission	132 kV	Transmission	Frontier Power
Walney 2 OFTO	100% Blue Transmission	132 kV	DNO	Frontier Power
Greater Gabbard OFTO	100% Equitix	132 kV	Transmission	Balfour Beatty Power & Transmission
Humber Gateway OFTO	80% Equitix 20%...[3]	275 kV	Transmission	Balfour Beatty Power & Transmission
Thanet OFTO	80% Equitix 20%...[3]	132 kV	DNO	Balfour Beatty Power & Transmission
Gwynt y Môr OFTO	60% Balfour Beatty...[3] 40% Equitix	132 kV	Transmission	Balfour Beatty Power & Transmission
Burbo Bank Extension OFTO	50% Diamond...[1] 50% Infrastruc...[2]	400 kV	Transmission	RES
West of Duddon Sands OFTO	50% 3i Infras...[4] 50% Dalmore...[5]	400 kV	Transmission	Frontier Power

Figure 20 - Ownership and Operating Companies for Offshore Wind Projects

(The Crown Estate, 2019b)

In order to sell that electricity to the local infrastructure at port, there would be a lot of judicial hurdles to jump. But certainly, there are 132kV DNO connections to the local network in most cases. There are many different companies involved in the journey of the power therefore a cross party agreement would need to be had before directly using the wind power to charge vessels could be feasible.

2.8.2.2 Voltage

Flowing through these wires is a massive voltage that, if ‘hooked up’ to a nearby load without first going through the proper treatment at the substation, would likely cause major damage to whatever load it touches i.e. a vessel. Furthermore, the power entering the substation has a predetermined price. Reducing the power delivered would undoubtedly lead to a lower purchase agreement. Although, as can be seen in Figure 20, the company involved with the transmission are sometimes the same that are in charge of operations and so maintenance; in that case, it is possible that through the local distribution network, a 33kV/11kV connection could be made (Scottish Power, 2017).

2.8.2.3 Health & Safety

As with any high voltage applications, there is a high risk to human life and the less human activity in the vicinity of these voltages the better. Allowing the voltage to be transformed down through the substation and then be fed into the local infrastructure to be employed to assist the port electrical infrastructure in charging would be much safer. There would need to be highly trained technicians for the split connection,

2.8.2.4 Cost

Offsetting the amount of energy delivered to the transmission utility company would detract from the predetermined Power Purchase Agreement (PPA). Within the PPA there would be an agreed delivery of energy and so reducing that would lead to a renegotiation for a reduction of sales, of which the utility company would pay a premium (Nadine Gatzert, 2016).

Therefore, this must be compared to the prospect of charging overnight from the grid. The price of electricity is very cheap overnight on the grid and so it would most likely be more cost effective to sell the energy and primarily charge overnight. However, if grid prices rise in the future the viability of charging via wind power will increase.

2.8.3 Matching Charging Requirements to Supply Opportunities

As with the new IMO regulations, vessels in port must be connected to the local grid in order to run the hotel loads to reduce emissions. Therefore, there would already be a connection if considering charging a battery from the grid. This would reduce capital costs quite considerably, however; this depends on the type of charger. If a supercharger, similar to the Tesla Model 3 chargers where to be adopted then the local distribution line would be able to accommodate a charging facility but would need to be fitted by a trained electrician.

2.9 Appraisal of Charging Technologies for Onshore Charging

2.9.1 Key Characteristics to Consider

On-shore arrangements for battery-operated vessels have typically used a grid connection in order to slow charge overnight for ferry service. In the case of a WFSV in operation, it would be beneficial to forecast for rapid charging to allow the vessel to fulfil unplanned maintenance quickly. Such chargers are in operation, namely the Tesla Version 3 supercharger that can charge with a rated capacity of 250kW for four vehicles at one time, from a 1MW battery bank supplied from an 11kV grid connection normally used for transmission (Tesla, 2019) (Alfredsson, 2018). However, considering a single prototype, the 250kW capacity could be met by a standard 415V three phase supply (Global Maritime Energy Efficiency Partnerships, 2018) Therefore, consideration must be given to the availability of such infrastructure at ports and the differentials in charging a considerably larger battery onboard a vessel.

2.9.2 Meeting Charger Requirements

Shore power has led to connections varying between 240V – 11,000V at port for vessels of varying electrical requirements. For an offshore support vessel, a connection of 415V is already assumed to be well sized by the outlining by the IMO (Global Maritime Energy Efficiency Partnerships, 2018).

The DNO’s have a legal obligation to connect customers requiring a connection in their network (Parliamentary Office of Science and Technology, 2001). Therefore, it is certainly feasible to envisage a rapid charging station being constructed at port.

2.9.3 Security of Battery Health

Battery manufacturers will provide the consumer with guidelines as to maximise the lifespan of the battery. In current EV markets there is a great emphasis on extended battery life and range which has seen the development of technologies based on improving the State of Health (SOH) of a working battery, most commonly through an on-board Battery Management System (BMS) (M. Berecibar, 2016). Therefore, onboard BMS would look after the SOH of a battery automatically via the vessels electronic control room.

One aspect in which operations could improve battery SOH would be in ensuring a healthy depth of discharge is adhered to. The depth of discharge is the percentage detracted from full charge for a battery system. While each battery will have differing guidelines, a good estimate for real life applications of Lithium-Ion batteries would be to never exceed 80% discharge (M. Berecibar, 2016). Therefore, when estimating battery size for application, a further 20% battery capacity should be considered.

Finally, consideration must be given to the type of charger to make the connection that we require from the charger to the vessel. There has been development in the field of induction loop charging which uses magnetic coupling to charge batteries, which would be beneficial mainly due to the removal of a human operated connection, and so health and safety precautions and the need for trained professionals. However, the induction loop technology does not have the power to cope with what is known as level 3 rapid charging (Murat Yilmaz, 2013) and so plug in would be the more favourable option to consider.

3.0 Methodology

3.1 Case Study Particulars

In order to make an accurate prediction of the pricing for hybrid scenarios; a reference vessel, wind farm and profile must be established to determine the sizes for fuel and charge apparatus, and so the Capex of the vessel. Furthermore, the price for the vessel builder/owner and client who charters and fuels the vessel must be determined for each technology over 25 years, with consideration to the rising price of energy. In order to achieve this, scenarios must be chosen, involving the implementation at the design stage to begin operation in 2020 in order to fully understand the benefits of each.

Microsoft Excel ©

Microsoft Excel is a leading software for analytics and spreadsheets. The user-friendly interface will provide the perfect model to run a 25-year cost analysis simulation. Once the price variations have been multiplied cumulatively by the original fuel price, and the 25-year capex costs/fuel savings are established, a ROI vs fuel saving analysis will show weather the hybrid transition can be mutually beneficial.

Vessel

A calculation of some of the major WFSV providers fleets in Appendix A shows that the average WFSV is most like the Green Quest with an average length of 20m. Therefore, the Green Quest will be used as the reference vessel in this case and the Wind Supplier will be analysed based upon the increased size, power and speed.

Wind Farm

Crown Estate Reference 1GW Wind Farm

Profile

143 days of Annual Maintenance

Assumptions

- Only fuel and charter costs are considered for client OPEX.
- Average maintenance and replacement costs over 25-year lifespan assumed to directly influence charter rate.
- Work time for technician is assumed to be 6 hours for planned maintenance.

- Operational wave height and weather interferences neglected as they are out with the scope of this case study.
- Hull maintenance is neglected.

3.2 Cost of Vessel Technology for Case Study Scenarios

3.2.1 ICE

Capital Cost

The cost for the Green Quest is highlighted in Table 2 as well as a listing for a similar vessel details of which are in Appendix A (Seaboats, 2019) using a conversion rate of 1USD = 0.8Sterling. The cost for the Green Quest and the Wind Supplier is sensitive information and so can be assumed to be relative to engine power to allow for a down/up scaling.

Table 2 - Comparison of Vessel Characteristics

Vessel	Engine (kW)	Speed (nots)	Length (m)	Fuel Consumption (l/h)	Cost (£)
New Build WFSV	1440	25	20.8	N/A	1,838,597
Green Quest	1300	22	17.8	200	1,654,737
Wind Supplier	2880	25	32	**384**	**3,677,194**

Fuel Costs

The cost of fuel for one WFSV has been established to be £1246. However, this will not represent both of the WFSV's as one has almost twice the fuel consumption. Therefore, considering the MV Wind Supplier to be the top end of the scale for fuel costs a percentage increase can be made:

$$\therefore GQ\ fuel\ costs = 1246\ x\ 143 = £\mathbf{178,178/y}$$

$$\%\ Increase\ of\ Fuel\ Consumption = \frac{384}{200} = \ +192\%$$

$$\therefore WS\ fuel\ costs = (1246\ x\ 1.92) x\ 143 = \textbf{£342,101/y}$$

Maintenance Cost

In chapter 2.3.3 the average maintenance cost per year for WFSV's is found to be £17,820/y. Applying the same theory as for fuel consumption, the increase in mechanical maintenance costs can be likened to the difference in engine power. The relationship of maintenance costs between mechanical and hull is 57.5:42.5 respectively (Burman, 2002).

$$GQ\ Mechanical\ Maintenance\ Costs = 0.57\ x\ 17{,}820 = \textbf{£10,157}$$

$$\%\ Increase\ in\ Power = \left(\frac{2800}{1300}\right) + 215\%$$

$$\therefore WS\ Mechanical\ Maintenance\ Costs = 2.15\ x\ 10{,}157.4 = \textbf{£21,877}$$

As of 2021 all vessels that do not meet NO_X Tier III limits of a 75% reduction from HFO standards will have to employ an apparatus to meet this requirement. Of these the most popular is the Selective Catalytic Redactor (SCR). The cost for the SCR is \$125/HP (Sorrels, 2016) and so at today's exchange rate of \$1 = £0.8 the cost would be £100/HP and so £74.2/kW.

The Swedish Environmental Research Institute has the cost for a marinized SCR to be $€_{2010}$88.7/kW (Katarina Yaramenka, 2017). Using specifically the average 2010 exchange rate of €0.86=1£ (Statista, 2019) the cost becomes £76.2/kW. A medium value of £75/kW can be assumed based on these two resources.

Therefore, the capital cost for each vessel is:

$$Green\ Quest\ SCR\ Capital = 75\ x\ 1300 = £97{,}500$$
$$Wind\ Supplier\ SCR\ Capital = \ 75\ x\ 2880 = £216{,}000$$

The SCR operates by diluting the exhaust with Urea, typically 10% of MGO volume and achieves an 80% reduction in NO_X emissions for compliance with Tier III. The cost of Urea is 20% of MGO. (Katarina Yaramenka, 2017). Due to the daily refuelling of Urea, this would be considered an additional fuel cost as of 2021.

Urea costs for MV Wind Supplier = $0.1\ x\ (\big(0.2\ x(2392\ x\ 143)\big) = \textbf{£6841/y}$

Urea costs for Green Quest = $0.1\ x\ (0.2\ x(1246\ x\ 143)) = \textbf{£3563/y}$

Annual mechanical maintenance for the SCR is 0.5% of the capital investment (Katarina Yaramenka, 2017) and so for each vessel:

SCR Maintenance for MV Wind Supplier = 0.05 x 216,000 = **£10,800/y**

SCR Maintenance for Green Quest = 0.05 x 97,500 = **£4875/y**

Therefore, the total maintenance costs for ICE in each vessel post 2021 are:

Table 3 - ICE Vessel Maintenance Costs

Vessel	Annual Maintenance Cost (£)
Green Quest	15,032
Wind Supplier	32,677

3.2.2 Hybrid Costs

Capital Costs

The cost for a 250kW supercharger and the initial maritime hybrid system sized to 30% at £480/kWh in 2020 would be:

$$\boldsymbol{GQ\ Hybrid\ Capital\ Costs = 236,962 + ((0.3\ x\ 1300)\ x\ 480)) = £424,162}$$

$$\boldsymbol{WS\ Hybrid\ Capital\ Costs = 236,962 + ((0.3\ x\ 2880)\ x\ 480)) = £651,682}$$

Fuel Costs

As discussed in Chapter 2.7.4. the assumed price of electricity for overnight charging is £45.24/MWh.

For a battery bank of 390kWh, the cost of charge would be:

$$Cost\ of\ Charge = \frac{45.24}{1000}\ x\ 390 = £17.64/day$$

The annual cost of charge is then:

$$Annual\ Electricity\ Costs = 92\ x\ 17.64 = \boldsymbol{£1622.88/year}$$

For a battery bank of 864kWh, the cost of charge would be:

$$Cost\ of\ Charge = \frac{45.24}{1000}\ x\ 864 = £39/day$$

The annual cost of charge is then:

$$Annual\ Electricity\ Costs = 92\ x\ 17.64 = \pounds\mathbf{3588/y}$$

The reduction of MGO consumption is difficult to predict due to the lack of hybrid WFSV's however a 19% reduction can be ascertained from literature (MAN, 2019) (Siemens , 2015).

Therefore, the annual fuel costs would be:

$$Hybrid\ Fuel\ Costs\ (WS) = 3588 + (342{,}101\ x\ 0.81) = \pounds\mathbf{280,689/y}$$

$$Hybrid\ Fuel\ Costs\ (GQ) = 1622.88 + (178{,}178\ x\ 0.81) = \pounds\mathbf{145,947/y}$$

Maintenance

The cost of the Lithium-Ion replacements over 25 years has been determined to be:

- 2025 - £120/kW
- 2030 - £80/kW
- 2035 - £80/kW
- 2040 - £80/kW

Considering an exchange rate of 1USD=0.8Sterling

Table 4 - Marinized Battery Cell Replacement Costs (25y)

Year	Green Quest	Wind Supplier
2025	120 x 390 = £46,400	120 x 864 = £103,680
2030	80 x 390 = £31,200	80 x 864 = £69,120
2035	80 x 390 = £31,200	80 x 864 = £69,120
2040	80 x 390 = £31,200	80 x 864 = £69,120
Total (pounds)	£140,000	£311,040

Assumptions are that the system maintenance is negligible, in line with the MV Hallaig (Anderson, 2012) and implementation of hybrid systems into vessels is thought to bring down mechanical maintenance costs by 30% (CMAL)

$$GQ\ Hybrid\ Maintenance = 0.7\ x\ 10{,}157 = \mathbf{7109/y}$$

$$Wind\ Supplier\ Hybrid\ Maintenance = 0.7\ x\ 21{,}877 = \pounds\mathbf{15313/y}$$

The amount of Urea required would decline at the same rate as the MGO therefore:

$$GQ\ SCR\ Urea\ Reduction = 3563 - (0.81\ x\ 3563) = \pounds\mathbf{676/y}$$

$$WS\ SCR\ Urea\ Reduction = 6841 - (0.81\ x\ 6841) = \pounds\mathbf{1299/y}$$

Considering the price of battery replacements and SCR:

$$GQ\ Hybrid\ Maintenance = 7109 + 140{,}000 + (10{,}522\ x\ 24) = \pounds\mathbf{399,637}$$

$$WS\ Hybrid\ Maintenance = 15{,}313 + 311{,}040 + (22{,}873\ x\ 24) = \pounds\mathbf{875,305}$$

Table 5 - Total ICE Costs for Vessel Owner (25y)

Vessel	Capital + SCR (£)	Maintenance +SCR (£)	Total (£)
Green Quest	1,752,237	370,925	**2,123,162**
Wind Supplier	3,893,194	806,125	**4,699,319**

Table 6 - Total Hybrid Costs for Vessel Owner (25y)

Vessel	Capital + SCR (£)	Maintenance +SCR (£)	Total (£)
Green Quest	2,176,399	399,637	**2,576,036**
Wind Supplier	4,544,876	875,305	**5,420,181**

Green Quest Added Costs for Vessel Owner

$$GQ\ Owner\ Added\ Costs = 2{,}576{,}036 - 2{,}123{,}162 = \pounds\mathbf{452,874}$$

Wind Supplier Added Costs for Vessel Owner

$$WS\ Owner\ Added\ Cost = 5{,}420{,}181 - 4{,}699{,}319 = \pounds\mathbf{720,862}$$

4.0 Results & Discussion

In order to accurately simulate the fuel price over 25 years, the shift in prices must be considered. The UK Government released an energy price forecast in 2018 that lists the major energy commodity prices such as crude oil and electricity until 2035. The ideal lifespan for simulation is 2020-2045 and so the remaining years price differential can be taken from the trend of the previous 5 years.

Once an accurate figure for fuel prices over 25 years is acquired, the potential fuel savings can be weighed against the added cost to the vessel owner. If the fuel savings are greater than the added operator costs then an increased charter rate, within the limits of the fuel savings can cover the costs for the vessel owner and create a mutually beneficial agreement.

Client Economics

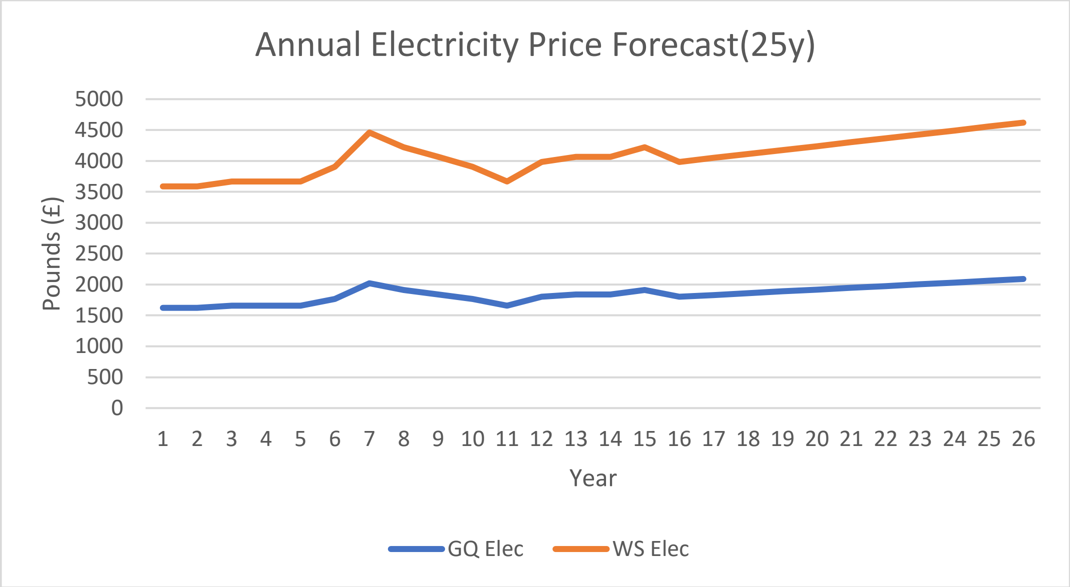


Figure 21 - Annual Electricity Price Forecast (25y)

Figure 21 depicts how electricity prices are expected to grow over the coming decades. This is most likely due to a higher electricity demand due to electric vehicles and a greater cost of producing renewable energy on the grid. However, the annual rise in charging price will be insignificant, rising by only £500 & £1000 respectively. However, hybrid technologies are likely to improve and so the benefits of the batteries are likely to outweigh the growing cost. For instance, the first WFSV hybrid will be ready for charging offshore (NOS, 2019) and so could double the potential benefits of the technology, or halve the amount of space and added weight required.

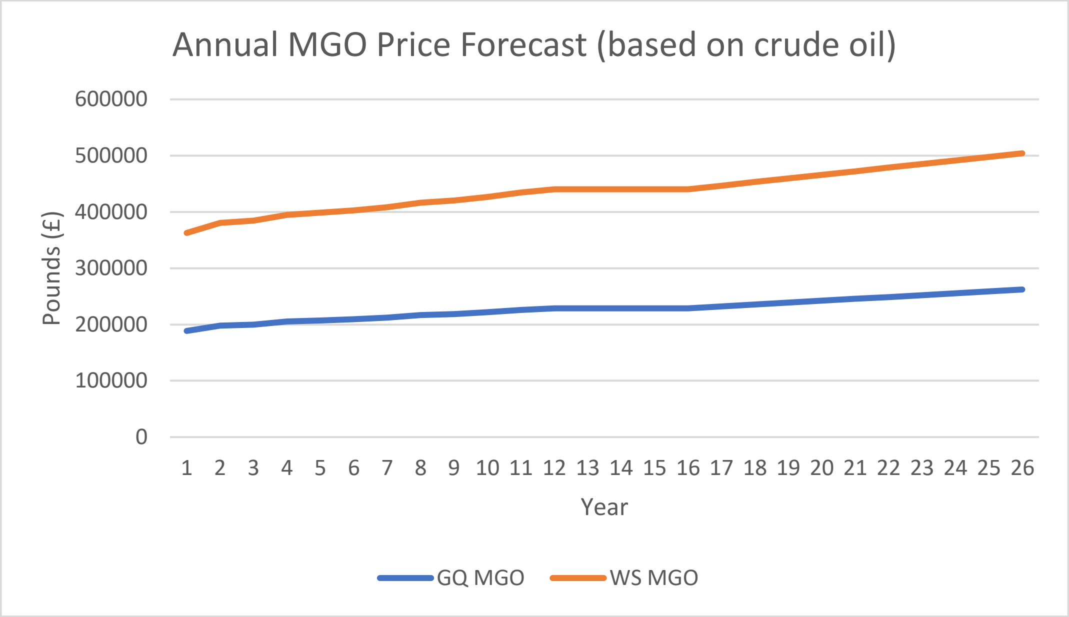


Figure 22 - Annual MGO Price Forecast (based on crude oil)

Figure 22 correlates the MGO price increase to the rise in crude oil prices. The government expect a heavier tax for carbon fuels and as global stocks are reduced, prices are likely to rise. While the rise is gradual, by the end of the lifespan of a WFSV the fuel costs for vessels with high fuel consumption could rise by more than 20% which is reflected in the Wind Supplier MGO costs. This rise in costs gives impetus to the technologies that reduce fuel consumption such as hybrids.

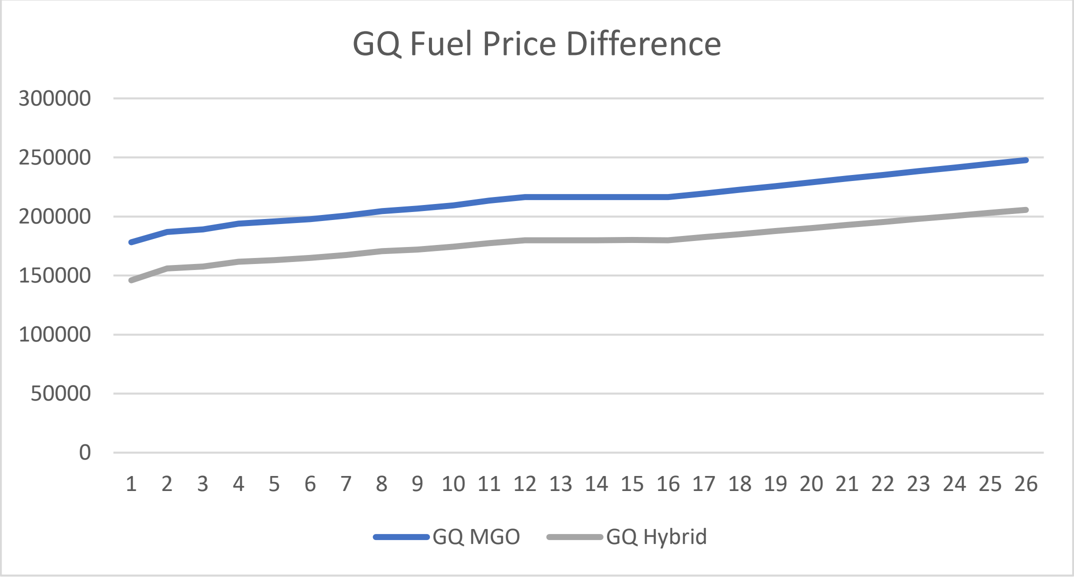


Figure 23 - GQ Fuel Price Difference

Figure 23 compares a 25-year scenario for the Green Quest operating with and without a hybrid propulsion system. Towards the end of the 25-years the comparatively high rise in MGO price against electricity price becomes apparent and the reduced fuel consumption becomes more prolific in reducing costs. The initial price difference is £32,230 while 25 years later, the saving is £42,083, which is a 30% increase. Therefore, just for 143 days of operation, potential increased annual capital could be offset by an increased charter rate up to £225/d and £494/d respectively. Ideally, a value that would attract clients with savings while being cheaper for the vessel owner would be the best-case scenario.

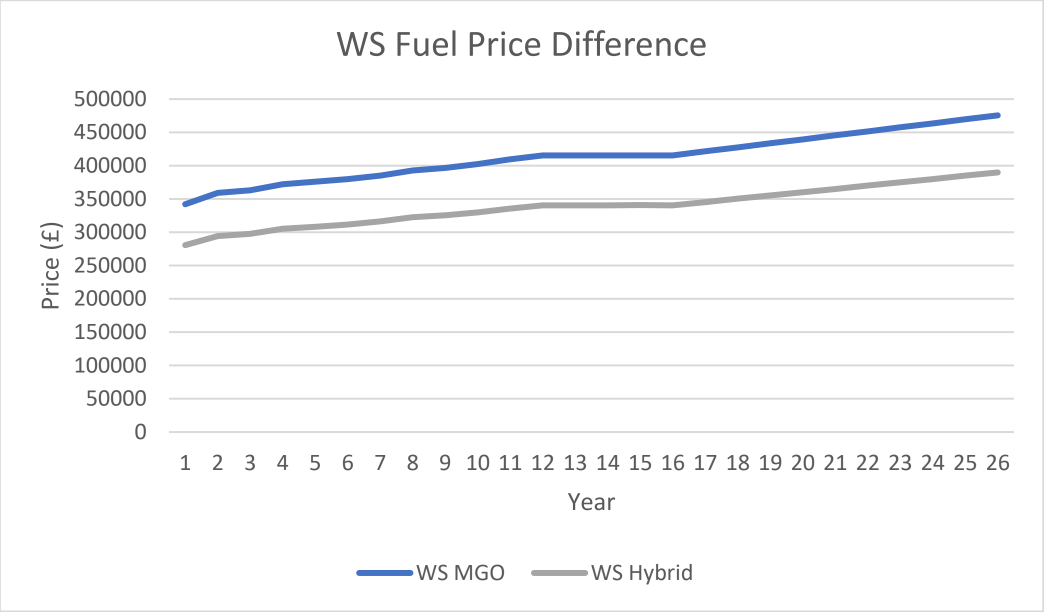


Figure 24 - WS Fuel Price Difference

Figure 24 compares a similar scenario for the larger, less efficient vessel. The benefits of the hybrid system are more profound in this case. The price difference in 2020 is £61,411 while in 2045 that increases to £85,736 which is a 39% increase. This would open £429/d and £599/d of potentially negotiable funds. The Wind Supplier’s electricity bill is more than twice that of the Green Quests yet increased MGO reductions overcome this to further increase savings from the smaller vessel.

The annual savings made from the hybrid technology steadily increase to become extremely profitable for the client. Over the course of 25 years, a small WFSV could save £942,710 in fuel while the larger model would save £1,934,620. These are significant savings and although dependant on the price shift, offer an explanation as to why many WFSV companies are investing into hybrid technology. However, this saving would be enjoyed by the client, at no extra cost to themselves. Therefore, there is certainly scope for suggesting deficits incurred by the vessel owner could be offset by these savings.

Vessel Owner Economics.

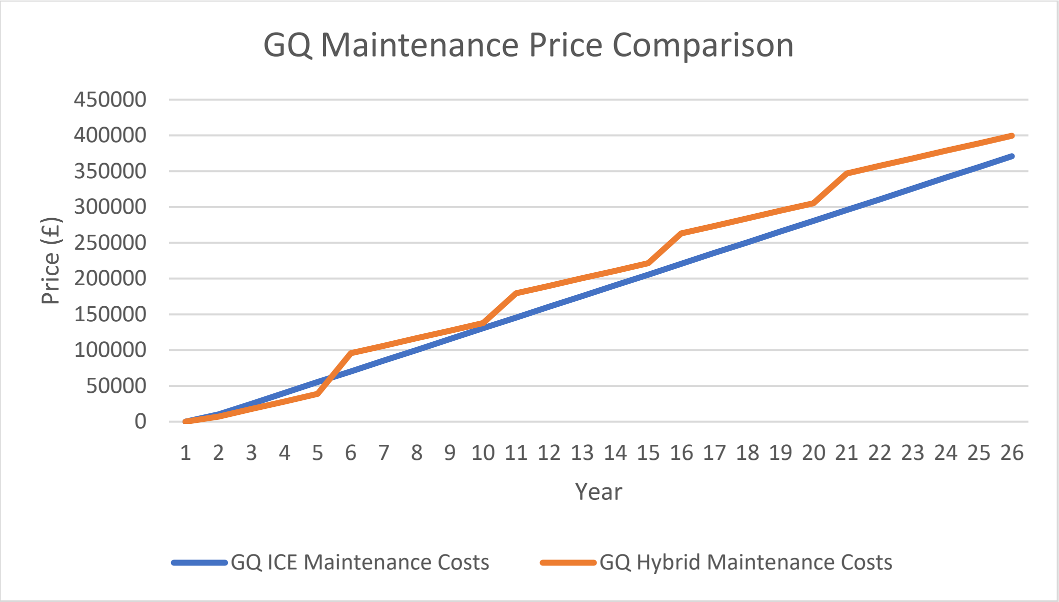


Figure 25 - GQ Maintenance Price Comparison

Figure 25 shows the Green Quest’s maintenance costs. As the initial battery system is considered as a capital cost for the vessel, the maintenance trend is positive for the hybrid system. Both the 30% reduction in mechanical maintenance and a reduction in Urea necessary due to a lower fuel consumption are the two key factors in keeping maintenance costs low. Although every 5 years there is a considerable cost of replacing the battery cells, which has a negative effect. However, the projected fall in price of these cells prevents the hybrid costs becoming too great. This is a key positive economic factor of hybrid technology and must be a key consideration for companies considering upgrading their fleet.

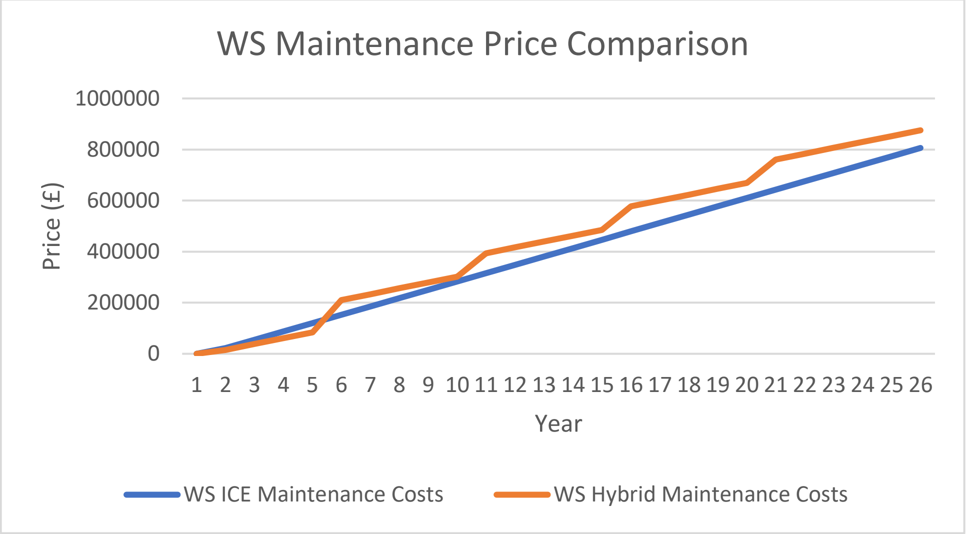


Figure 26 - WS Maintenance Price Comparison

The positive effect on maintenance is less profound for the larger vessel case, due to higher cell replacement costs as shown in Figure 26. After every 5-year increment the increase in price for the hybrid system increases. Clearly the reduced maintenance costs are not solely sufficient to cover the costs of battery replacement. Therefore, in the case of chartering out a vessel, where the fuel savings are not directly had by the vessel builders, a higher charter rate must be considered to, at the very least, bring parity with ICE costs.

Estimation of potential charter rates

Finally, investment impacts for the vessel owner and the cost saving for the client must be compared in order to suggest a reasonable charter cost.

Green Quest Cost Analysis

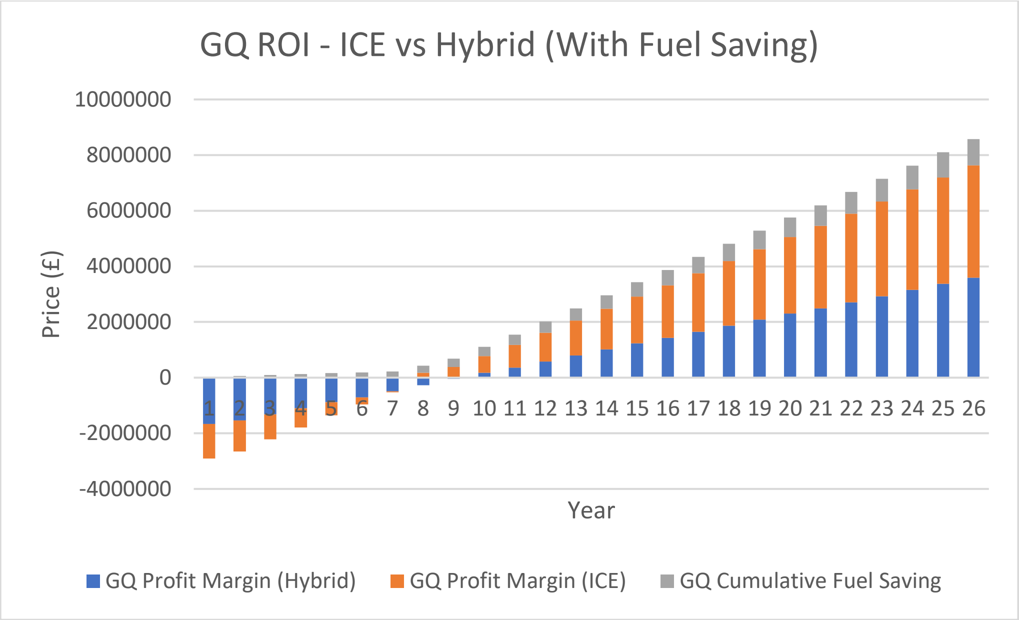


Figure 27 - GQ ROI - ICE vs Hybrid (with fuel saving)

Figure 27 compares the return of investment for the vessel owner and the potential fuel savings for the client at a charter rate of £2908. For the case of an ICE engine, ROI is achieved after 7 years while in the case of a hybrid vessel, ROI is increased to 9 years. As can be seen, fuel savings can become an important factor in stabilising this relationship, although its influence may not be sufficient until later years when an increase in fuel prices occurs. A further analysis of figures is provided in Table 7.

Table 7 - Green Quest 25y Cost Analysis

Year	GQ Added Costs	GQ Fuel Saving	Charter Profits	GQ Profit Margin (Hybrid)	GQ Profit Margin (ICE)
2020	430819	32230	415701	-1663198	-1239036
2021	-3047	31018	645701	-1537807	-1116693
2022	-4509	31354	875701	-1318330	-901725
2023	-4509	32284	1105701	-1098852	-686757
2024	-4509	32656	1335701	-879375	-471789
2025	41890	32920	1565701	-706297	-256821
2026	-4509	33227	1795701	-486819	-41853
2027	-4509	34078	2025701	-267342	173115
2028	-4509	34522	2255701	-47864	388083
2029	-4509	35152	2485701	171612	603051
2030	26690	36004	2715701	359890	818019
2031	-4509	36418	2945701	579368	1032987
2032	-4509	36382	3175701	798845	1247955
2033	-4509	36382	3405701	1018323	1462923
2034	-4509	36311	3635701	1237800	1677891
2035	26690	36418	3865701	1426078	1892859
2036	-4509	36985	4095701	1645556	2107827
2037	-4509	37551	4325701	1865033	2322795
2038	-4509	38118	4555701	2084511	2537763
2039	-4509	38684	4785701	2303988	2752731
2040	26690	39251	5015701	2492266	2967699
2041	-4509	39817	5245701	2711744	3182667
2042	-4509	40384	5475701	2931221	3397635
2043	-4509	40950	5705701	3150699	3612603
2044	-4509	41517	5935701	3370176	3827571
2045	-4509	42083	6165701	3589654	4042539

The overall difference in profits for the two technologies are:

$$GQ\ Profit\ Margin\ Differential = 4{,}042{,}539 - 3{,}589{,}654 = £452{,}885$$

As a sense check, this value can be compared to the vale obtained in the section 3.2.2 which was £452,874 and so is well within a reasonable margin of error for rounding. This substantiates conclusions made from Excel simulation.

The total fuel savings amount to £942,710 over the 25 years, which is more than double the lost profits to the vessel owner. Therefore, for parity, the daily charter rate must be increased by the proportion of lost profits compared to fuel savings which is 48%. If fuel funds were circumvented to charter rate for parity a further £490,209 would be available for negotiation.

In order to contemplate this figure, the annual discrepancy in profits can be broken down to a daily figure, along with the daily fuel saving.

$$GQ\ Daily\ Lost\ Profit = \frac{(\frac{452{,}885}{25})}{143} = \pounds\boldsymbol{126/d}$$

$$GQ\ daily\ fuel\ saving\ (2020) = \frac{32230}{143} = \pounds\boldsymbol{225/d}$$

For the case of the Green Quest in 2020, the daily fuel saving is 78% more than the potential increase in charter rate and therefore, there is scope for a mutually beneficial agreement. This would be the decision of the vessel owner and there would be many considerations, such as maximising profits to enable further vessel retrofitting. However, a 50/50 split of the remaining profits could be achieved after parity by the following calculation:

$$GQ\ New\ Charter\ Rate = \frac{225 - 126}{2} + 126 = \ 2907.5 + \pounds 175.5 = \pounds\boldsymbol{3083/d}$$

$$\therefore Additional\ profit\ for\ Owner = 49.5\ x\ 143 = \pounds\boldsymbol{7078.5/y}$$

$$\therefore Annual\ Saving\ for\ Client = \frac{(225 - 126)}{2}\ x\ 143 = \pounds\boldsymbol{7,078.5/y}$$

After the ROI period, there is potential for vessel companies to negotiate a further increase to the charter costs, reflective of the 30% increased saving of the client.

Wind Supplier Cost Analysis

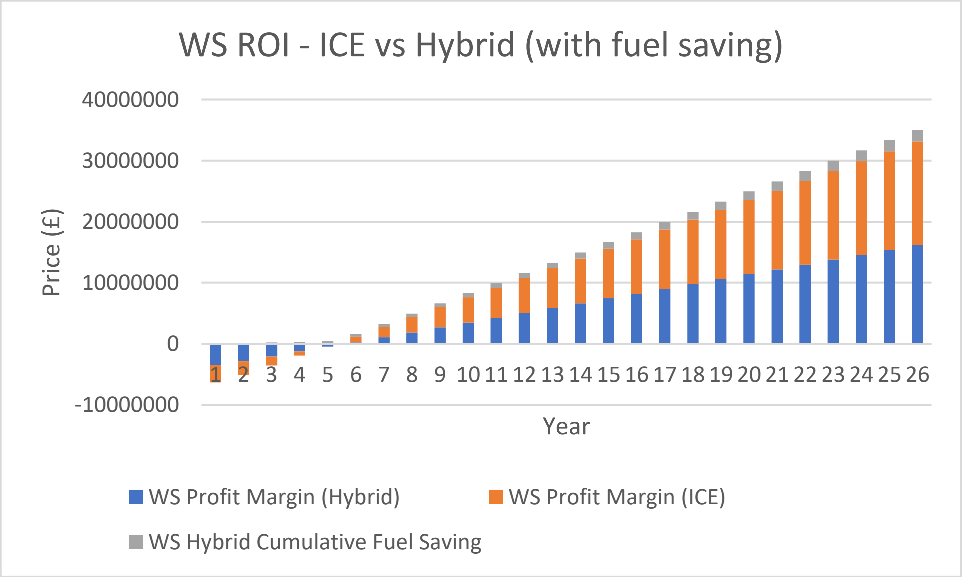


Figure 28 - WS ROI - ICE vs Hybrid (with fuel saving)

The larger WFSV will have a faster payback period than the smaller one, four years for an ICE vessel and five years for a hybrid version as shown in Figure 28. Similar to the smaller vessel, the fuel saving increases gradually over time, while the higher charter rate shortens the ROI timeline. The significant reduced maintenance, up until the fifth year, enables the hybrid scenario to just fall marginally short of matching the ICE ROI.

Table 8 - Wind Supplier 25y Cost Analysis

Year	WS Added Costs	WS Fuel Saving	Charter Profits	WS Profit Margin (Hybrid)	WS Profit Margin (ICE)
2020	651682	61411	831402	-3497474	-2845792
2021	-6563.1	64625	1662804	-2897385	-2252267
2022	-9803.1	65260	2494206	-2088857	-1453542
2023	-9803.1	67046	3325608	-1280329	-654817
2024	-9803.1	67760	4157010	-471801	143908
2025	93876.9	68236	4988412	233046	942633
2026	-9803.1	68752	5819814	1041574	1741358
2027	-9803.1	70418	6651216	1850102	2540083
2028	-9803.1	71291	7482618	2658630	3338808
2029	-9803.1	72522	8314020	3467158	4137533
2030	59316.9	74188	9145422	4206567	4936258
2031	-9803.1	74942	9976824	5015095	5734983
2032	-9803.1	74863	10808226	5823623	6533708
2033	-9803.1	74863	11639628	6632151	7332433
2034	-9803.1	74704	12471030	7440679	8131158
2035	59316.9	74942	13302432	8180087	8929883
2036	-9803.1	76022	14133834	8988615	9728608
2037	-9803.1	77101	14965236	9797143	10527333
2038	-9803.1	78180	15796638	10605671	11326058
2039	-9803.1	79260	16628040	11414199	12124783
2040	59316.9	80339	17459442	12153608	12923508
2041	-9803.1	81418	18290844	12962136	13722233
2042	-9803.1	82498	19122246	13770664	14520958
2043	-9803.1	83577	19953648	14579192	15319683
2044	-9803.1	84656	20785050	15387720	16118408
2045	-9803.1	85736	21616452	16196248	16917133

Table 8 shows the figures for the WS simulation, which contrast the difference in profit margins, showing that in the fourth year, the hybrid version profits are at -£471,801 while the ICE vessel breaks into the positive at £143,904. As the maintenance projections indicated, a further increased charter rate will be necessary in this case. A sense check with the deficit calculations from chapter 3.2.2 that predicted a £720,862 shortfall will validate projections.

$$WS\ Profit\ Margin\ Differential = 16{,}917{,}133 - 16{,}196{,}248 = £720{,}885$$

This is within an acceptable rounding error for validation.

As with the Green Quest a comparison of the fuel savings and lost profits must be made to accurately suggest a new charter rate. The total fuel savings for the WS would be £1,934,620, lost profits account for 37% of the fuel savings over 25 years, leaving £1,218,810 extra profit, if parity was secured through allocating fuel savings to charter. In order to estimate a daily allocation for parity both fuel savings and profit deficit must be broken down to daily rates.

$$WS\ Daily\ Lost\ Profit = \frac{(\frac{720{,}885}{25})}{143} = \boldsymbol{£201/d}$$

$$WS\ daily\ fuel\ saving\ (2020) = \frac{61411}{143} = \boldsymbol{£429/d}$$

The initial fuel saving is 213% of the profit deficit, meaning there is a more beneficial agreement possible for the larger vessel. Again, assuming a 50/50 split after parity is achieved the potential charter rate and fuel savings would be:

$$WS\ New\ Charter\ Rate = \frac{429 - 201}{2} + 201 = \ 5814 + 315 = \boldsymbol{£6129/d}$$

$$\therefore Additional\ profit\ for\ Client = 114\ x\ 143 = \boldsymbol{£16,302/y}$$

$$\therefore Annual\ Saving\ for\ Client = \frac{(429 - 201)}{2}\ x\ 143 = \boldsymbol{£16,302/y}$$

Therefore, it is entirely possible that, after 25 years, a cumulative saving for the client of £400,800 would be a substantial gain for the company. Applying an increase relative to the increase in fuel savings of 39%, after 25 years the potential added profit could be £557,112. This would substantiate 85% of the initial added capital investment for another vessel at today's prices.

The smaller vessel would generate £176,962 extra over the 25-year period at the same rates, and so while with a smaller increase in fuel saving of 30%, potential added profits after 25 years would be £230,050. This would account for 54% of the additional capital for a replacement vessel.

Within these two statistics, the difference in net gains for the two generations of vessels is clear. For the larger vessel the economic argument is significantly greater than for the smaller vessel and so as the industry moves further offshore and large WFSV's increase in numbers, the argument for hybrid systems becomes greater. However, both scenarios are profitable and would result in a rare double positive of improving profits while reducing emissions.

Emissions

As this is an application that is not yet in use for WFSV's, an accurate emissions reduction is difficult to postulate due to the varying operations and vessels. There is certainly a great saving to be made while in DP mode and operating on fully electric, rather than an ICE engine at low and inefficient power levels. Reducing CO_2 by 30% and NO_X by 25% across the board in WFSV's would be considered a potential maximum reduction for the scenarios conveyed here. Considering it is a consequence of a profitable transition, this is an excellent step in meeting emissions targets, particularly when combined with an SCR which would reduce 80% of NO_X emissions.

Although these reductions are significant, more must be done to meet the target of a 50% of all emissions set by the IMO for the year 2050. Battery technology may well continue to improve and offer improved reductions on its own, especially with the potential of charging at sea and doubling capacity. Furthermore, multiple options have been set out in this research including LNG DF and Hydrogen PEMFC. Considering the added benefit of reducing waste energy and generating at source Hydrogen seems the more sustainable option, especially considering the WTW emissions of LNG production. Therefore, converting to hybrid in 2020 would be a first step, likely within the next two decades, when one of these technologies becomes mature enough to offer a similar, cost-effective transition, emissions will be reduced to meet, if not, exceed targets.

Effect on Industry

Considering that, on average, wind turbines require one annual service visit, but three to four corrective maintenance visits (Christine Rockmann, 2017), the potential savings are increased significantly. If the case of the new generation of WFSV's is taken, per visit, a saving of £114 is possible, this value could be multiplied by four and for every turbine in a 1GW wind farm to ascertain potential impacts.

$$Potential\ Saving\ of\ 1GW\ Wind\ Farm = (114\ x\ 4)\ = £65{,}208/y$$

The percentage decrease of WFSV fuel costs at an increased charter rate is:

$$WFSV\ \%\ Decrease = \frac{114}{2392} = 4.7\%$$

Considering the prospected rise in offshore wind and the UK legislating for 30GW on the grid by 2030, a widescale uptake of this technology could incur some significant economic and emissions savings.

Limitations of Case Study

Access to Sensitive Information

Fully accurate costings for various inputs were not available due to the sensitive nature of the information. Therefore, values have had to be derived from literature or scaled up/down. This is likely to have an effect on the accuracy of capital costs, maintenance costs and fuel costs. However, conservative estimates of savings should counteract potential discrepancies.

Neglecting of Battery Weight Implication

Added weight of vessel could impact the fuel efficiency of these vessels. However, the extent of which is considered negligible due to the comparative weight of the system and vessel gross tonnage.

Lack of In-Situ Profiles

The profiles of both windfarm maintenance and WFSV operation have been taken from substantiated literature. While these sources deliver the profiles to a high degree of accuracy, Precise profiles for both would lead to a more accurate representation, and so result.

Lack of In-Situ Example WFSV

As this is a field of research still under development, and not to be put into practice until 2020, many of the reductions and performance differentials have had to be taken from much larger vessels and so may not be accurate to a WFSV.

5.0. Conclusions & Recommendations

The offshore wind industry is set for a meteoric rise to become a staple of the UK grid infrastructure. In doing so, the O&M of the industry is predicted to increase exponentially; as new wind farms are added, and existing turbines require more maintenance as they age. The vessels involved in relaying technicians to carry out this maintenance will increase in size and use in the coming years, bringing with them increased fuel costs and emissions. If the current fleets are not upgraded, the potential costs to the environment and windfarm operators could be extremely high. Of these fleets, the Wind Farm Support Vessel is heavily relied upon for transfers and the vessels are undergoing an upscale in reflection of the increasing distance from land that the wind farms are constructed.

In terms of alternative propulsion for vessels, there are three principle technologies going forward; Lithium-Ion Hybrid, LNG and Hydrogen. Currently, LNG favours large slow to medium speed vessels while hydrogen is still in its early stages but has an optimistic future, particularly when coupled with renewable electricity. However, until these technologies mature to offer replacements for MGO, Lithium-Ion Hybrid technology would seem to be the best case for small high-speed vessels, as the EV boom is driving prices and energy densities to be competitive with crude oil-based fuels.

The potential for inflated savings due to the changeability of a WFSV's operational profile makes instantaneous power from batteries far more efficient than ICE's. If an additional 30% of engine rated power is added in parallel hybrid then the potential fuel savings for both traditional WFSV's and the larger next generation model is significant. Along with which drastic emissions reductions are possible. The additional capital costs over the lifespan of these vessels is far outweighed by the potential fuel savings and an amicable increased charter rate could be more profitable for the clients, while reserving a fuel saving for mutually increased profits.

Recommendations for Future Research

As a field of research, alternatively fuelled offshore workboats are both cutting edge and optimistic. The relevance of this topic will only increase in years to come and for the potential to be realised, research and development must intensify. A comprehensive study will have access to full maintenance profiles and state of the art technological implications for potential vessel emissions and profits. A competent design for hybrid implementation on a small vessel and charging facilities both at port and at sea would allow for prototypes to give industry confidence to invest. Furthermore, additional alternative fuels must be simulated for WFSV operations in order to compare benefits and costs, and perhaps to indicate a timeline for a level of maturity that will replace ICE's.

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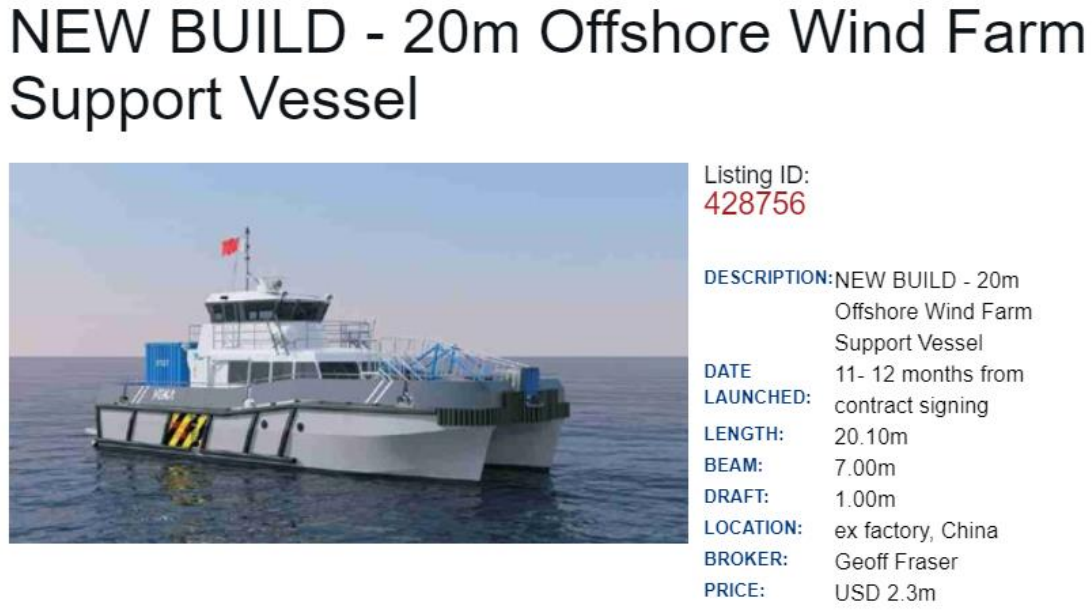
Appendix A

Reference Vessel Inputs

Capital Cost (Seaboats, 2019)



NEW BUILD - 20m Offshore Wind Farm Support Vessel

Listing ID:
428756

DESCRIPTION:	NEW BUILD - 20m Offshore Wind Farm Support Vessel
DATE LAUNCHED:	11- 12 months from contract signing
LENGTH:	20.10m
BEAM:	7.00m
DRAFT:	1.00m
LOCATION:	ex factory, China
BROKER:	Geoff Fraser
PRICE:	USD 2.3m

Average Size

<u>MPI </u>(MPI, 2019)

Vessel Lengths = 15+15+17+17+17+17+19+19+19+19+20+20.85+20.85 = 237.5m

Average = $\frac{237.5}{13} = \mathbf{18.1}\boldsymbol{m}$

<u>NOS </u>(NOS, 2019b)

Vessel Lengths = 23+20+23+25+23+20+23+20+20+20+20+20+20+26+24+15+27+27+27+25+26+25+18+15+15+32+23+25 = 627m

Average = $\frac{627}{28} = \mathbf{22.3}\boldsymbol{m}$

<u>NSL </u>(NSL, 2019)

Vessel Lengths = 18+16+18+18+15+19+19+21+22+22 = 188

Average = $\frac{188}{10} = \mathbf{18.8}\boldsymbol{m}$

<u>Windcat </u>(Windcat Workboats, 2019)

Vessel Length = 15+16+18+19+18+22+22+19+23+27.8+25.8 = 225.6

Average = $\frac{225.6}{10} = \mathbf{22.5}\boldsymbol{m}$

<u>Total Combined Average</u>

Averages = 18.1+22.3+17.8+22.5 = 80.7m

Average = $\frac{80.7}{4} = \mathbf{20.1m}$

Appendix B

The results of daily price differences from 03:00 to 15:00 are represented in Tables below for a week in each available relevant month.

April

Date	Morning Price (03:00) (£/MWh)	Day Price (15:00) (£/MWh)
14	23.26	54.27
15	28.92	30.01
16	51.87	33.22
17	42.50	32.64
18	33.26	53.26
19	30.00	22.46
20	53.00	33.70

$$\%\ shift = \frac{Average\ Morning\ Price}{Average\ Daytime\ Price}$$

$$\%\ shift = \frac{37.5}{37} = +\mathbf{1}\%$$

May

Date	Morning Price (03:00) (£/MWh)	Day Price (15:00) (£/MWh)
5	52.39	18.79
6	39.75	29.13
7	44.64	30.40
8	40.30	42.88
9	54.00	107.00

10	63.00	28.96
11	54.00	12.37

$$\%\ shift = \frac{Average\ Morning\ Price}{Average\ Daytime\ Price}$$

$$\%\ shift = \tfrac{49}{38} = +\mathbf{28}\%$$

June

$$\%\ shift = \frac{47.3}{54.4} = \mathbf{-13}\%$$

July

Date	Morning Price (03:00) (£/MWh)	Day Price (15:00) (£/MWh)
24	30.3	45.63
25	30	53.64
26	10.5	31.34
27	39.73	40.76
28	22	36.37
29	36	52
30	15.46	24.94

$$\%\ shift = \frac{Average\ Morning\ Price}{Average\ Daytime\ Price}$$

$$\%\ shift = \tfrac{26}{40} = \mathbf{-35}\%$$

August

Date	Morning Price (03:00) (£/MWh)	Day Price (15:00) (£/MWh)
4	31.08	51
5	32.49	42.87
6	28.74	28.83
7	20.78	16.38
8	21.20	55.50
9	34.34	27.9
10	10.98	32.73

$$\%\,shift = \frac{Average\ Morning\ Price}{Average\ Daytime\ Price}$$

$$\%\,shift = \frac{25.65}{36.45} = \mathbf{-30}\%$$

The overall average percentage difference in price = (1 + 28 – 13 – 35 – 30)/5 = **-9.8%**