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Abstract

In the last few years, the car industry has developed hybrid battery systems with lower battery price, higher capacity and improved safety. These improvements in performance have led to an increased interest to utilize the technology in marine applications. To satisfy the requirements of redundancy in critical situations vessels are required to run multiple engines at low to medium loads during most of operations in station keeping. Traditional combustion engines are designed to have the optimal level of fuel consumption and lowest emission per kilowatt hour when operating at medium to high loads. This practice therefore represents an overall loss and is unfavorable for environment and fuel consumption.

This thesis investigates the effect and viability of applying a Hybrid Battery System (HBS) on a Platform Support Vessel (PSV) by using the battery to optimize the original power system. For the case study, the vessel Viking Energy has been considered. Viking Energy is the first vessel with a HBS approved as a redundant power source in critical operations. The system allows the vessel to reduce the numbers of active engines while ensuring instant available power if required. The remaining active engines are then operating closer to the optimal level, ensuring lower emission and fuel consumption per kilowatt hour. This study analyzes and quantifies the effect in fuel consumption and cost after implementing the HBS to the PSV. It also analyzes the weathers influence of the fuel consumption for the vessel with and without HBS. The study is based on a six-month sample period where the HBS was fully operative. The analysis gave an annual reduction in fuel of 13% comparing the sampling period with historical data given the same time distribution for the vessel. Normalizing both to actual distribution over a three-year operation period gives a calculated reduction of 17% due to more favorable distribution. The difference is mainly due to higher portion of Dynamic Positioning (DP) mode in the historical data. The economical evaluation concluded that the minimum threshold for overall fuel reduction to be 15% for the investment to break even in a ten-year perspective. A vessel is recommended to operate 34% or more of the time in DP or a mode providing similar level of fuel saving to meet an overall reduction of 15%.

Preface

This thesis represents the final part of my master degree in Mechanical and Structural Engineering with specialization in Offshore Constructions at the University of Stavanger. The thesis was established in collaboration with Westcon P&A as a result of their contribution and success within Hybrid Battery Systems for the offshore industry. I want to express my gratitude to my external supervisors Ragnar Langåker and Kristian Matre. Their daily effort and expertise have been substantial and of major importance. I also want to express gratitude to Elizabeth H. Lindstad for contributing with her research and knowledge on the subject. I want to express my gratitude to my faculty supervisor and professor at the University of Stavanger, Arnfinn Nergaard for his support and guidance throughout the work of my master's thesis. Special thanks to the shipping company and the industry partner for the willingness to provide information and data that has been essential for my thesis. And last I want to thank my family and friends that have contributed to guidance and good technical understanding leading to many good discussions. Finally, I want to thank my beautiful wife that has supported and motivated me throughout the master study.

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Abbreviations

AC	Alternating Current
BC	Black Carbon
BMS	Battery Management System
BS	Battery System
C-rate	Charge/discharge rate for a battery relative to one hour
CAPEX	Capital Expenditure
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Cycle life	The number load cycles or time for the battery capacity to decrease below 80% of the initial capacity
DC	Direct Current
DF	Dual Fuel
DOD	Depth of Discharge
DP	Dynamic Positioning
EC	Energy Control
ECA	Emission Controlled Areas
EMS	Energy Management System
ESS	Energy Storage System
FPSO	Floating Production Storage and Offloading facility
GHG	Greenhouse Gas
GWP	Global Warming Potential
HBS	Hybrid Battery System
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
N_2O	Disulfur monoxide
NMC	Lithium Nickel Manganese Cobalt oxide
NO_X	Nitrogen oxide
NPV	Net Presence Value
OC	Organic Carbon
OPEX	Operation Expenditure
PM	Particulate Matter
PMS	Power Management System
PSV	Platform Support Vessel
RPM	Revolutions per Minute
SFOC	Specific Fuel oil Consumption
SO_X	Sulfur oxide
SOH	State of Health
SOC	State of Charge

1. Introduction

In 2003, the vessel Viking Energy was built by Kleven Verft AS sited at Ulsteinvik in Norway on behalf of the shipping company Eidesvik Offshore AS. The ship was among the first Platform Support Vessel (PSV) to operate on liquid natural gas (LNG). In over a decade the ship has served the oil & gas industry executing tasks in a reliable and efficient manner.

After 12 years of operation, the vessel is setting a new milestone. Equipped with a technology that represents a solid step towards a more viable and environmental technology for the offshore support industry. Summer 2016 the ship was sited in Westcon's ship yard in Ølen, located on the west coast of Norway for seven days. When the vessel left the yard, it was equipped with a Hybrid Battery System (HBS). Making it the world's first vessel approved to utilize a battery as a power source in critical situations [1]. This can be when the vessel is operating few meters from an offshore structure, and the power system must are dependent on instant power withstand the environmental loading to maintain position and to prevent impact.

As this industry is competing to get contracts, some shipping companies are constantly searching for new, cost-effective and viable technologies for fuel reduction and to obtain an attractive vessel [2]. During a time that the industry is under considerable pressure by society and market to reduce cost and emission. That have resulted in high focus on reducing operating cost for the oil business [3] [4]. In addition, new contract models from the charterer in the oil business contain regulations to promote greener ships, as we have seen in the ferry sector [5] [6].

The past four years the battery prices have dropped by 60-70% and are expected to continue to decrease [7]. At the same time power and energy density increases, cycle life, safety and durability continues to improve. This new technology opens up for new markets and applications not viable with conventional batteries [8]. Overall fuel consumption is claimed to be reduced by 20%, resulting in emission savings corresponding to the fuel saving. Most savings are gained in operations where load demand is highly variating, and redundancy requirements are high. The highest fuel reduction potential is claimed to be when the vessel operates in station keeping.

The battery main purpose is to take care of the load variation, while the engine works at optimal load as a middle-value of the load oscillations. Mainly the system operates in the following three applications:

- **Peak shaving:** The battery discharges on high loads and charges on low loads, while the engine remains on stable load level.
- **Spinning reserve:** the battery adds redundancy to the power system. This results in fewer engines online and the remaining engines loading is raised to a more efficient level.
- **Start-stop mode:** at low loads the engine load is increased to optimal load and charges the battery. When the battery is fully charged, the engine stops and the battery supplies the system until the battery is empty. Then the engine is activated, and the process is repeated.

The Specific Fuel Oil Consumption (SFOC) in gram per kWh, for marine combustion engines is significantly lower when they are operating between medium and high loads, and the different modes described previously allows the engine to work in more optimal loads [9]. Figure 1 shows the curve of SFOC with respect to maximum continuous rating (MCR).

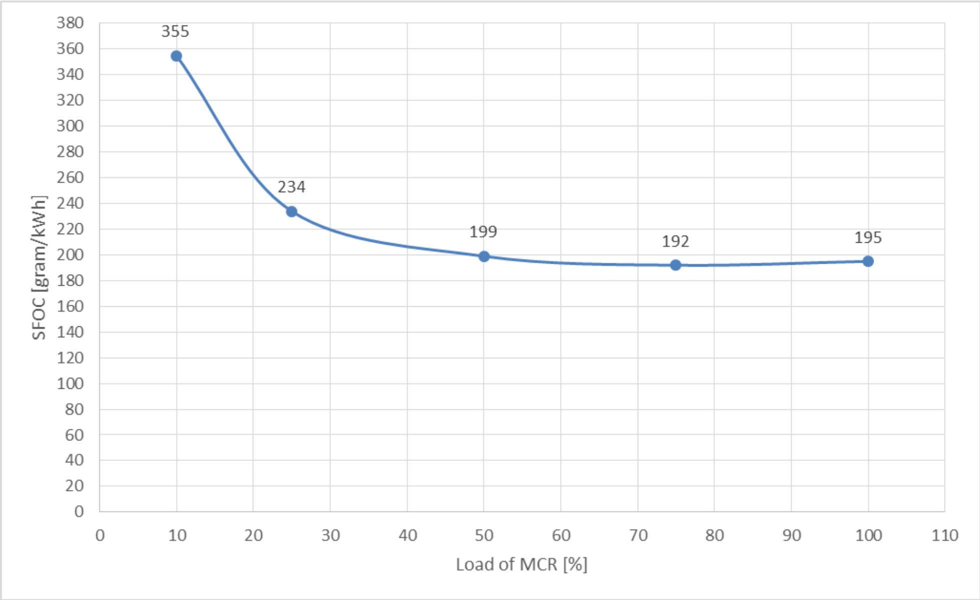


Figure 1: Specific fuel consumption for a typical marine engine [10].

The large variation of energy requirement for PSV makes this ship type highly attractive for battery application. And potentially reduce fuel consumption and emission, enhance response, less maintenance, higher redundancy, flexibility and less noise by allowing engines to run closer to optimal load [8].

1.1. Objectives

The prime objective for this thesis is to analyze and quantify the effect of applying a Hybrid Battery System (HBS) on a Platform Support Vessel (PSV) by using the battery to optimize the original power system.

To meet the prime objective, the following secondary objectives will to be met:

- Generally describe the technology and the advantages of implementing the system.
- Identify and discuss general frame conditions for applying a HBS on a PSV.
- Briefly describe other vessel that potentially can gain benefits from a HBS.
- With the vessel Viking Energy as a case, analyze and discuss experience from installation and operation of the HBS for the first six months of operation.
- Discuss factors that might have an impact on overall performance of the system in the Viking Energy case.
- Analyze potential impact of weather on performance of the HBS.
- Present recommendations for further work.

1.2. Limitations

In the analysis in this thesis is based on data from one PSV vessel for a limited sampling period. HBS is a new technology and data covering longer time periods are challenging to obtain. Some of the result are dependent on work tasks of the vessel, engine type and operation profile. All this may differ for each individual vessel and may therefore not be directly comparable. The fuel consumption with the theoretical method is simplified by assuming only LNG consumption. Vibrations and noise reduction and increased responsiveness of the vessel is claimed to be a result of the HBS and is not evaluated in the case more than subjective limited statements from the vessels crew.

The thesis will be focusing on HBS as a retrofit and has not considered a vessel as new build when assessing the potential of technology. System optimization and design of the HBS will not be assessed. Weather impact on the vessel will be analyzed briefly and not be linked to AIS data.

1.3. Content

The first part is a literature study describing the industry today and the regulations considered to be relevant to the subject. Followed by describing the development and characteristics of batteries. Then the HBS is described and how the industry solves this today. All this is information has the purpose of giving the reader the knowledge required to sustain a proper understanding of the case evaluation further in the thesis.

The last part is a case study based on data from Viking Energy. The case study describes the HBS applied to the vessel and further it presents and discusses data from various subjects. And ends with a final conclusion and recommendation of the HBS.

2. Industry frame condition

All around the world ship is built, re-constructed and maintained. The ship industry can operate worldwide within all waters granted the country have coastline. The classification societies play an important role in verification and assure compliance with the standards for all ships. Among others DNV-GL which is a classification society that have defined rules for classification. For a vessel to be operative, it must fulfill the standards for the current classification society. The rules of classification involve clear demands for a vessel to be able to hold a battery exceeding a capacity of 50 kWh on board. All PSV in use, is under an agreement with the charterer. The agreements are stated in the contract between the charterer and the shipping company. Charterer is the company renting the ship, in this context often an oil company. The government and major industry organizations uses funding as a tool to inflect the technological trends in desired direction. This is also the case in the ship industry.

2.1. Class notation

Classification society provides and maintains technical standards for construction and operation of ships. Class societies are responsible for verifying that systems are built to the given standard carry out surveys to assure compliance. The vast majority of commercial ships are constructed and classed by standards provided by classification societies. The standards define what is considered to be todays accepted engineering practice to maintain safety for personnel and the ship, reliability, availability, durability and efficient operation [11]. The standards are issued by classification societies as rules that are published.

In Norway DNV-GL is responsible for the majority of classifications and are therefore responsible for verifying the technology and construction discussed in this thesis [12]. Class notations most relevant in terms of battery hybrid technology are Part 6 Chapter 2 [13] and Part 6 Chapter 3 [14] under DNV GL rules for classification of ships (RU-SHIP). This is to provide equal or higher level of safety and reliability as conventional system for large battery systems [15]. There are two levels of class notations when large battery system is installed on board a ship [13]:

- ***Battery safety notation***; General requirement mandatory where battery is used for power source when battery capacity exceeds 50kWh. The application is additional source of power or for improved dynamic performance of power.
- ***Battery power notation***; Additional notation for vessels when battery is used as propulsion power during normal operations, or when battery is used as redundant source of power for main or/and additional source.

If a battery is to replace one or more generator, the ship must hold battery power notation. This notation is more comprehensive and challenging to fulfill than the safety notation in terms of safety, energy management and testing. The most important requirement in this notation is that the battery must provide sufficient capacity for the vessel to abort the operation and evacuate out of danger when the battery is used as a redundant source of power. The classification society demands the shipping company to review all the operations of the vessel and find the time duration of abortion. And then, the maximum abortion time defines the time the requirement for the battery. The battery must sustain the capacity to power the vessel at that time requirement to hold the class notation. For Viking Energy, the maximum time duration to abort an operation is 7 minutes. This time is used as input in the consequence algorithm for the dynamic position system. This consequence algorithm estimates continuously with the maximum time if enough energy is available in the battery to evacuate the current operation in the current condition. The capacity of the battery is required to be tested each year to determine the State of Health (SOH) [13] [16].

2.2. Contract description

In the oil business ships are operating under contractual agreement. Agreements involves issues between the shipping company and the oil company, referred to as the charterer. The traditional contract is formed in such a way that the charterer covers the fuel cost [17]. This is mainly to provide full freedom to take decisions that may affect the fuel consumptions. This practice is an easy way to avoid the potential conflict of interest when the ship is executing tasks. Regarding fuel reducing actions and technology it may cause a leak of motivation and interests as traditional contracts provides little economic benefits to the shipping company.

If a shipping company installs a HBS in a ship, they pay the cost of the installation and takes the economic risk. When the ship is operative, it may use less fuel as the oil company pays the fuel they gain the direct benefit. The oil sector is under considerable pressure as the oil price is low and is looking for areas of reducing cost to increase profit. A new model for contracts an oil company was recently announced, with the purpose to share the economical profit from saved fuel with the shipping company. The model calculates expected fuel consumption for each operational mode based on historical data. If the ship uses less than 5% below the expected for that mode the saved cost is shared 50/50. And if the ship uses more than 5% higher than expected for that mode the cost is shared 65/35, ship owner and charter respectively. This model will not be applied during the winter months due to harsh and unpredictable weather. The fuel consumption will become an evaluation criteria with more focus, when vessels signs and enter into contracts [5]. In addition to the new contract model, there are indications that the charterer most likely will demand vessels with battery notations in the future.

2.3. Incentives and funding

As a tool from the government for pushing and motivating industries to navigate towards greener trends, they support viable and promising funding schemes [18]. This is a dynamic economical support continuously adopt to new technologies. In Norway, there are mainly two founding opportunities for ship owners in the nation:

- Enova
- NOx fond

For member states of EU or EUS there is also funding opportunities through LIFE, supporting environmental and nature conservation projects. The project must apply for funding and each project is considered individual [19].

For the case of Viking Energy, Enova was strongly involved with funding. This involved a support of 7.5 MNOK which involved a significant share of the Capital Expenditure (CAPEX) of the HBS. For future projects, it may not be that high, as the risk for such projects will decrease as it becomes more commercialized. This means that for the technology to be viable in long term, it must provide profit regardless of incentives.

3. Environmental impact

Transportations at sea is considered to be the most cost-efficient option of transportation. In addition to worldwide trading much of the world's oil reserves are located at sea. Norway have strong relations to the sea, both historical and in modern time. The topography of the country also involves much fjords and mountains. Therefore, in Norwegian waters ship pollution is shared between the oil related activities, fishing and passenger transport. The environmental impact caused by activities at sea worldwide is estimated to be around 3.3% of the global anthropogenic emissions stated by the second IMO (International Maritime Organization) GHG study in 2009 [20]. In response to the emission numbers from this report the IMO tighten the regulations regarding emission in several areas. One of the response involved introduction of areas of emission limits and NO_X limits globally and within these limits.

3.1. Regulations

In 1973 the International convention for the prevention of Pollution from Ships (MARPOL) was adopted and further entered in force 02.10.1983. The convention includes marine accidents normal operation in terms of pollution and targets to minimize impact and risk related to this. In 1997 the Annex VI was included, aiming for minimizing and prevent emission of Nitrogen Oxide (NO_X) and Sulfur Oxide (SO_X) [21]. IMO has defined Emission Controlled Areas (ECA) worldwide as shown in Figure 2. The areas assigned to these regulations are considered to be vulnerable and/or involves a risk to human health in terms of pollution. In Europe, the Baltic Sea have suffered for pollution related to SO_X, NO_X and Particulate Matter (PM) from ship activities. Ships operating within these areas have to use fuel with low Sulfur content or implement emission mitigation technology [22]. In the North Sea and Baltic Sea, the ECA only involves SO_X limit. The NO_X is limited with a regulation named Tier 1, 2 or 3 depending on the year of construction. Where Tier 3 applies for ship built from and after 2016. NOx limits are given as a function of the Revolutions per Minute (RPM) of the engine based on vessels type and size. The rules of Sox apply to all ships, regardless of the construction date for vessels commercial size. The requirements can be met by operating on low-Sulfur fuels, the requirements open up for technological approaches of meeting the emission level.

Figure 2: Existing and future Emission Control Areas worldwide [23]

Existing ECA involves [24]:

- Baltic sea (SO_X, adopted: 1997, entered to force: 2005)
- North Sea (SO_X, 2005,2006)
- North American ECA, including most of US and Canadian coast (NO_X and SO_X, 2010, 2012).

This leads to that all ships operating within these areas must use fuel with Sulfur of 0.1 % at this time. Today's limit and future restrictions can be seen by the line labeled as ECA in Figure 3. Outside these areas IMO have currently set the limit to 3.5%, represented by the line labeled GLOBAL and future restrictions. But as indicated, this may be reviewed. This will result in increased demand for low Sulfur fuel in the world. In a long-term perspective, cleaner and better technology must be developed and not only low Sulfur fuel, to satisfy the limits. In general, the lower Sulfur content the fuel contains, the more expensive fuel. Therefore, the fuel cost for shipping companies increase.

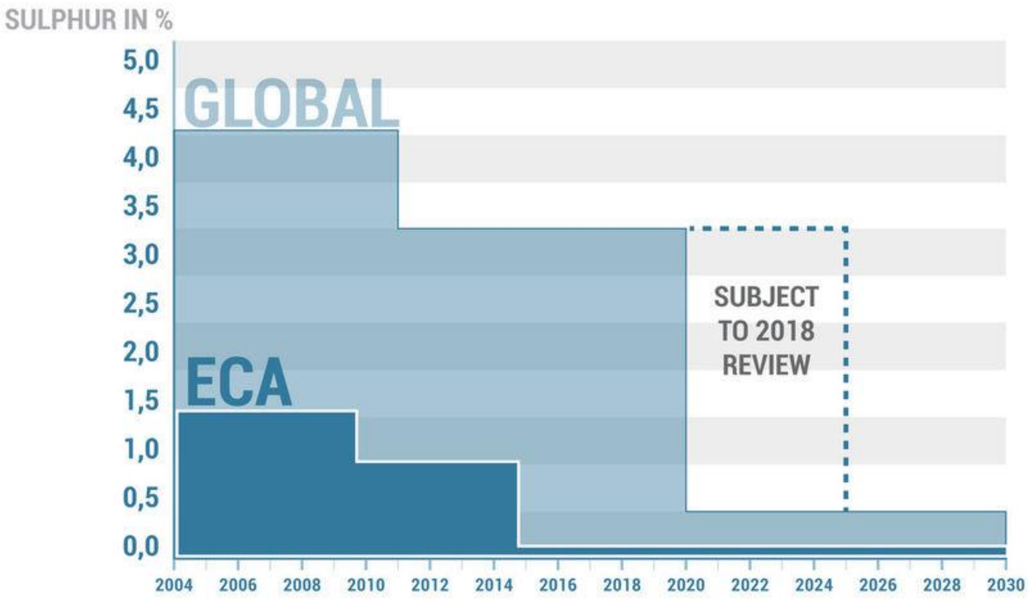


Figure 3: MARPOL Annex VI Sulfur fuel content limits [24].

This type of regulations is important statement and require ship designers to reconsider conventional options in terms of fuel and technology to sustain a long lifetime of new build ships. However, the substances regulated are not related to GWP, and are mainly connected to local air quality [21].

3.2. Emission to air

Ships in operation emits different categories of emission. The categories are water, air, land and noise. Emission to air caused by exhaust is the greatest contributor to global warming among these categories. Exhaust gas is formed during combustion, consisting of various substances is formed and produces emission to air. Fuel is injected into the cylinder, mixed with air and ignited by spark or compression. Marine traffic in a global emission perspective has the following contribution according to IMO second study [20]:

- CO_2 – 3,3%
- SO_X – 4-9%
- NO_X – 10-15%

Emission from exhaust have both local and global effects. NO_X and SO_X are mainly connected to local air quality and have residence in the range of 1 to 3 days after emitted. The emission can contribute to pollution inland by hundreds of kilometers [25]. Further CO2 mainly contributes to global warming effect. The ECA introduced by IMO is mainly motivated by regulating the local air quality in areas considered to be highly impacted.

There are various types of impact categories to consider in terms of environmental strain. It is up to the author to determine what category to use, as the standard not say what method to use. The selected impact category is Global Warming Potential (GWP). The method is aiming for quantifying the how much GWP each pollutant contributes to global warming. Greenhouse Gas (GHG) is defined as a gas that when it is emitted to air, absorbs heat and re-emits it. This makes the atmosphere of the planet warmer than it would have been without this gas. Vapor also is a GHG but is not considered [26].

Climate effects from shipping includes the following substances and the respective effect [21]:

- CO_2 including CO, has a warming effect (Carbon dioxide and Carbon monoxide)
- CH_4 has a warming effect (Methane)
- BC has a warming effect (Black carbon)
- N_2O has a warming effect (Disulfur monoxide)
- NO_X leads to producing tropospheric O_3 which further leads to positive radiative forcing and reduction of ambient CH_4 that has a cooling effect (Nitrogen oxide)
- SO_X that has a cooling effect (Sulfur oxide)
- OC has a cooling effect (organic carbon)
- Low level clouds can be formed or changed and has a cooling effect.

BC emitted in the Arctic where snow and ice are presence, will increase the surface temperature compared to emitting the same quantity in areas closer to equator [27]. As the sea ice in the arctic is decreasing, has opened up for more activities in these areas. On that basis, the GWP for Arctic regions are included in addition to World regions, and is provided on next page.

Table 1: Emission factors in grams per kilowatt for Marine diesel oil (MDO), Marine gas oil (MGO) and LNG liquid natural gas dual fuel (DF) fueled engines as a function of power and engine type [21].

	MDO 0.5% sulfur		MGO 0.1% sulfur		LNG DF	
Load	High	Low	High	Low	High	Low
CO_2	630	700	630	700	475	530
CH_4	0.05	0.1	0.05	0.1	4.00	8.00
N_2O	0.02	0.02	0.02	0.02	0.02	0.02
SO_X	2.2	2.4	0.45	0.5	0.1	0.4
NO_X	6.0	9.0	6.0	9.0	2.00	4.00
CO	1.4	1.4	1.4	1.4	1.4	1.4
BC	0.050	0.200	0.025	0.150	0.005	0.050
OC	0.2	0.2	0.2	0.2	0.2	0.2

Table 1 lists the amount of gram pollution emitted per kWh produced during combustion of Marine Diesel Oil (MDO), Marine Gas Oil (MGO) and Liquid Natural Gas (LNG) respectively given with high and low load. Whereas high corresponds to the range of 75% and low 25-30% of MCR (Max Continuous Rating). It can be observed that all engines generally emit more pollutants at low loading due to ineffective combustion. An engine uses more fuel per kW at low loads, but also releases more pollution.

Table 2: Pollution substances and the impact categories in CO_2-equivalents [21] [28].

Emission category	GWP_{20} World factor	GWP_{20} Arctic factor	GWP_{100} World factor	GWP_{100} Arctic
CO_2	1	1	1	1
CO	5.4	5.4	1.8	1.8
CH_4	85	85	30	30
N_2O	264	264	265	265
BC	1200	6200	345	1700
NO_X	-15.9	-31	-11.6	-25
SO_2	-141	-47	-38	-13
OC	-240	-151	-69	-43

In Table 2 the pollutants emitted during combustion is listed. Pollution grade of the substances is given after GWP and is specified by the areas emitted with respectively world and arctic standard with the time perspective of 20 and 100-year. The values is provided by Intergovernmental Panel on Climate Change (IPCC) and International Marine Contractors Association.

The world factors are the average for the four regions: East Asia, South Asia, Europe and North Africa and North America. The world figures are representative of the impact of emissions in oil and gas regions such as the North Sea and the Gulf of Mexico. While the arctic factor will be representative for emitted pollutant in areas such as Barents Sea [9].

Addressed emission in Norway

To address the vessel types responsible for emitting GHG within Norway each vessel type is shown in Figure 4. There it can be observed that the main contribution can be connected with passenger transport, offshore supply vessels and fishing vessels. The contribution is 1.09 ton, 0.9 ton and 1.06 ton CO_2 respectively.

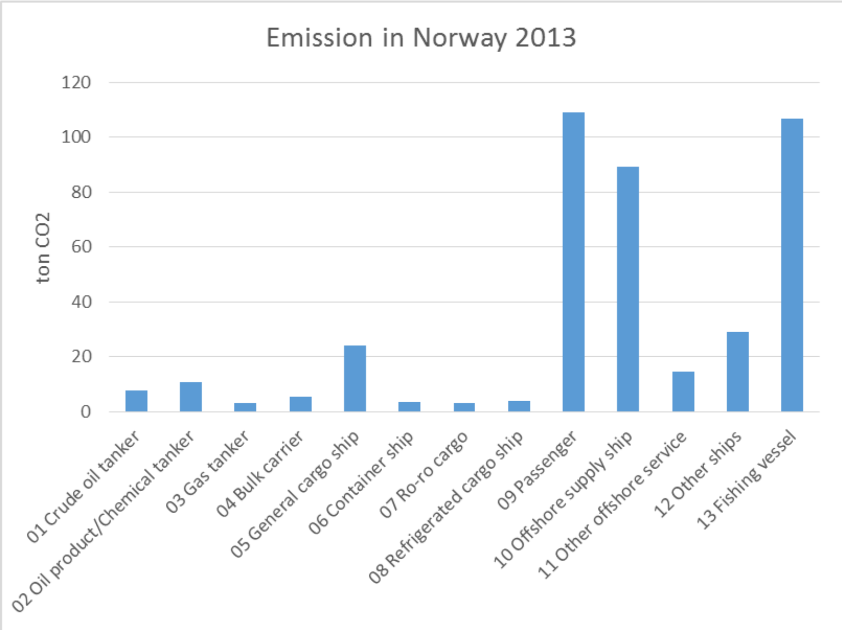


Figure 4: CO_2 emission in Norway distributed by ship types [29].

4. Ship characteristics

PSV executes various tasks all after charterers demand and need. For the vessel to be able to perform the daily duties, they rely on engine power of significant size compared to the car industry. The engine is often referred to as mover. All movers, independent of working field will have a defined range of operation with the related power generated. This involves areas where the combustion process will variate.

The power system in vessels must me dimensioned to withstand environmental loading in all weather conditions. This means that a common PSV will be equipped with a total engine power of 10 MW. This will give the vessel sufficient power to perform the intended duties in close to all weather conditions. The reality is that the vast majority of time in operations happens at a lower and different power level due to regular weather conditions. When that is the case and there will be one big engine or prime mover operating at ineffective load the solution is to replace it with a set of smaller engines. In this way, the power production is split into smaller units and the running engines will be closer to optimal load, as Figure 1 was illustrating. Then the number of engines running are a result of the continuous demand. To utilize this principle the vessels also must implement diesel-electric power system from direct mechanical propulsion. The categories of propulsion setup are listed in section 4.1.

This setup is known as a power plant principle and has emerged as the basic standard for vessels operating with a highly variating power demand. This involves vessels as icebreakers, tugboats, PSV, but has also found its way to ferries and other special vessels [9]. The efficiency improvement at lower loads by the power plant principle is based on the efficiency profile of engines.

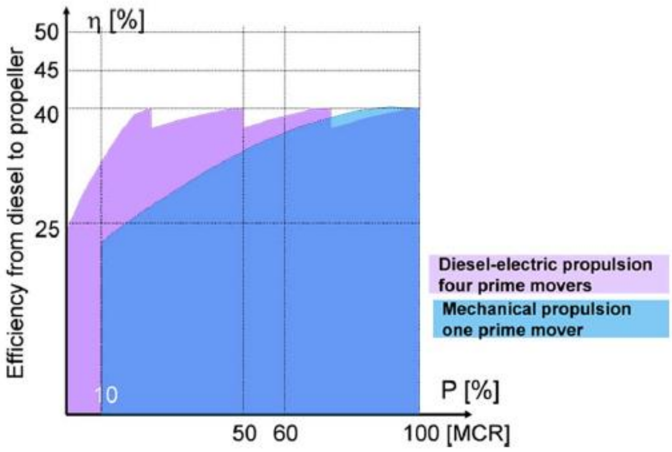


Figure 5: The principle of power plant, one prime mover and the related efficiencies [30].

It can be observed that in the range from 20% to zero MCR, the efficiency continues to decrease. Further, as the load increases the efficiency drops in a repetitive way. This represents the potential of further optimization. In combination with the use of batteries this potential can be further exploited.

4.1. Types of Ship Drivers

A ship needs a large amount of power to sustain propulsion, positioning and hotel loads. Hotel load or auxiliary is the ship miscellaneous power consumers of lower voltage. In terms of mechanical and electrical power systems, there is mainly four categories [11]:

Mechanical-drive ship*:* The prime mover directly drives the propeller via mechanical gears and a long shaft running through the center of the ship, and the ship service generators power the electrical service loads. Most merchant cargo ships today fall in this category.

Electrical-drive ship*:* The propellers are driven by large electric motors powered by dedicated propulsion generators, and separate generators produce service/hotel power.

Integrated-electric ship: the main generators generate all required power for both the propulsion and the ship service loads with no separate ship service generators. The propellers are driven by large electric motors. The main generator with no separate ship service generator provides the service load. The service load is provided via step-down transformer from the main bus. Viking Energy is equipped with this type of ship drive, among many other PSV's.

All-electric ship*:* When all subsystems are electric powered, the ship is all electric.

Electrical drive and integrated-electric are referred to as diesel-electric propulsion. Diesel-electric propulsion is common today, especially within the PSV where the load variation is considerable. However, the associated installation cost is higher than conventional.

The system separates the power generation into several smaller units instead of one big motor. This opens up for starting and stopping engines as the power demand is shifting. In this way, the generators can run closer to optimal load. This is very convenient for ships that have a wide range of load demand. And operational saving makes up for the increased installation cost of these ships [30]. The result is then better efficiency on lower loads as illustrates Figure 5 in the start of this chapter. Further, it provides greater flexibility, higher redundancy and increased maneuverability in terms of station keeping. Due to the efficiency and highly flexibility, the majority of PSV is equipped with electrical-drive, integrated-electric or a combination of these two.

4.2. Operation modes

PSV share different tasks within the oil & gas sector. They may be divided into four categories; supply; standby; anchor handling and subsea operations. But despite the different working tasks, they still have common operation modes, such as:

- Transport from and to oil field, Transit High and Low speed.
- Position keeping near installations, DP.
- Position keeping outside of safety zone for installations, Standby.
- Port stay with loading and offloading, Harbor.

Figure 6 shows a typical annual operation profile showing modes and the corresponding average power demand for each mode. The distribution will be individual for each vessel depending on working tasks, fields distance from land, urgency of mission and so on [9]. The modes DP and Standby are both related to maintaining position with high and low redundancy requirement. Principle and classes regarding position keeping is described in the next section.

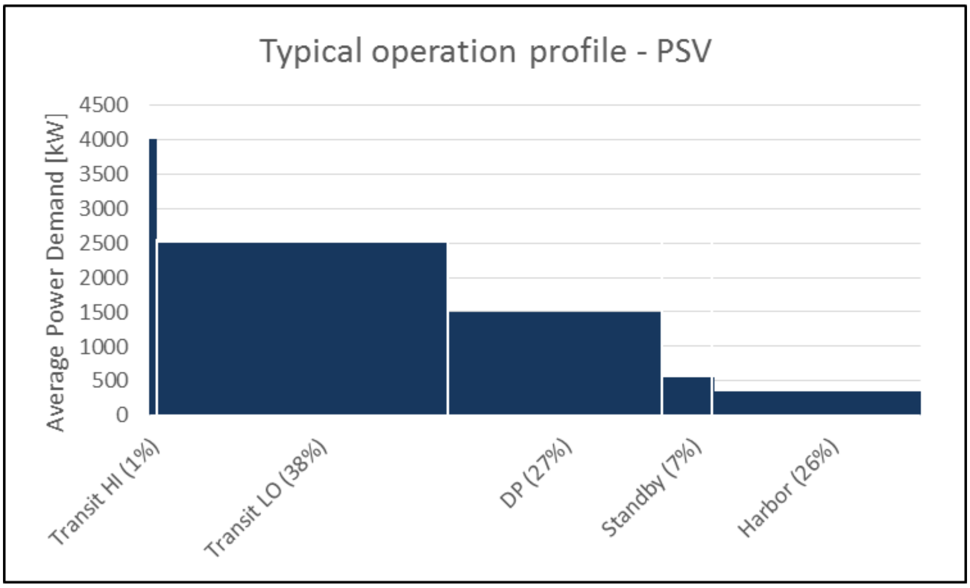


Figure 6: Annual operation profile for a typical OSV [9].

4.3. Station keeping

PSV often work close platforms when e.g. delivering well. To prevent drift off from position due to waves, wind and currents they are equipped with a Dynamic Positioning (DP) system.

DP is a system that automatically maintains vessels position by controlling the existing propulsion system. With input from various types of sensors and algorithms, calculate direction and amount of thrust. To run in this mode, power resources must always be available with high redundancy to handle the peak loading caused by environmental loads, thus numbers of generators are running to supply the system [9]. In addition the engines takes time to deliver more power, to compensate for this, the engines are maintained at a higher level than necessary.

A vessel at sea is subjected to forces from wind, waves and current as illustrated in Figure 7. To prevent drift off from a position due to these forces the propulsion system must generate forces in opposite directions. The position-reference system measures the changes in position, heading and speed. This involves gyrocompass, vertical reference sensors and wind sensors. To maintain positions the system must control all degrees of freedom in the horizontal plane; sway, surge and yaw [31]. This mode is mainly used when drift off can have fatal consequences e.g. when operating near an installation or doing subsea operations.

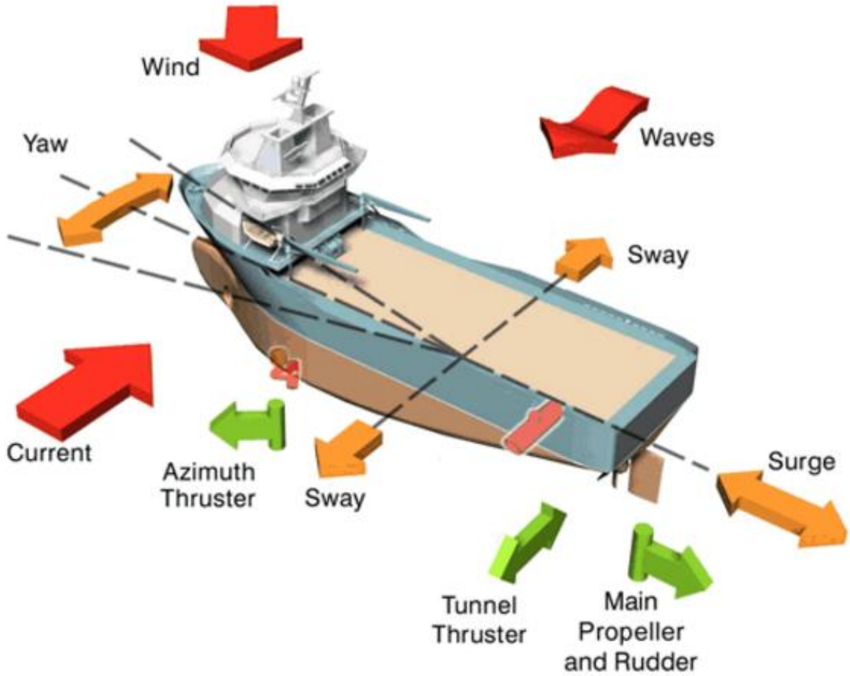


Figure 7 Basic motions in ship and forces influencing the position [31].

Dynamic position systems are divided into three categories from one to three there three is the strictest class. The classes are defined as following [32] [14]:

- Class 1: Has no redundancy. One single failure may cause drift off. Involves DYNPOS(AUTS), DPS(1) and DYNPOS(AUT) notation.
- Class 2: Requires a system with redundancy. Involves DPS(2) and DYNPOS(AUTR) notation.
- Class 3: Same redundancy in the system as class 2 but in addition shall withstand fire and flood, this requires an additional independent control compartment. This involves DPS(3) and DYNPOS(AUTRO)

4.4. Combustion

When ships are designed, the intended lifetime is often 25 years or more. Therefore, ship designers must be aware of possible future challenges, among other things, regarding future ship fuels and legislation. This chapter will involve the engines manner of operation and fuel types will be described in terms of marine applications.

4.4.1. Engine profile

The efficiency of all types of combustion engines is highly dependent on the power demand. When an engine operates at low power, the fuel consumed per energy output is high. This means that when the engine operates at 80% load, it consumes less fuel per kWh produced, compared with two engines operation at 40% load. This is often the case for the offshore vessels due to high redundancy requirements. It is then more convenient to run one or more engines at medium to high load thus keeps pollution and fuel consumption per kWh to a minimum. Any engine loads away from the sweet spot will result in increased emission. When moving away from the sweet spot, other components in the system also differs from designed optimal speed such as propellers, generators etc. As the sweet spot is located around 70-85% of maximum engine load, the gap between the sweet spot and 100% is referred to as "sea margin". This is due to the increased resistance in terms of rough sea, wind and environmental loads that may increase [33]. The typical engine for marine application thermal efficiency in the region of 43% [20]. That is an efficiency number as a function of loss.

Engines for marine applications can be either constant or variable speed. Constant speed is most common for PSV. This means that the engine is designed to maintain a constant RPM and the load variates by how much electricity the generator produces. This is because the generator depends on the RPM to deliver the frequency (Hz) of the current to the power system. The load variation the engine experience is then a result of how much power the generator produces.

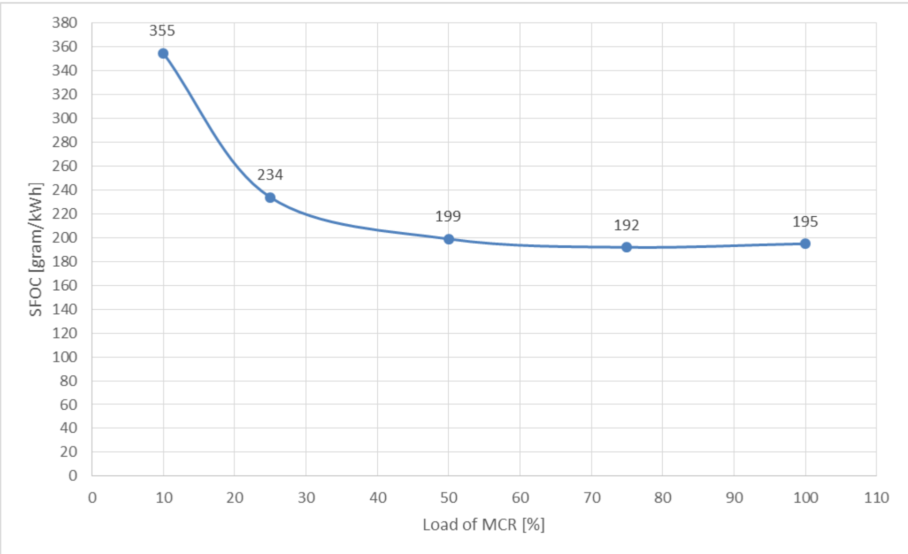


Figure 8: Specific fuel consumption (g/kwh) with respect to load percentage of max power for a typical PSV [10].

4.4.2. Fuel types

The majority of marine vessels machinery is operated on diesel, referred to as MDO or MGO. MGO and MDO have no significant differences concerning emission factors. The MDO and MGO are commercially available worldwide and is a conservative and low-risk fuel for ship owners regarding availability.

Natural gas is a fuel type that has been more commercialized the last decade and is a mixture consisting of a range of hydrocarbons. The main component is CH_4, up to 90-95%. Compared to other petroleum products, the chemical properties of the LNG mixture emit less CO_2, NO_x, BC and PM during combustions. And SO_X is not emitted at all, which otherwise contributes to acid rain [34]. Furthermore, there is no visible smoke, sludge deposits, lead emission, and benzene emission is reduced.

The number of ships using LNG is increasing fast as more infrastructure planned and built along main shipping routes. LNG is attractive commercially and available worldwide in quantities that can meet fuel demand of shipping for future decades. The main argument for replacing oil-based fuel with LNG is the reduction in local air pollution. This results in advantages regarding human health and the environment [35]. This is due to cleaner burning technologies and lower content of pollutants. And since it is lighter than air and has high ignition temperature, the safety level of the fuel is high [36].

4.4.3. Engine type

In Norway, there are mainly two types LNG fueled engines in operation, this is spark ignited lean burn gas engines or lean burn Dual Fuel (DF). DF can be operated on MGO, LNG or heavy fuel oil [37]. Marine engines can be divided into slow, medium or high speed. Most marine engines are fitted with slow or medium speed diesel engines for propulsion, dependent on their design and operational profile [38].

Most common marine LNG engines operated on natural gas are DF. DF engines mean that the engine can operate in gas or liquid mode. Instead of using spark plugs when operating on LNG there is injected a very small amount of diesel into the chamber. The cyclic manner of operation for a lean burn DF engine is shown in Figure 9. First, the air and gas are injected together with a small amount of ignition fuel. Second, the composition is compressed and third it ignites. When operating with a lean air-gas mixture and high specific power output the diesel provides reliable and powerful ignition in the chamber.

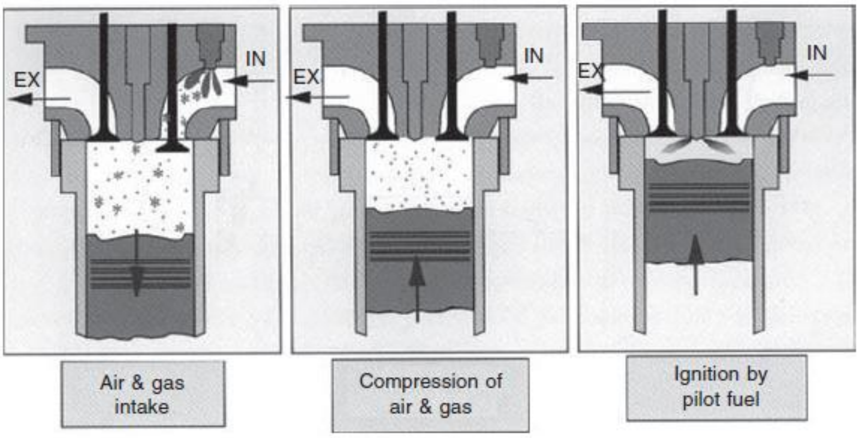


Figure 9: Lean-burn DF combustion process [36].

When the engine operates in gas mode the air and fuel ratio is increased, it is called lean burn principle when the cylinder has more air than necessary to provide a complete combustion. This is done to avoid self-ignition (knocking), reduce NO_x emission and increase thermal efficiency. Dual fuel engines provide benefits as reduced engine maintenance and longer intervals between engine overhauls [36].

When a DF engine operates on LNG, the pressure with respect to the air/fuel ratio defines an operation window that can be seen form Figure 10. The air/fuel ratio around 2.1 gives high thermal efficiency, lowest NO_x emission and represent the point of optimal operation, 47% [36].

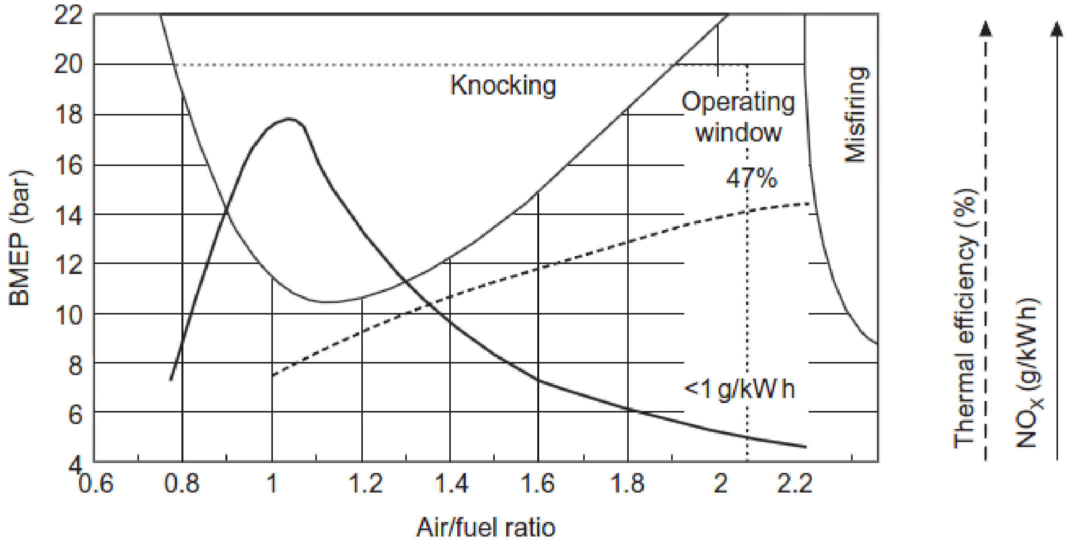


Figure 10: Operations window for a Wärtsilä DF engine [36].

When operating on MDO or MGO, normal diesel concept using high pressure fuel injection is applied. First challenge LNG engines is that emission of non-combusted CH_4 can be high at low loads. This is called methane leak and will contribute to global warming. There are challenges related to quantify this effect because the operation practice will be individual for each ship. The mitigation of global warming potential will depend on this effect [34]. LNG DF engines are a preferred option because it provides greater efficiency on medium to high loads, and that diesel engines sustains better efficiency at low loads. Second, the engines use significant time to increase load. In operations where load demand can change rapid, to compensate for this the practice is to running the engines on higher load level than necessary [39].

This slow response time, makes vessels with LNG DF engines more attractive to hybrid technology with the related benefits [22]. The potential benefits will be described in more detail in section 6.3.

5. Energy storage

Energy storage devices stores energy for future utilization by various types of technologies. In this thesis, the main focus will be on batteries. This is because for the high charging efficiency, small loss of energy while discharging and high specific energy in addition to the favorable economic development. Table 3 shows that the Lithium-ion batteries scores among the top for charging efficiency and has the highest high specific energy. As a comparison, gasoline has 12 200 Wh/kg [40]. In simple terms, a battery is an electrochemical system that can store and provide electrical energy with very high responsiveness and minor energy loss. This provides a system freedom to store excess energy and further utilize it when the energy demand rises again. This benefit combined with great development in both increasing performance and decreasing prices on the battery market, makes batteries a compatible and viable alternative for the marine applications. Energy per weight for lithium-ion can be as much as eight times more than traditional batteries, like lead acid [8]. Lithium-ion batteries consist of high energy density in combination with flammable electrolyte makes safe designing more challenging in terms of temperature, voltage and current in and out.

Table 3: Charge efficiency and specific energy of various energy storage technologies on cell level [41].

Storage type	Compressed air	Flywheel	Superconducting magnetic energy storage	Super-capacitors	Lead-Acid batteries	Nickel based batteries	Lithium ion batteries
Charge Efficiency (%)	70	90	99	99	90	90	99
Specific Energy (Wh/kg)	30	130	50	30	40	120	200

An ion is an atom or a molecule where the total number of electrons is not equal to the total number of protons, giving it a net electric charge positive or negative. As mention above a battery is an electrochemical device that stores electrical power through chemical reactions, driven by electrolytes. Battery consist of two terminals that either gains or receives electrons. The battery consists of Li^+ that escapes from positive and negative materials when charging and discharging. Delivered by the electrolyte, through the separator to the cathode. The separators task is to divide the positive and negative electrodes, but allowing flow of ions (Li^+) [42]. This forces the electrode to travel through the external circuit where the load is connecter as shown in Figure 11. Within Lithium-ion batteries there are various types of combinations of elements.

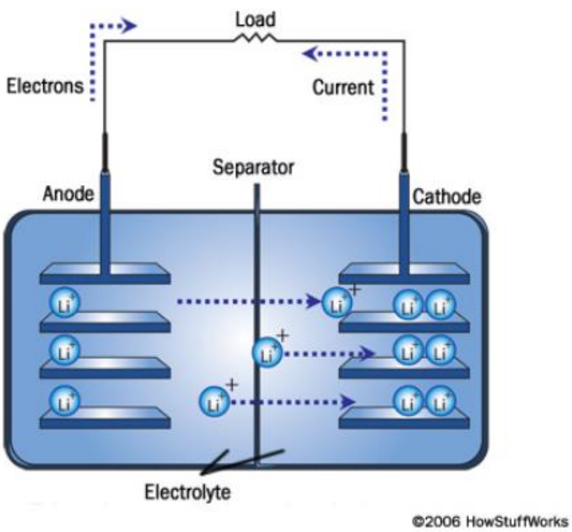


Figure 11 Manner of operation for a Lithium ion battery when discharging [43].

5.1. Types of chemistries

There are mainly two categories of electrochemical batteries: *primary* and *secondary* batteries. Both convert chemical energy to electrical energy, but for primary batteries the reaction is non-reversible. A secondary battery is known as a rechargeable battery, since the chemical reaction is reversible [11]. This thesis will exclusively look into secondary batteries. When considering energy density and specific energy it is important to address whether it is at cell level or at pack level. The energy density will be higher on cell level compared to pack level due to arrangement, spacing and necessary devices. Lithium-ion secondary cells have some of the highest energy density, among the highest power densities of any cell commercially available today. The good energy properties of lithium-ion have opened up for maritime use. Lithium-ion is the lightest of all metals, has the biggest electrochemical potential and provides the largest specific energy per weight. Lithium-ion batteries can be safe in operation if, current, voltage and temperature limits are monitored and maintained. There are many types of lithium-ion batteries on the market. To compare the most common lithium-ion chemistries, properties of the batteries are compared by Table 4. Industrial applications require battery systems (BS) that have good loading capabilities, deliver a long life and provide safe and reliable service. In broad terms, lithium-ion batteries can be optimized for either power or energy applications, or a combination of both [44].

Table 4: Comparison of Lithium-ion chemistries at cell level [45]

Cathode Material	Voltage (V)	Specific energy (Wh/kg)	Energy density (Wh/L)	Thermal Stability
Cobalt Oxide	3.7	195	560	Poor
Nickel Cobalt Aluminum Oxide (NCA)	3.6	220	600	Fair
Nickel Cobalt Manganese Oxide (NCM)	3.6	205	580	Fair
Manganese Oxide (Spinel)	3.9	150	420	Good
Iron Phosphate (LFP)	3.2	90-130	333	Very Good

Lithium nickel manganese cobalt oxide (NCM), $LiNiMnCoO_2$

One of the most successful Li-ion systems is a cathode combination of nickel-manganese-cobalt. The NCM combines nickel and manganese. Nickel is known for its high specific energy but poor stability; manganese has the benefit to achieve low internal resistance but offers a low specific energy. Combining the metals enhances each other strengths. The cathode combination are one-third nickel, one-third manganese and one-third cobalt. But this may vary between manufacturers. This provides a blend that also lowers the raw material cost due to reduced cobalt content [46]. There is a rapidly development towards NCM-blend Li-ion system to be built economically and achieve good performance. The three active materials of nickel, manganese and cobalt can easily be blended to suit a wide range of applications for energy storage systems (EES) that have frequent load variations.

5.2. C-rate

The C-rate is a measurement of charge-, discharging rate relative to one hour, often referred to as power to capacity ratio. If a battery of 2000 kWh is charged with 2000kW in one hour, the battery provides a C-rate of 1C. Higher C-rate means more heat development and more loss in the process of charge-/discharging. Additionally, more stress to the batteries and better cooling arrangement [47]. When dimensioning a battery for hybrid applications in cases of battery power notation, the C-rate of the battery is an important characteristic. Batteries for this purpose needs to be able to discharge at high rate when used as spinning-reserve, in case of engine failure [48].

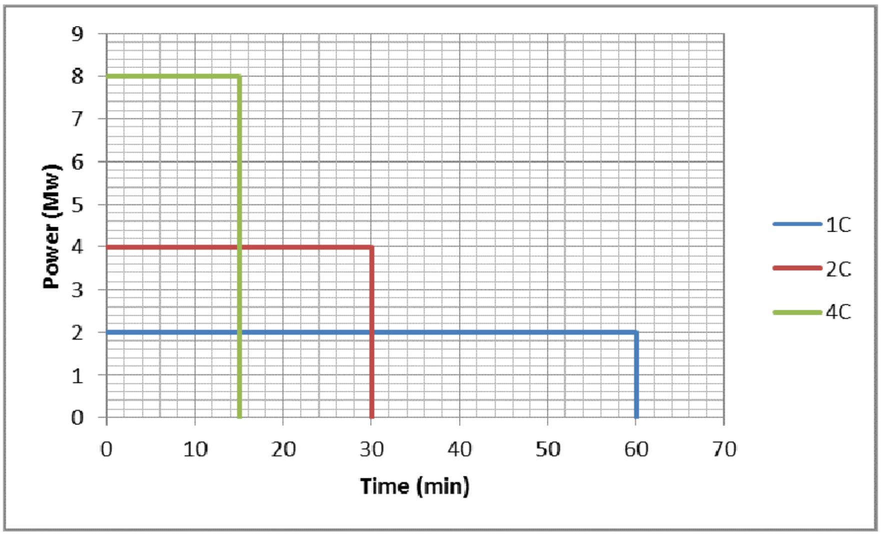


Figure 12: C-rate for charging with respect to the time of fully charged [41].

5.3. Batteries for ships

When batteries are used for ship applications the batteries are arranged in system to form a grid. This is done to make the system less vulnerable, also sustain the voltage, energy required and implement various electronic control systems. The battery consists of one or more battery pack. The battery for such purpose is more than just some cells in a box. First the cell, is the smallest electro chemical unit. The cell type 18650 is often used with the active material NCM, which is a cylindrical type of cell. It may also be punch or button geometry.

Figure 13: Geometries of battery cells. From left cylinder, punch and button respectively.

Then cells are stacked in groups and forms the module-bank. Further, module-banks are fitted together to defined the sub packs. The sub-pack is the smallest unit that can be electrically isolated and replaced. The sub packs are wired up in series to gain the system voltage, and are defined as rack or string. One battery string can work for the intended purpose as a standalone unit [49]. The strings are connected in parallel to form the total battery system (BS) and the energy of the system. There are three levels of BMS: sub-pack, string and for the total BS. The reason for making modules of the BS is to provide control in terms of safety and performance [48].

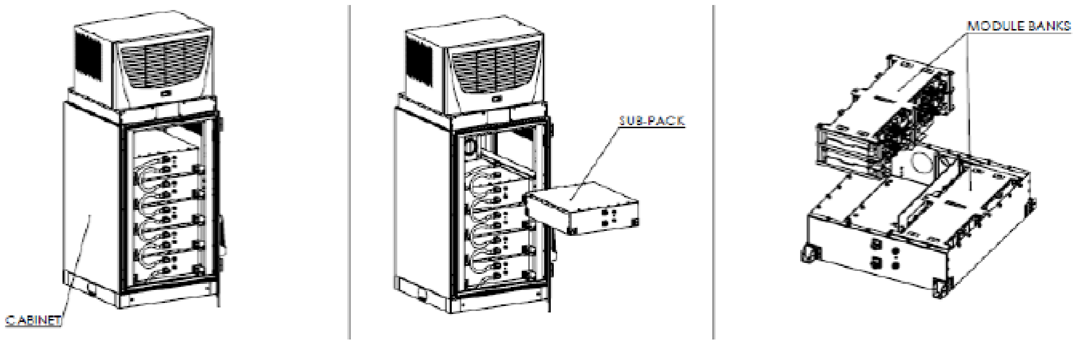


Figure 14: Typical BS modules for PSV applications [48].

As an example, the battery on board of Viking Energy have the following arrangements with punch geometry cells listed in Table 5.

Table 5: BS for Viking Energy [50].

Cells in module bank	14
Number of module banks	2
Sub-packs per string (in series)	17
Strings (in parallel)	7
Total independent batteries	2

Components and systems typically in a ship BS:

Cell

The cell is the smallest unit of electrochemical storage in a BS. This is where the energy is stored. They can be either cylinder cells or punch cells, dependent on what properties are desirable. A typical cell will have the energy density of 200 Wh/kg [51]. The cells are stacked in modules where each module is equipped with the first level of battery management (BMS).

Sub-pack

A set of modules banks forms the sub-pack. Each sub-pack has the second level of BMS.

Pack

The sub-packs are connected in series to for a pack to form the system voltage. The pack is often referred to as string or rack. The string contains the system voltage. All the packs are then connected in parallel to form the complete system energy (kWh).

Battery space

The spacing where the battery unit is called battery space. Sufficient ventilation, gas and fire alarms are required at this level.

Battery Management System (BMS)

Battery Management System is comprising control, monitoring and have protective functions of the BS. It is responsible for monitoring voltage, current and temperature limits within the BS.

Power Management (PMS)

The main purpose of the PMS is to at any time is sufficient power available of the actual operating condition [52]. This may be grouped into management over power generation, load and distribution.

Energy Management System (EMS)

For a PMS to have extended functionality involving monitoring and control of the energy flow it can be called EMS. The EMS ensures that installed and running equipment are utilized with optimal fuel efficiency [52].

5.4. Performance development

Over time all batteries, including lithium-ion batteries will experience increased internal resistance and loss of capacity. This mechanism of degradation will happen due to numbers of cyclic charging, discharging and calendar effects as time goes. The ability to withstand these two mechanisms are referred to as cycle life and calendar life. In general, the larger depth of discharge (DOD) the more performance degradation. The degradation mechanism rate and pace will also depend on temperature, as the temperature increase the more rapid degradation, and may result in reduced lifespan, energy capacity and further affecting the SOH. Low temperatures bring other risks. This in combination with high current, dendrites can occur on the battery electrodes and will reduce the battery capacity permanently. Similar can occur if battery leaves long periods with low state of charge (SOC). The temperatures at many levels are therefore monitored and controlled, this is the BMS purpose. Depending on cell type and chemistry ideal temperature ranges from 20-30 ^{o}C [8].

5.5. Cost history and trend

As mentioned above lithium-ion has high power and energy specifications. The battery prices (per kWh) over the past five years have dropped by more than 50% as seen in Figure 15 [7] [53]. It reflects the improvements in battery chemistries, manufacturing process, scale of production and competitive pricing. The car industry is highly responsible for this development within battery technology and pricing. This development has brought batteries to a level suitable of the demands of power in vessels. Also, vessels require similar system design as in the car industry and gives foundation for synergies between the industries. The number of electric vehicle sold have almost doubled from 2014 to 2015 by 290 000 to 462 000, respectively. So far, no bottlenecks have been detected in the manufacturing process [7].

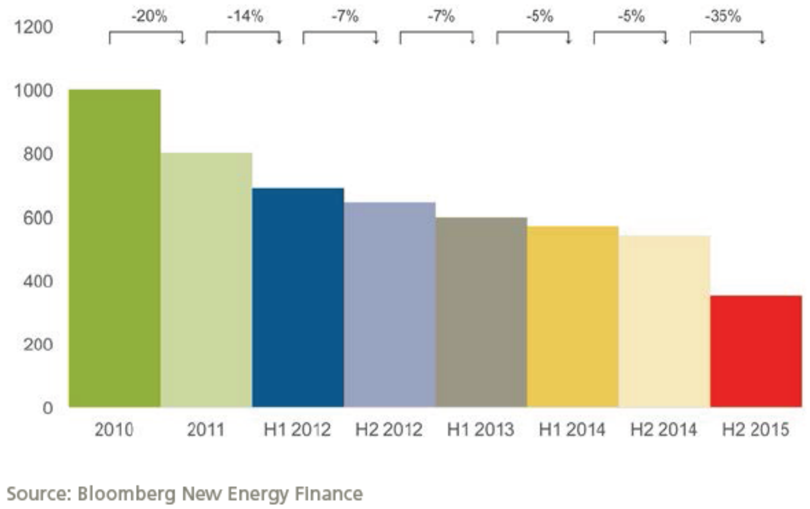


Figure 15: Development in battery prices USD/kWh per year and percentage drop from year to year [7]

The viable Lithium supplies in the world are concentrated to geographical areas, the prices of the metal are not predicted to affect the battery prices. No doubt that the metal is viable for functionality it still represents less than 2 % of cell level cost, and a possible price increase will have limited consequences. It is also predicted that equipment cost will continue to decline by higher level of automation, increase quality, reducing scrap level and cutting labor costs [7]. To illustrate the historical development of battery performance and cost it is most comparable to take base in one cell type. The 18650-cylindrical lithium cell is used as an example. The past 23 years have performance and cost development increased, on cell level, and are predicted to continue, according to LG Chem. From 1997 to 2014 the development is the following [54]:

- 1 300mAh – 3 200mAh
- Specific energy: 292 Wh/L – 700 Wh/L
- Price per energy: 950 USD/kWh – 180 USD/kWh

In July 2012, according to McKinsey&Company the current battery price was at 600 USD/kWh the article predicted the price on cell level to reach 200 USD/kWh within 2020 and 160 USD/kWh within 2025 [55]. And as mentioned above, in September 2016, according to LG Chem [54] the battery price at cell price have reached 180 USD/kWh. The energy density has the following history and expected development for NCM chemistry on cell level [51].

- 2013: 160 Wh/kg
- 2016: 200 Wh/kg
- 2018: 280 Wh/kg

6. Hybrid-battery system

Improving the power system of a vessel can improve overall performance and lower fuel consumption. For optimization of the power system can be approached by several focus areas, but the focus in this thesis will be around hybrid technologies with batteries combined with the conventional power system in the ship. The battery will store energy that corresponds to a generator. This will contribute to additional redundancy due to instant access of energy in case of failure. Then the number of engines running can be reduced without affecting the safety level. The result is engine load level is raised and the outcome is less fuel consumed for the same power. This is illustrated in Figure 16.

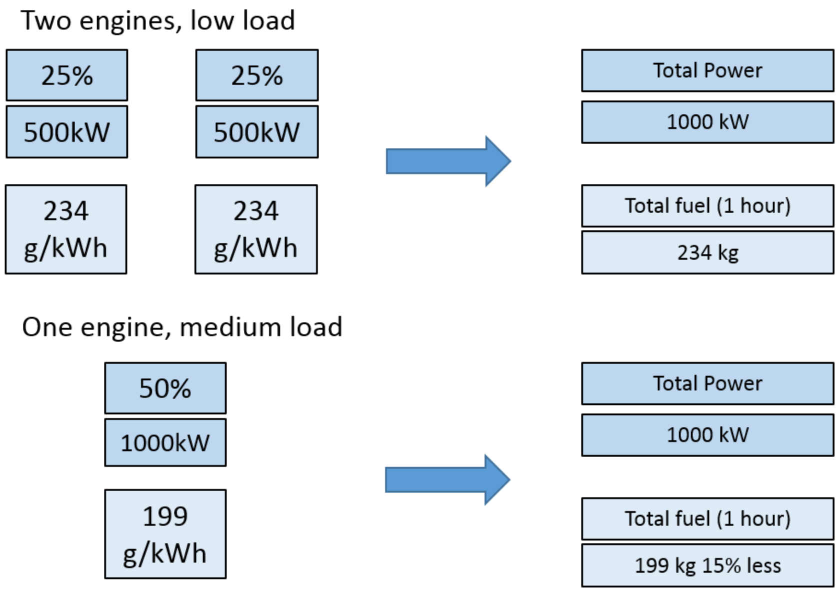


Figure 16: Generators of 2000 kW producing 1600kW in two scenarios and the related fuel consumptions. Shows the principle of how ESS can increase system efficiency.

This combination can improve overall performance and give additional redundancy and versatility to the ship power systems. The result is less fuel consumption, higher safety and responsiveness. The last years this has been made possible by the development of the batteries in performance, price and lifetime. In broad terms a battery hybrid system consist of two main components. This is the energy storage and the prime mover that produces the energy. A basic principle is sketched in Figure 17.

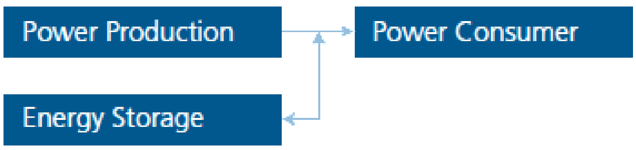


Figure 17: Concept of hybrid system for propulsion purposes.

The efficiency of the system will depend on the losses associated with the components within the system. The HBS aims to bring the online prime movers as close to optimal loading as possible. There will be a loss related to store the energy, but the alternative is to not utilize the potential of the engines. There are some configurations to implement the battery in the conventional power system and related pros and cons. The loss will be determined by the configuration and the components efficiency.

The focus in this thesis is towards PSV, there are several other types of ships that can gain benefit from hybrid battery system. The benefits will be closely connected with the operational profile and the related power range of the ship. These benefits must be weighed against cost and safety before employing a hybrid battery system.

6.1. Principle

Figure 18 shows a very simplified layout of a hybrid system cold look like in ship with diesel electric propulsion system. As seen from the figure the energy storage unit charges both by shore connection and when cold ironing but normally by excess energy. Excess energy can be available since the main engine runs constant on optimal load, but the propulsion power demand is variating. Usually diesels-electric system will have two generators running or more depending on the power and redundancy demand. Shutting down one engine is one of the advantages with hybrid system, the possibility to reduce the number of engines running at the same time. This Figure 18 illustrates power production arrangement, main components involved for propulsion and station keeping, battery system and indicating auxiliary system.

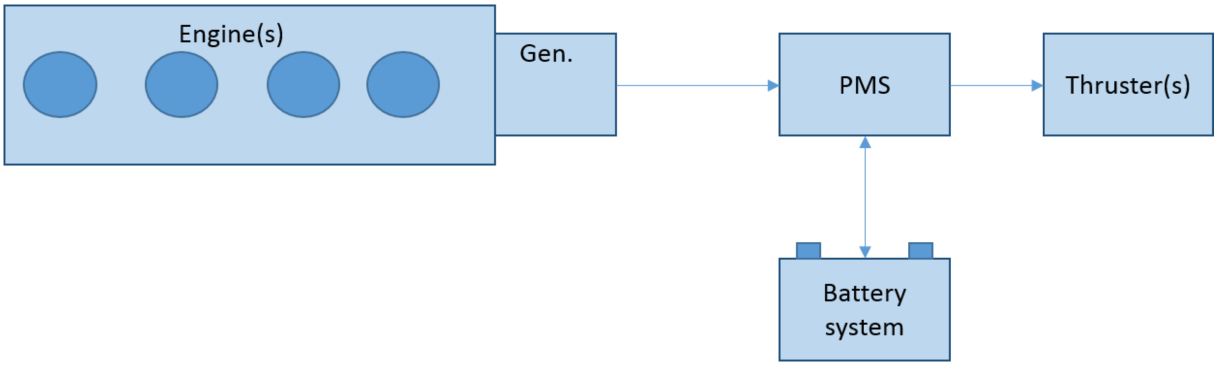


Figure 18: Simplified overall layout of a Hybrid Battery System (HBS) [23].

6.2. Efficiency of system

When selecting concept for either retrofitting or new build many considerations must be done for each special case. One important consideration when selecting a system is the overall efficiency of it. The efficiency presented in Figure 19 represents the optimal efficiency for both systems. The generator efficiency will decrease rapid below 25% load. The prime mover efficiency drops slowly and steady from the most efficient point around 80% load. All component is presented with the optimal efficiency. The efficiency for the conventional powertrain sustains an efficiency of 22% while the battery provides 53%, from well to propeller. This means that the loss of related to battery powertrain is over doubled.

Taking these facts to consideration battery powertrain are shown to be more attractive. In the context of hybrid technology, this means that sending power in to the battery gains some loss. If the alternative is to not utilize the power, batteries can store the power with acceptable efficiency. In a hybrid battery system, sending power via the battery system is associated with 10% loss [16].

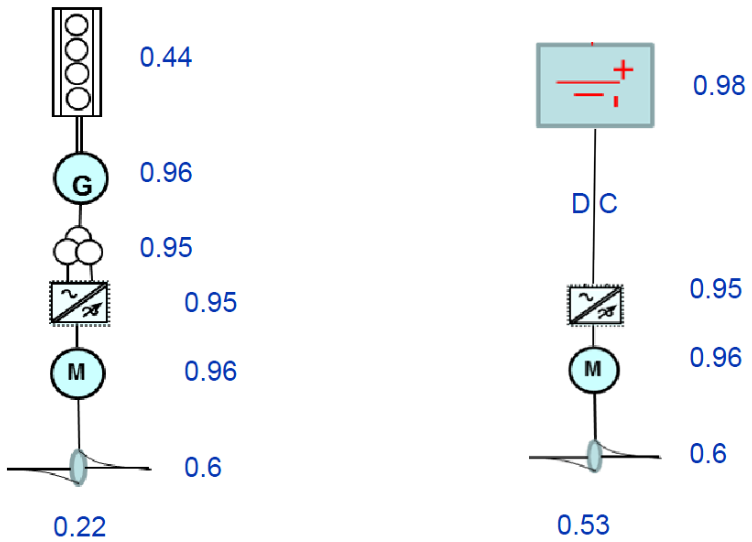


Figure 19: Present efficiency comparison make [41]

6.3. Potential benefits and challenges

Battery systems can assure great flexibility and freedom to store and utilize energy that else would not be utilized. The car industry has been pioneers in using the benefits of batteries in combination with combustion engine. They have proven that battery can help smooth the load profile of the engine. In Table 6 bellow, the category of positive conditions and modes that battery hybrid systems can bring.

The use of battery in marine power system opens up a new level of flexibility and freedom to store and utilize energy when it is most beneficial for the system. This is a benefit that has been well proven by hybrid the car industry. In a hybrid car, the battery help the engine to run more steadily and efficient and assures high response. When the system energy demand drops below optimal engine level, the engine is maintained at optimal level. The difference between the system demand and the produced power charges the battery. In opposite cases where the system power demand increases beyond optimal engine load level, the battery discharges. All these benefits can be implemented to marine propulsion system, by utilizing battery power to avoid engine operating in inefficient regions. The limited all-electric range allows the ship to shut off its engines some tens of km away from the harbor, improving local air quality [56]. Potential of reducing fuel with this technology are greatest if the energy demand varying and/or low.

Table 6: Modes of the hybrid battery and the related symbol [30].

Spinning reserve	*Peak shaving*	*Enhanced dynamic performance*	*Start stop philosophy*	*Cold ironing*	*Reduced maintenance*
			0 CO_2 NO_x db		

Spinning Reserve

The easiest way to satisfy the redundancy requirements when operating in DP or Standby is to operate a set of engines at low load. In case of failure, the resilient engines are ready to take more load. By involving the battery system in operations with these requirements, one or more engines can be stopped, if the battery is big enough. In case of failure the battery takes immediately over. Making the engine(s) left running to operate closer to optimal level. This results in greater redundancy, probably improved environmental regularity number (ERN) and increased overall efficiency of the running engines. ERN is a rating of vessel ability to hold position. This is what is meant by spinning reserve.

Peak shaving

The power demand variate highly due to environmental loading and consumers demand to the generators. This results in stressful loading on the engines. To spare the engine(s) from these variations, the battery takes the peak loads. While the engine(s) is maintained on a stable MCR. Peak shaving and fuel saving is achieved by allowing the engines to run on more constant load, battery discharges at the peaks above optimal loads, and charges at loads below optimal load. This is called peak shaving.

Enhanced dynamic performance

The battery has immediately response on load variation, peak shaving. But if the load demand rises to a higher level over longer time, the system must decide whether to continue discharging or start process of starting up an additional engine. The additional engine can slowly accelerate to this load level. This characteristic enhanced the dynamic performance of the conventional system can be treated as an extended function from the peak shaving. It will also have potential of increasing power availability of the system resulting in a more agile and responsive system.

Start-stop philosophy

This can be used at low loads, mainly related to Transit at low speeds and harbor stay. The process starts with raising the engine load to "sweet spot". The power higher than the consumers demand charges the battery. When the battery reaches the upper SOC, the engine(s) stops. Then the vessels power demand is delivered from the battery, until the lower SOC is reached. Then the engine starts up and the process is repeated. This mode ensures quiet engine rooms and reduced fuel consumption and emission in harbor, stand-by and sensitive environment. As the battery gives possibility for storing excess power produced, we can bring the load of the generator up to around 80% (sweet spot), the residual electricity is then charged into the battery, leaving the SFOC to an optimal level. Furthermore, when the batteries SOC has reached top level (80%), the generator is stopped. Then battery serves the system as the only energy source until the SOC has reached the lower level (20%), the time this takes depends on the load demand, but can typically be between 10 – 30 minutes. Then the generator comes online again charging the battery, and the cycle is repeated.

Cold ironing

Easier implementation of cold ironing mode for shore power, reducing local emission. Cols ironing means that a vessel uses onshore electricity to cover the power demand when sited at port. The onshore grid can have imitated capacity for some operations e.g. heavy lifts, the battery system can implement peaks having.

Reduced maintenance

As a result of less running engines running and enhanced dynamic performance the cost related to maintenance may be reduced. The system will have less running hours per generator due to less generators online and is predicted to be reduced by approximately 20% for the total lifetime of the battery system. The industry agrees on that the engines will have a "nice life" and probably leas to less breakdowns. According to Caterpillar, which is a major producer of diesel and natural gas engines for the maritime industry is indicating that in addition to reduce engine online hours the time intervals between maintenance can be expand by 20% due to less stressful loading. Thus this is hard to quantify before more years of experience is gained [16]. The reduction in online hours will be further evaluated in section 7.6.2

Potential Challenges

Challenges are related to that the technology is new and have not been operative for longer periods before. There is much new information for operators and the complexity of the vessels power system will be increased. If popper crew training is not a focus are when installing a HBS, if not this may lead an additional cost of hiring an external supplier to do services. Further, it can lead to a reduction in battery capacity due to unfavorable loading and conditions. But in theory, the HBS is maintenance-free. The cost of the system can also be a challenge if the saving is not in a range that defends the investment. In addition, with time all batteries will reduce capacity due to aging and cyclic loading, this is further described in section 5.4 and evaluated in section 7.7.2.

6.4. Other relevant vessels

The class society of DNV GL are classifying the majority of ships in Norway, and therefore they can provide information about numbers of vessels registered with battery safety and battery power notation. This is represented in Figure 20 and shows that vessels with batteries for hybrid or fully electric applications is a growing trend. The light blue bars show the vessels planned or under progress to be classed. The blue bar indicated the vessels that hold the class. This show that battery safety and power notation growing and this will gain more experience and knowledge to the industry.

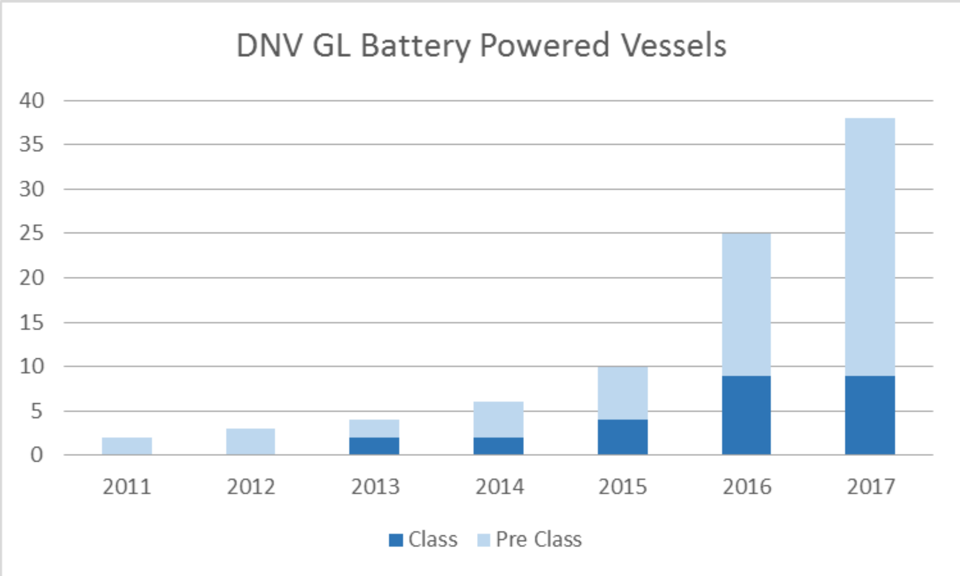


Figure 20: Vessels registered with battery safety or battery power notation from DNV GL.

Due to various types of operation patterns depending on the vessel type, some vessels types are more attractive to hybridization. The most relevant ships that correspond to the characteristics above are given in this section. In general, vessels that spend significant time in station keeping and exposed to high peak loads, have the greatest benefit of hybrid battery systems. Also vessels that covers a wide power demand and operated most of the time at low loads. If a vessel are frequent at harbor or are sited there for longer periods will have benefits form cold ironing which can be implemented when installing a HBS. And qualitative assessment of the following vessels applicability for a HBS are provided in Appendix A.

Platform supply vessels

These vessels are designed to support offshore oil & gas installations and spend in general much time in station keeping and is designed to execute their tasks in almost all weather conditions [52]. These modes are associated with high redundancy requirements and multiple engines operating at low to medium loads. Therefore, provided that the vessel operates significant time in these modes, they are applicable a HBS.

Rigs and FPSO

Rigs for oil & gas production, drilling and Floating Production Storage and Offloading (FPSO) have common characteristics regarding power production. The main purpose for power production in these vessels are to supply power to perform the tasks onboard. Position keeping is relevant for deep-water and when stationed at fields with high subsea infrastructure density where anchoring is not an option. Then the vessel operates in DP. These vessels have typically large thruster power, in addition to power related to production, utilities and hotel loads. Additionally, crane operations associated with drilling equipment demands high peak loads which result in generators at high loads. The battery system can help taking the peak loads and be charged when the demand has dropped. Further, it may increase the overall efficiency of the power plant.

Special vessels

Various kinds of vessels exist for special applications as pipe laying and subsea well intervention. In operation, they are highly dependent on station keeping to assure successful operations. They spend a significant time amount operating in this mode. And the load variation related to station keeping makes these vessels relevant to hybrid battery systems.

Tugboats

These vessels have a great range of power demand, from maneuvering itself to ships many times its own size. This means that the power system must be designed to handle the high loads the vessel will be exposed to. This means that when the vessel operated under conditions not related to towing, the engines will operate at low loads. This can be mitigated by a hybrid battery system.

Ferries

During the voyage ferries the power system operates close to optimal MCR, then a battery system is unnecessary. But when entering and leaving harbor the power demand is low and ferries are most likely to enter and leave harbor frequently on a daily basis [56]. The time spent in harbor makes room for implementing battery system to improve the overall efficiency. Short voyages, low loads at harbor makes room for frequent charging, this makes ferries attractive for both hybrid systems and all-electric systems.

Icebreakers

The load range icebreakers are designed for are wide. The load variation can be big and change rapid, which requires the power system to sustain a high response performance. But much of the operations may happen at a lower and different level. Thereby this vessel type can be suitable for hybrid battery systems [52].

Lifting vessels

When doing heavy lifting much power is required to lift objects. When lowering objects or operating on active heave compensation much energy is involved. If a hybrid battery system is implemented the energy that elsewise goes to heat can be absorbed by the battery and increase the overall performance of the power system. This makes lifting vessels interesting for hybrid battery systems.

Research vessels

Vessels for geotechnical, fishing and oceanographic research all which share very strict underwater noise requirements [52]. There is science issuing the noise reduction standard used in silent vessels today [57]. The HBS may increase the operational performance as well as possibilities for operation periods only on battery. This may totally eliminate noise disruption in survey data.

6.5. Power system

The common way to categorize the grid types is by type of current, DC or AC the main distribution system delivers. The main distribution system is typically referred to as the main switchboard or bus onboard a vessel. There are two types of currents; alternating current (AC) and direct current (DC). The vast majority of PSV today uses AC distribution system [52]. New development of power electronic converters has resulted in a trend towards DC distribution systems [58].

Typically, the power system consists of four to six diesel generators that feed power into the main switchboard [52]. From the main switchboard, the power is fed through transformers & converters to the thrusters. The Figure 21 a) represents a typical power system for a PSV with AC distribution and the related components. It shows the layout for a typical PSV with conventional AC system and new DC system respectively [30].

Figure 21: Illustration of power system power with AC a) and DC b) of a typical PSV [30].

Increased interest in integrating batteries with DC output, have resulted in more focus towards DC distributed systems as shown in Figure 21 b). There have been indicated benefits related to dc distributed system. This could be due to smaller numbers of switchgears and transformers that provide space and weight savings. The DC system has reduced some stages of transformation [58], hence higher efficiency of the system. In addition, indications of efficiency improvement which is caused by that the generator(s) is not “locked” to the specific frequency (typically 60 Hz). This allows each power consumer to operate closer to optimal speed and can indicate mitigation of fuel and emission [30].
One disadvantage to DC grid is the large currents in case of shorting. This may represent the greatest challenge related to DC grid.
DC grid is a novel technology and only a handful of vessels are delivered and in operation with dc grid. One of the vessels has reported significant fuel savings in some modes [30]. To go for AC or DC grid is a consideration mostly related to new build vessels due to complexity and cost for an already operative vessel.

Generator

The prime mover usually drives the generator set. The combination of combustion engine and generator are referred to as a diesel-electric system. Generators are synchronous machines. The most common produce AC currents. Then the current is set with a frequency (Hz) as a function of poles in the generator and RPM [52]. This means that for the generator to deliver 60Hz, a certain RPM must be kept. That is why the engine has constant speed, and what is meant by the generator is "locked" to a frequency.

Main bus

The main bus, often referred to as switchgears is the electrical system that distributes the power to propulsion and the ship. The bus is usually split in two, three or four to fulfill the required redundancy requirement of the vessel [52].

Transformers

To obtain different voltage levels transformers are used. They then provide a galvanic insulation and isolate parts of the electric power system. Sometimes transformers are also for phase shift to feed frequency converters, in order to reduce distorted currents into the network [52].

Inverter (DC to AC)

Converts currents from DC to AC.

Rectifier (AC to DC)

A rectifier is a device that converts AC to DC.

6.6. Configurations

As a normal “energy system” for a PSV consist of two or more diesel or gas engines, the generators must be synchronized before energy can be delivered to the main bus. The Figure 22 shows a brief description of two layouts for AC distributed system. On the left side of Figure 22, the batteries are connected directly to the bus since batteries deliver DC, the current must go through an inverter for further distribution. There are also converters from the AC bus to the main thruster. The electric converters are necessary to be able to control the speed, torque and power of the propulsion motor, which typically represents 2% loss [8]. Both of the configurations have two generator sets. One way of improving the efficiency can be to distribute the batteries directly to the propulsion converters in this way one conversion step is removed as illustrated on the right side of Figure 22. This may result in improved response and reduced loss. But as a downside, the batteries mainly contribute to local benefits and not gain benefits to other consumers e.g. crane operations. If the capacity of the converter is limited. Further, increased complexity of control and management system and more cabling can result in higher installation cost.

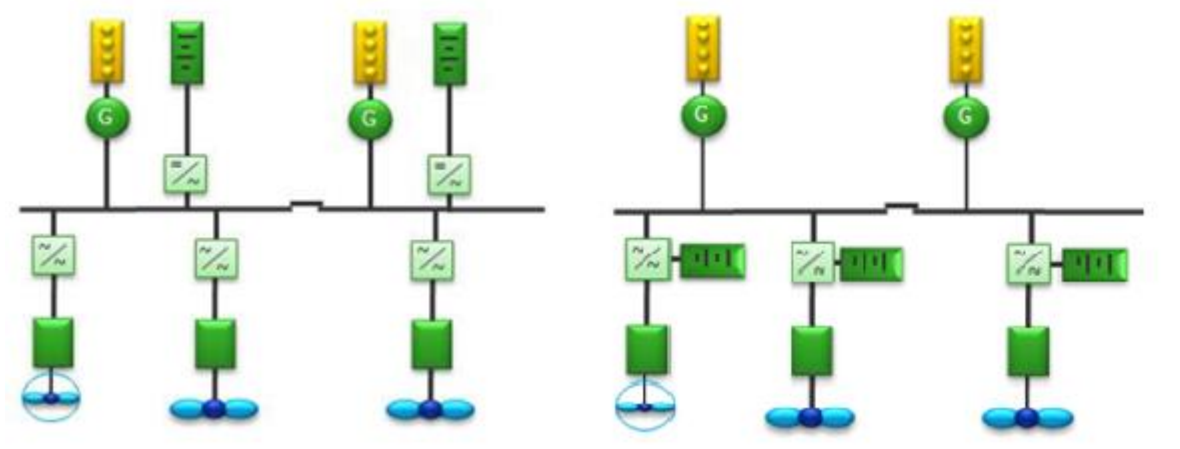


Figure 22: AC distribution configurations, battery connected to the main board and distributed battery respectively [8].

6.7. Risk and safety

As presented in the subjects above batteries can assure benefits and increased performance. This is a new power system, and the associated risk is slightly different from the safety related to conventional power systems. The risks are manageable, but risks and challenges need to be addressed to provide a safe battery system. Identification of failure modes is required in the class notation. Most lithium-ion battery failures result in reduced power, capacity or temporary inoperability. The goal is that any failure can occur in a safe way. Failure can include scenarios like; thermal events, fire, and thermal runaway; release of gas, explosion or toxic environment. The outcome of such event may depend on the system design regarding safety. Battery specifications are driving factors for designing the safety system, main specifications to consider according to DNV GL will be:

- ***Cell chemistry:*** The temperature where the battery goes to thermal runaway depends on the battery chemistry. In a situation of thermal runaway, heat produced also differs from various chemistries.
- ***Cell size:*** The heat produced is highly dependent on the size of the cells, larger cells produce more heat and gas under a thermal event.
- ***Cell form:*** The resilience towards failure can depend on the cell shape (cylindrical, pouch, button).
- ***SOC:*** Represent the amount of energy within the cell or battery system. More energy results in greater production of gas, heat and material combustion.

Possible failure modes include; failure within the cell; short circuit internally or externally; overcharge or over-discharge, to high temperature; external heat source. All these issues are important to consider in the cell environment considering temperature, humidity, pressure, ventilation and isolation towards these failure modes. A fatal event is if one cell failures and propagates further to other cells, sub-packs, and modules. It is therefore very important for cells and modules to withstand possible propagation failures [8].

This means the system needs to be monitored regarding the parameters discussed, on several levels within the battery. Insulation between all cells, racks, and sub-packs is crucial for sustaining a safe failure. Operating the system outside the safe limits provided by the supplier may also cause failure.

7. Case study

This case study will discuss and evaluate the benefits and challenges of the Hybrid Battery System (HBS) applied to the vessel Viking Energy. Eidesvik Offshore ASA is the owner of Viking ENergy. The vessel is under long term contract and is used to transport goods, drilling equipment and various supply materials to the offshore fields. The battery installed onboard Viking Energy are supplied by LG Chem located in South Korea. The implementation of the Battery System (BS) to the original power system was designed and executed by Westcon P&A.

In May 2016, the Platform Supply Vessel (PSV) Viking Energy was equipped a BS based on one container with the power electronics and one with the battery. Together the containers form the HBS. The vessels size and operation profile are considered to be representative for an average PSV serving the Oil & Gas industry.

This chapter will evaluate the hybrid battery system onboard Viking Energy. The chapter contains seven sections with the following structure:

- The first section provides information about the source of the data.
- The second section describes the system components, modes and how the hybrid system interacts with the conventional power system.
- The third section describes the structure of the evaluation that is to be done.
- The fourth section discusses and presents the operational time distribution for various time periods.
- Fifth section provides an evaluation of the aspects considered as the main benefits of the HBS.
- The sixth section gives an evaluation of the benefits considered as other.
- The seventh section discusses possible challenges related to the HBS.

7.1. Sources of information

The analysis is based on information provided by collaboration partners of the thesis. The prime data source is provided from Enova's final report of the project including operational and consumption data [59]. The report is based on empirical data from the vessel and consists of good quality. The technology is young and historical data for long timespan are challenging to obtain. System and battery specifications are provided by Westcon P&A. They have also supported with knowledge and experience related to battery hybrid technology. Weather data from the Hindcast NORA 10 model are provided by senior scientist Magar Reistad at Norwegian Meteorological Institute and first amanuensis Sverre Haver at the University of Stavanger [60] [61]. Various information mostly regarding combustion and emission are given by Senior Research Scientist Elizabeth H. Lindstad at SINTEF Ocean AS [39]. Qualitative data from crew members have been collected by audio recording when visiting the ship on 23.02.2017.

7.2. Description of hybrid battery system

Vessels operates in different operational modes as described in section 4.1, which is five modes for this vessel. The battery system is used differently dependent on which of the five modes the vessel is operates in. The applications of the BS includes peak shaving, spinning reserve and start-stop and are described in section 6.2. The BS application are linked to the different vessel modes as described in Figure 23. The different applications of the battery have various properties and is therefore implemented in different operational modes. The battery system can be used to systematically optimize the utilization of the running engines.

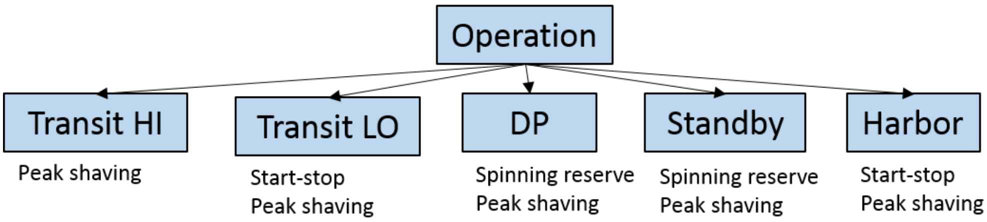


Figure 23: Operational modes for the ship and the battery systems applications.

7.2.1. Overall topology

The overall system topology is shown in Figure 24. The battery system consists of two container modules. One contains the Energy Storage System (ESS), the battery, and the second is the Energy Control (EC), the power electronics. The power electronics main task is to convert power, controlling and distribution to the bus. The bus has a voltage of 690V and a frequency of 60Hz, which corresponds to an AC distributed configuration. Power to consumers for propulsion and station keeping are distributed from the main bus. The hotel and auxiliary load will be transformed from the main bus to 440V and 230V but is not shown in this figure. These are systems supplying the vessels consumers on lower voltages. Since the whole ship power system is derived from the main bus the battery system will affect the entire ships power system. The term generator are used as the power producer and the engine drives the power producer.

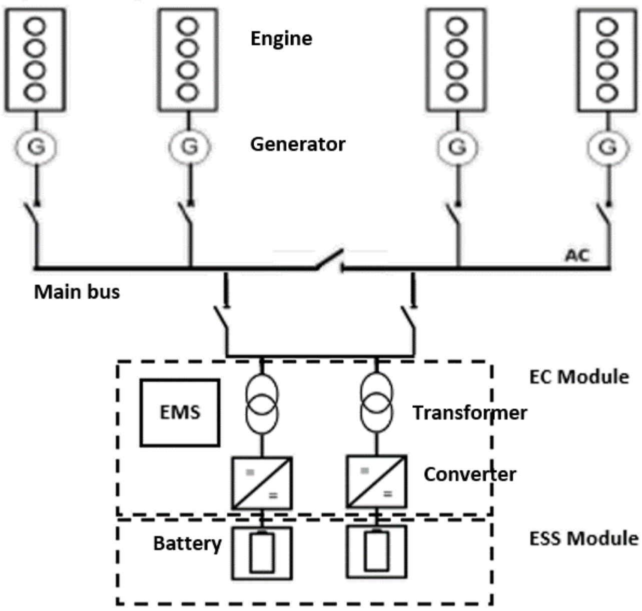


Figure 24: Overall topology of the power system of the vessel with the HBS [10].

Power setup

This specific vessel has a total installed power of 8040 kW distributed amongst four engines. The engines are DF and can be operated on LNG and MGO. Each engine has a MCR of 2010 kW. This type of engine setup provides good flexibility and gives a wide range of power. The bus is split between port and starboard side of the boat by a main switch that results in two independent systems. This is a requirement according to the class notation "DYNPOS AUTR" to provide the necessary redundancy in case of failure [14]. This type of setup is called "split bus". Each engine is also equipped with a switch before connected to the main bus, this means that each engine can be operated independently.

Energy management system

To make the energy storage integrated in the ships power supply, control and management system are important. The charging and discharging is monitored and controlled by the EMS and the power conversion is done by the converter. The converter consists of converter/inverter module, LC-filter and the power transformers that controls the frequency. The converter unit converts or inverts the electricity from DC to AC or vice versa to be able to combine the battery with the AC bus. The power transformers assure that the AC from the batteries are synchronized with the AC of the bus before delivering the power into the bus. The systems interface are designed to act as similar as a conventional generator. The energy system can be connected to either port- or starboard side of the main switchboard, this gives the freedom to reduce running hours evenly between all four generators [10]. The main task for the EMS is to provide decisions and monitor parameters involved in balance cells, state of charge and state of health [62].

7.2.2. Energy Storage

Dimensioning batteries involves balancing between capacity (kWh) for storing energy and power (kW) to drive the electric current in the BS. Power optimized system have less active material, thin electrode coating thus much area exposed to drive the electric current. The system external to the cell must be dimensioned with power cables associated with high weight and high cost [48]. The power properties of the case have been designed for requirements of spinning reserve. This involves the vessel to be able to remove itself from the critical area in case of failure, when operating in DP mode.

Table 7: Battery specifications on board Viking Energy [50].

Total capacity	653kWh
Estimated capacity	503kWh
Cycle life	>6000
Calendar life (Years)	>10 Years
Spinning reserve requirement	7 min
C-rate charge/discharge	3
System voltage	690V
Operating temperature	$23 \pm 5C°$

The battery consists of two times six racks and sustain a voltage of 690V. It can provide power of 1600 kW and energy of 653 kWh. The cells consist of NCM chemistry and punch cells to provide the C-rate of 3. Punch cells have more area exposed to the active materials than cylindrical cells therefore better power properties. The requirement of the battery power notation is that the vessel must be able to be powered solely on the battery for minimum 7 minutes. This time requirement will be individual for every vessel. This is when operating with the battery as spinning reserve. The shipping company has determined that the power demand in normal conditions will be around 1600kW. And then with the lower SOC limit in Blue DP mode of 80% gives the following estimate.

$$\left(\frac{653\ kWh \cdot 0.8 - 653\ kWh \cdot 0.1}{1600\ kW}\right) \cdot 60 = 17\ minutes \qquad (7.1)$$

From equation 7.1 the battery system is calculated to run solely on the in 17 minutes. This is then well within the time requirement of 7 minutes.

7.2.3. System modes

The battery system provides different applications to take advantage of the power need associated with the operational modes of the vessel. This ensures the most efficient interaction between the BS, conventional power system, and provides longer lifetime of the batteries. The system can be operated in the following modes [10]:

- ***Blue:*** when load demand is oscillation, peak shaving is enabled. Then the State of Charge (SOC) is in range of 50-80%
- ***Blue ECO:*** when vessel operates at low loads, start-stop is activated. The engine is then loaded around 80% and the excess power charges the battery. When the battery has reached the upper SOC the engine stops the engine and the battery supplies the system until lower SOC is reached, and process is repeated. SOC 20-80% includes peak shaving.
- ***Blue DP:*** when operating in position keeping or with higher safety requirement. One or more engine shuts down and increases the loading on the residual online engines to a more effective level. In case of failure the battery goes online and supplies the system for minimum 7 minutes, also known as “spinning reserve”. Therefore, the lower SOC is 70-80% to secure enough energy in case of failure.

7.2.4. Battery interaction

Figure 25, Figure 26 and Figure 27 provide operational load examples of how the hybrid battery system operates at different loading. Describing start-stop, spinning reserve and peak shaving by example. The time is along the horizontal axis and load is along the vertical axis.

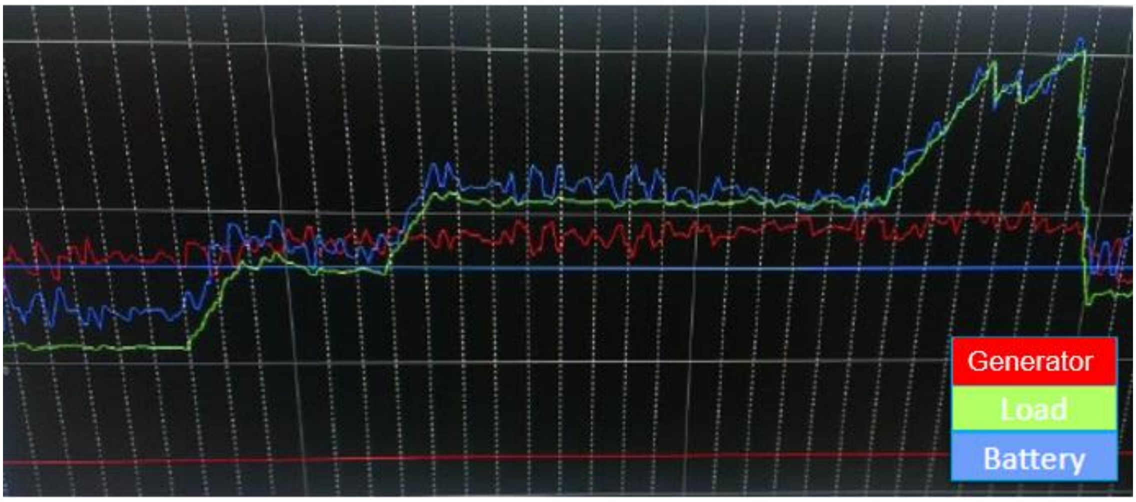


Figure 25: Load versus time showing optimal loading of generator and battery takes care of excess load [10].

It is observed from Figure 25, that the generator is maintained around optimal load at 80% indicated by the red line. The load demand is represented by the green line, and the battery load is shown by the blue line. At first the battery power use is lower than the generator, meaning that the battery is charged. Further the load rises above the generator, the battery takes over the load above optimal load, and prevent starting a second generator and/or unfavorable loading of generator. In addition to the general peak shaving the system takes active care of load increment over time, within a time limit, to prevent startup of additional generator. This goes under enhanced performance and can be treated as an extended peak shaving. Figure 25 could be a typical example of the *"Blue"* mode, where peak shaving and enhanced performance are implemented.

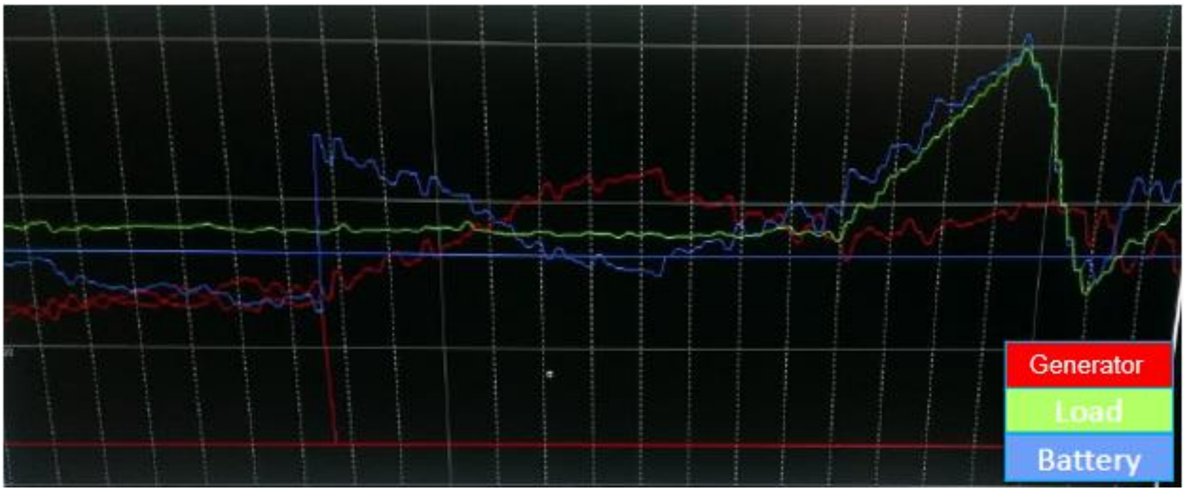


Figure 26: Load versus time, provoked shut down of generator, the battery takes the load immediately [10].

Figure 26 starts with two online generators, one generator is provoked shut down. The battery takes immediately the load, at the same time the remaining generator gradually increases power and the battery gradually transfers the load to the remaining generator. This prevent the generators to be exposed to stressful loading and assures more favorable load variations for the engines. It represents how the loading of the engine is brought to a more favorable load pattern by the battery.

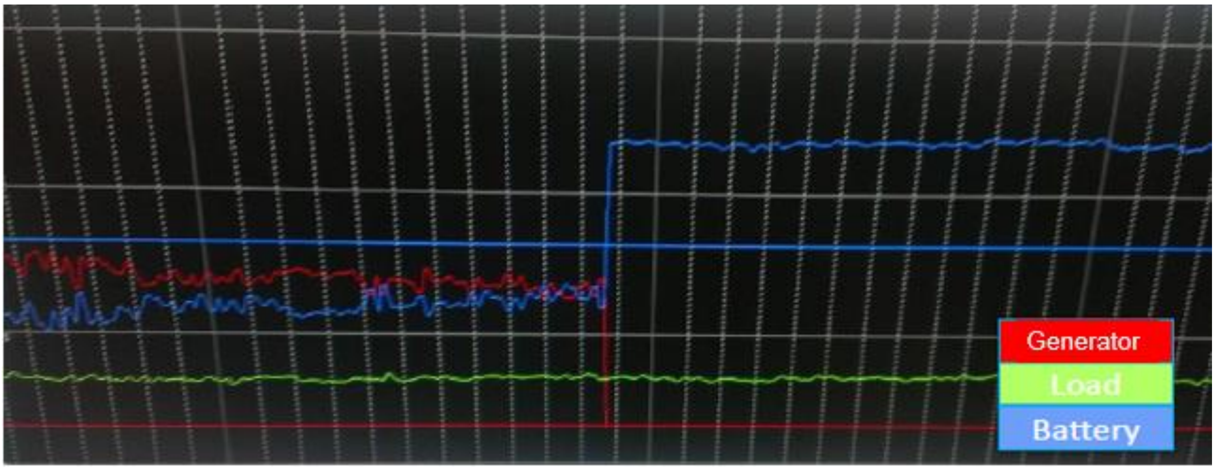


Figure 27: Load versus time provoked failure of generator, all load transferred to the system [10].

Figure 27, illustrates the event of generator failure e.g. when operating in "*Blue DP"* mode. This event illustrates the role of the battery as spinning reserve. When the generator is stopped, the battery takes instantly over the load demand. When operating in Blue DP the lower SOC is maintained in the range of 70-80% to ensure enough energy for abortion of the operation. In case of critical situation leading to e.g. abandonment; the battery can be operated until 15% SOC. The battery lifetime is highly permanently reduced by letting the SOC drop that low. Battery degradation is more described section 5.4. The probability of the event to happen are low and may never happen.

To summarize the HBS of the vessel:

- The way the system is selected to interact with the power system module based, which gives a versatile HBS that requires low installation time and less complexity to the management system.
- The battery is interacting with the whole power system of the ship and not only consumers related to propulsion and station keeping, which will be the case for a distributed battery system.
- The disadvantage can be slightly less efficient power conversion as the main bus battery configuration involve one extra step of conversion.

7.3. Evaluation criteria

This thesis is divided into some focus areas in the evaluation. The evaluation is started with a cost benefit analysis where the benefits considered to be of main interest will be evaluated. Further the next section addresses other important benefits that is evaluated. And last, challenges related to the battery system is evaluated. The evaluation has the following structure:

- Consumption and cost benefits
    - Consumption
    - Weather impact on consumption
    - Economical
- Other important benefits
    - Environment
    - Maintenance
- Other important challenges
    - Crew training
    - Performance reduction
    - Generation development

7.4. Operational

The Figure 28 is made based on historical operating data from Eidesvik in the period from 2012 to 2015 and has formed the operational baseline for this case. The modes to be observed are: Transit HI at 1%, Transit LO with 28%, DP at 41%, Standby at 2% and Harbor at 29%. Transit HI and LO are modes reflects operations in transit from A to B, referring to high and low speed. Transit HI represents the vessel operating at speeds above 11 knots, often around 15 knots. Transit LO is the economical and preferable pace decided by charter and ship owner, typically around 10-11 knots [63]. The vessel operates in station keeping with DP and Standby modes. These two modes are mainly divided by the redundancy requirement of the power system. DP are associated with the highest redundancy level, e.g. vessel operates close to a platform. Further, Standby is often referred to as waiting on field and has low redundancy requirements. When the vessel is sited at harbor the power produced is mainly for operating crane for on- and off-loading of various supply and hotel load. All density plots are based on AIS data provided by the Norwegian Costal Administration [64]. AIS is short for automatic identification system, which is an automatic tracking system all commercial vessels are equipped with.

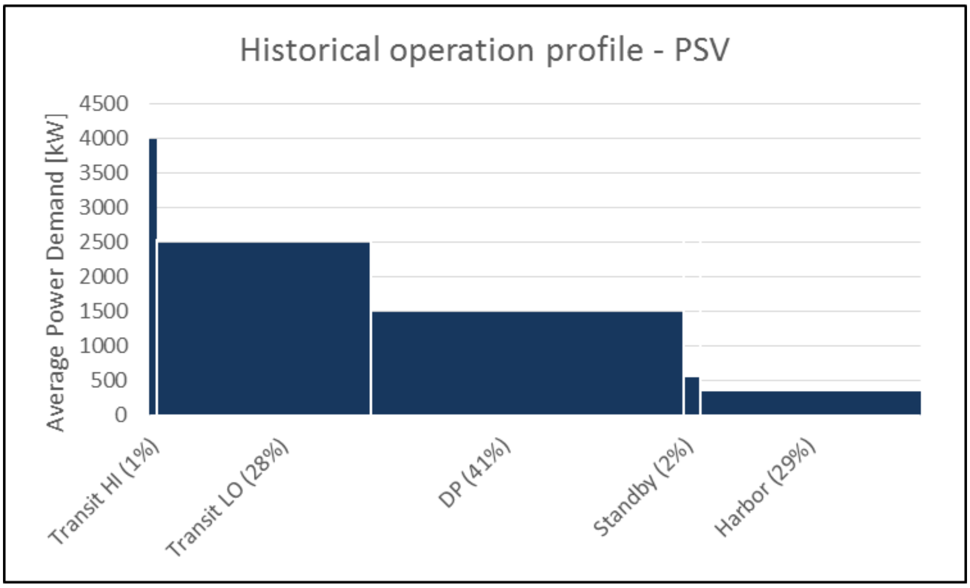


Figure 28: Operation profile for the vessel based on historical data from 2012-2015 showing the average power demand with respect to percentage annual time in the respective modes [59].

The vessel is under long term contract and appears to have predicable work duties and have room for good planning of the operations. Figure 29 shows the path of operation from 2012 to 2014 generated by AIS data [64].

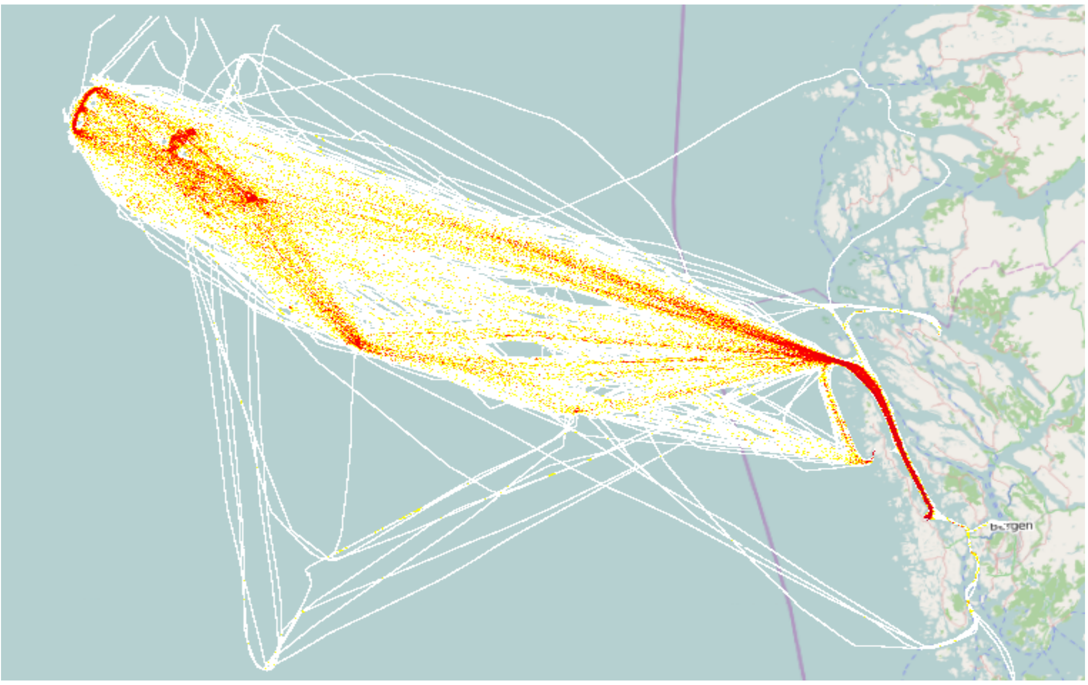


Figure 29: Density plot for the vessel from 2012 to 2014 [64].

The HBS was installed and tested and the vessel left the yard at 12.05.2016. The system was considered to be fully operative 01.07.2016 to 31.12.2016, and that is defined as the sampling period. Figure 30 shows the distribution of the operation profile for this period. Compared to the operation profile from 2012 to 2015 it can be observed that the ship has not operated in Transit HI and Standby. Transit HI is related to high speed steaming and are utilized in urgent operation. Standby are often related to waiting on field e.g. for better weather. This can indicate that the vessel has predictable work and good planning of the operations in this period. It also spends significant less time in the DP mode from 41% to 24% respectively. Further, the vessel operates more time in Transit LO and Harbor in the sampling period.

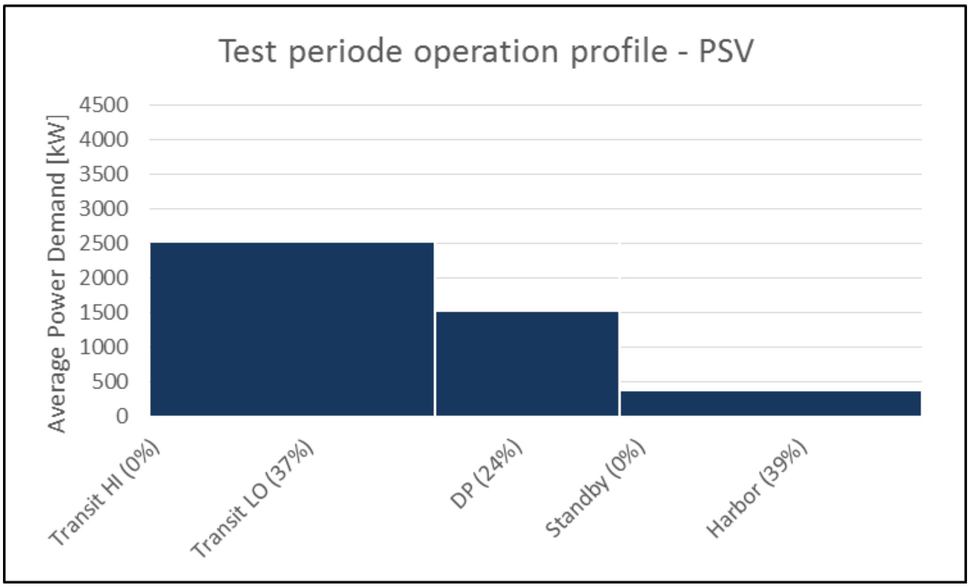


Figure 30: Operation profile to the PSV over the sampling period July to December 2016 showing the average power demand in each mode with respect to the time spent in each mode [59].

Figure 31 and Figure 32 are density plot of 2016 and 2015 for the vessel of the case. The plots represents the geographical path of operation for the vessel. The plots have much similarities and corresponds well with each other. This contributes to decrease the uncertainty associated with variation in working conditions for the vessel over time. From the final project report form Enova, the ship was stated to have similar work tasks from 2014 to 2016 [18]. This vessel mainly operates between the oil fields Gullfaks, Oseberg and Troll and back to shore to the CCB base sited at Mongstad and Ågotnes. With this information as basis, the vessel appears to be operating with an acceptable variations in geographical path and working tasks from 2015 to 2016.

Figure 31: Annual density plot of Viking Energy from 2016 [64].

Figure 32: Annual density plot of Viking Energy from 2015 [64].

7.5. Consumption and cost benefits

The following section discusses the main benefits of a HBS in a systematic approach.

7.5.1. Consumption

Reduced fuel consumption is considered the main benefit of the hybrid battery system. This section will first present and use a theoretical method for calculating reduction in fuel consumption by applying a HBS. The last part analyses the fuel consumption for different periods and concludes with a final fuel reduction.

Theoretical calculation

The shipping company must provide most of the input in the theoretical calculation method. This involves information of operational profile, number of generators running, and energy demand associated with each mode. In addition, the method depends on data related to Specific Fuel Oil Consumption (SFOC) and must be provided by the engine manufacturer.

The calculation done is based on qualitative consideration of the average power demand related to each mode and how many engines operating. Viking Energy is equipped with four engines at 2010kWh each. The average power demand in each mode from the qualitative consideration is set to be; Transit HI, 4260 kWh; Transit LO, 1800kWh; DP, 900kWh; Standby, 900kWh and Harbor, 500kWh. The operation time in each mode presented in Figure 28 is used in the calculation. The SFOC is based on an engine considered to be similar to the case and are shown in Figure 8 in section 4.4.1 [16]. This is because data of power demand and SFOC curve is not provided for the specific vessel. Due to lack of information about MGO to LNG ratio, it is assumed that the engine only operates on LNG. The engine usually switches over to MGO at low loads and use MGO as ignition fuel while operating on LNG. These assumptions gives additional uncertainty to the calculations.

The suppliers of the HBS use the theoretical method to estimate how much fuel reduction that can be expected by applying the HBS. This is done for each specific vessel before possible recommendations for investing. The theoretical calculation method has not been calculated by the supplier for this vessel due to limited time at the project. The calculations by the theoretical method based on these conditions is presented in Table 8.

The ship operates 1% of the time in Transit HI. For conventional setup this includes four generators operating at 52% load each. The hybrid setup removes one, resulting in a MCR of 69% on the remaining generators. Corresponding in a SFOC of 198 g/kWh and 191 g/kWh, respectively.

The vessel operates 28% of the time in Transit LO. For conventional setup it applies two generators which are reduced by one, for the hybrid setup. The MCR goes from 44% to 88%, which corresponds to SFOC of 200 g/kWh and 192 g/kWh, respectively.

The DP mode corresponds to 41% of the time operation profile for the vessel. For the conventional setup, this means that three generators are running at 15% load. The hybrid setup reduces the operating generators by one which raises the load to 22% for the remaining generators. These loads correspond to an SFOC of 304 g/kWh and 255 g/kWh, respectively.

In Standby the vessel operates 2% of the annual operation time. In the conventional setup, there is operating two generators each at 22% load. In the hybrid setup, the generators are reduced to one and the load is raised to 44%. The corresponding SFOC is 255 g/kWh and 200 g/kWh.

The harbor mode engages one engine in conventional setup, thus the engine number remains unchanged. By implementing start-stop application, all energy is produced close to the sweet spot, which is 192 g/kWh. The peak shaving mode is included by reducing the SFOC in the hybrid setup by 3%, in the modes applicable to peak shaving.

*Table 8: Theoretical method of calculating fuel consumption with four generators of 2010 kW each, shows how the load is increased for the remaining generators by applying HBS and the resulting expected fuel reduction in an annual year based on the operation profile for 2012 to 2015.*Peak shaving **Start-stop mode*

Conventional setup										
Mode	Hrs./yr.	G_N (kW)	MCR (%)	Total (kW)	No. G	MCR (%)	SFOC (g/kWh)	ton/hr.	ton/yr.	% red.
Transit HI	88	1065	52	4260	4	52	198	0.84348	73.9	
Transit LO	2453	900	44	1800	2	44	200	0.36000	883.0	
DP	3592	300	15	900	3	15	304	0.27360	982.7	
Standby	175	450	22	900	2	22	255	0.22950	40.2	
Harbor	2540	500	24	500	1	24	235	0.11750	298.5	
Sum									2278.26	
Hybrid setup										
Transit HI	88	1420	69	4260	3	69	191 *	0.78925	69.1	5.1
Transit LO	2453	1800	88	1800	1	88	192 *	0.33523	822.3	3.0
DP	3592	900	22	900	2	22	255 *	0.22262	799.5	14.7
Standby	175	900	44	900	1	44	200 *	0.17460	30.6	13.5
Harbor(start/stop)	2540	500	24	500	1	24	192 **	0.09600	243.9	6.9
Sum									1965.4	
Total reduction									312.9	13.7

By taking the weighted product of the MCR with respect to the annual time distribution of the estimated numbers, the MCR is increased from 26% to 42% without and with the HBS respectively. After applying the HBS the weighted product of SFOC is decreased from 255.9 g/kWh to 219.9 g/kWh with respect to the annual time distribution for the vessel.

In this way, the power system is utilized and the overall efficiency is improved. The main contribution to savings is due to reduced numbers of running engines, because battery acting as passive redundancy contributor, called spinning reserve.

Based on the operation profile from 2012 to 2015 the theoretical method of estimating fuel reduction is presented in Table 8 indicated a reduction in all modes. The fuel reduction in each mode was: Transit HI, 6.4%; Transit LO, 6.9%; DP, 18.6%; Standby, 23.9%; and Harbor, 18.3%. Overall reduction in fuel consumption was found to be 13.7% corresponding to 312.9 ton fuel annually.

The modes contributed to greatest reduction is DP, Standby and Harbor. These are modes associated with low rate of utilization of the power system with respect to max capacity. This can indicate that modes operating where generators are operating at low MCR can be expected to provide the greatest saving.

Data based calculation

In the following, fuel consumption data are presented in this order: Harbor, Transit HI & LO, DP & Standby and total reduction. The graphs is based on numbers provided from Enova's final report for the project of Viking Energy, which are empirical data from the vessel [59]. The data are given as monthly average consumption during 2015, 2016 and as annual average from 2012 to 2015. From 01.07 to 31.06.2016 the HBS is considered to be fully operative and is the defined sampling period.

From historical data, the harbor mode represents 29% of the annual operation time. From the sampling period, the mode corresponds to 39% of the annual operation time. In this mode, there is usually one generator operating between 10% to 20% load supplying the demand. Shutting down one excess generator in this mode is not applicable. Therefore, the savings in this mode could come from start-stop or peak shaving application. Start-stop mode involves high Depth of Discharge (DOD) and is the most stressful application for this BS. As a result of much energy in and out of the BS, significant heat is generated, and a well functional cooling system is crucial. Due to technical problems leading to insufficient cooling, the start-stop application has not been used during the period represented by these data [16]. Therefore, fuel reduction in harbor mode comes from peak shaving and the enhanced dynamic performance this involves.

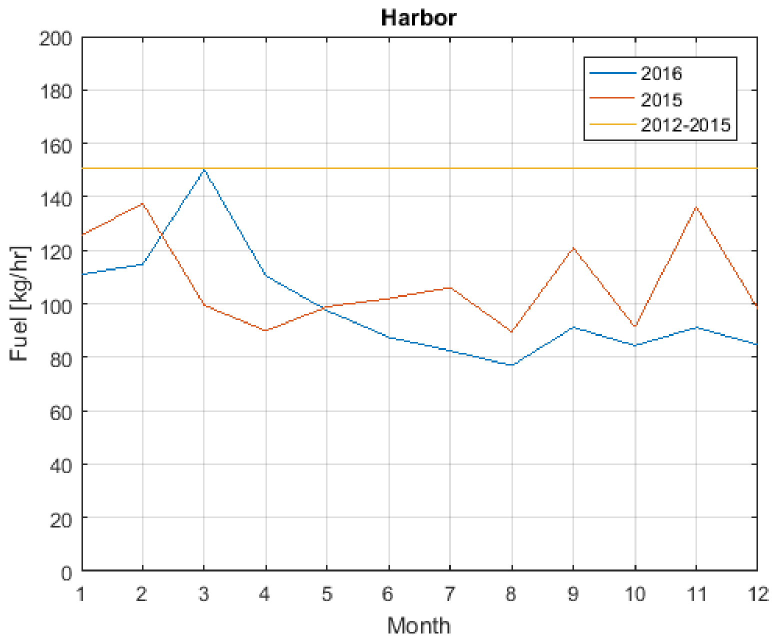


Figure 33: Fuel consumption in harbor mode for the respective periods [59].

Figure 33 shows the fuel consumption related to the harbor mode. The main observations in the figure are related to the monthly consumption from July to December 2016 illustrated by the blue line. The fuel consumption in 2016 is both lower than in 2015 and in the years 2012–2015 within the sampling period. The figure shows some remarkable indications of fuel saving. The highly variating fuel consumption from each month in 2015 makes it challenging to state a reduction factor. But the fuel consumed during 2016 seems to be stable. This could be a result of the HBS.

When the 2016 data in the sampling period is compared to 2012-2015 data the average reduced fuel corresponds to 43%. When taking the difference from 2015 to 2016 in the moth involved in the sampling period the reduction corresponds to 20% in average. These two numbers correspond poorly when quantifying the rate of reduced fuel for this mode. This incoherence represents uncertainty to these numbers.

However, variations in work duties, crew practice and time pressure may cause the differences observed. Based on these conditions, the reduction factor of 20% from 2015 data is decided to be used further.

From 2012 to 2015 the vessel operates close to 28% in Transit low speed and 1% high speed. In the sampling period, from July to December 2016, the vessel operates 37% in Transit low speed and close to no time in Transit high speed.

When operating in Transit HI, 3 to 4 generators are running at medium to high load with a speed of approximately 15 knots. In this mode only peak saving is implemented.

Operating in Transit LO the speed is approximately 11 knots and is considered to be the economical speed. Under normal conditions two generators are operating at medium load at this mode. For Transit LO the start-stop application are suitable but as described in previous page, this was not operative during the time represented by the data. Therefore, possible reductions must be linked to peak shaving, in this mode.

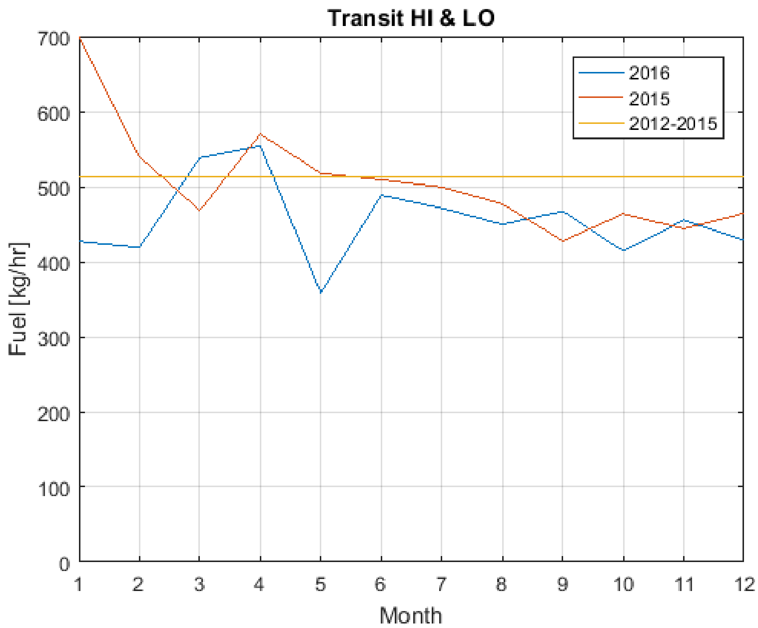


Figure 34: Fuel consumption in transit mode for the respective periods [59].

Figure 34 shows the fuel consumption for the transit mode of the periods covered by the data. This is when the vessel operates in steaming between operation sites and to shore. The blue line represents the fuel consumption in 2016, red line the fuel consumption in 2015 and yellow the annual average consumption in 2012-2015, given in fuel per hour.

The average fuel reduction during the sampling period in 2016 is 12% when comparing to annual average of the 2012-2015 data. Despite saving compared to these data, reduction is marginal when comparing to the consumption in 2015. The average fuel reduction is then 3% and does not correspond well with 12% fuel reduction found from 2012-2015 data. This incoherence challenges the certainty related to the numbers the data sets provides.

The fuel consumption varies for each month, and this can indicate unfavorable practices by operators. The vessel crew works on a three weeks on, and three weeks off schedule. This makes it challenging to imply correlation between operation practice and the variating fuel consumption as the fuel consumption is presented in monthly average values.

The influence of waves, currents and wind directions are assumed to be significant in this mode and further increase uncertainties associated with the data. The information at hand, both from crew members and AIS data, indicates that the vessel has low level of variation between work duties and area of operation during 2014 to 2016. Based on the conditions the data represents, the rate of 3% is considered to be in the true range of reduction in fuel consumption for this mode.

Station keeping reflects the time operated in DP and Standby which are operations at the field. These two operation modes are divided by high and low redundancy requirements. This is also implemented in the BS by increasing the SOC when operating in DP to assure enough energy available in the battery in case of failure. From 2012 to 2015 the vessel operates 41% of the time in DP and 2% of the time in standby. In the sampling period the vessel operates 24% of the time in DP and close to no time in standby. As these operational modes are closely linked together, they are represented as one category. Often when operating in DP a set of engines are running at low loads to fulfill the requirements of redundancy. Therefore, spinning reserve is applicable in addition to peak shaving.

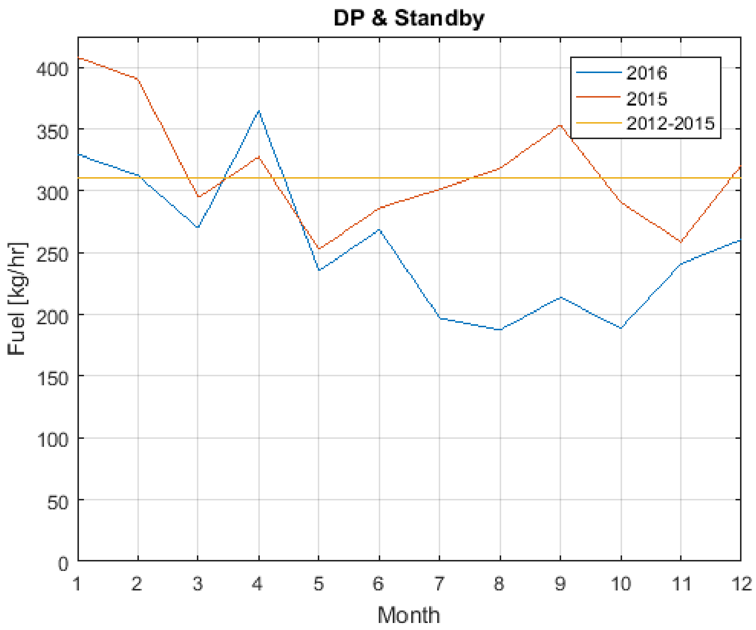


Figure 35: Fuel consumption in station keeping mode for the respective periods [59].

Figure 35 shows the fuel consumed when the vessel operates in station keeping mode for the gives time periods. The main observation is the low fuel consumptions during the sampling period shown by the blue line, compared to the 2015 and 2012-2015 data. The 2015 data also looks to comply better with the historical average in this category, compared to transit and harbor. The explanation to this may be that the work related to these modes has been similar from 2012 to 2015. It shows significant reduction of fuel consumption after applying the HBS might be explained by that this mode utilizes the power system of the vessel poorly. As a result of the redundancy requirements a set of generators are running, thus low loads on each generator and high SFOC.

This mode gives an average saving of 28% in the sampling period compared to the 2012-2015 data. The reduction relative to 2015 data is 26%. Thus in this modes the fuel reduction between both data sets corresponds well. Compared to transit and harbor mode, the reduction rate in station keeping represents less uncertainties.

The variations can be caused by several factors. There might be by different operation pattern within the operators of the vessel. But the data available does not give a conclusion basis for this. The fuel consumed looks to be lowest in July, August and October and increases in the last winter months. This may come from calm weather which leads to small utilization of the power system, thus gives greater saving. In the winter months, the vessel will be exposed to higher environmental loads, resulting in higher utilization of the power system, thus lower saving. In DP & Standby mode the environmental variations will be more dominating as the power system works to keep the vessels position in any sea state, in these modes. Due to asymmetrical shape of the vessel, the directions of the loads will contribute to different power demand to hold the position of the vessel. Based on these conditions the reduction rate is concluded to be 26% for DP & Standby mode.

That 2012-2015 data covers a longer time period of fuel consumption than the 2015 data. Comparing monthly fuel consumption with annual fuel consumption gives additional degree of uncertainty. This is because the annual fuel consumed for a vessel vary from season to season and the sampling period is six months. For that reason, the data from 2015 and 2016 are considered to be the most reliable data, as the monthly fuel monitoring started in 2015.

The data covers late summer, autumn and early winter, when the system was fully operational. It is known that small incidents have occurred to the battery system. Details for time of occurrence have not been provided. When issues occur, it can affect the crews thrust to the HBS and can further lead to less utilization. This is because it is up to the operator to decide when and how to use the BS.

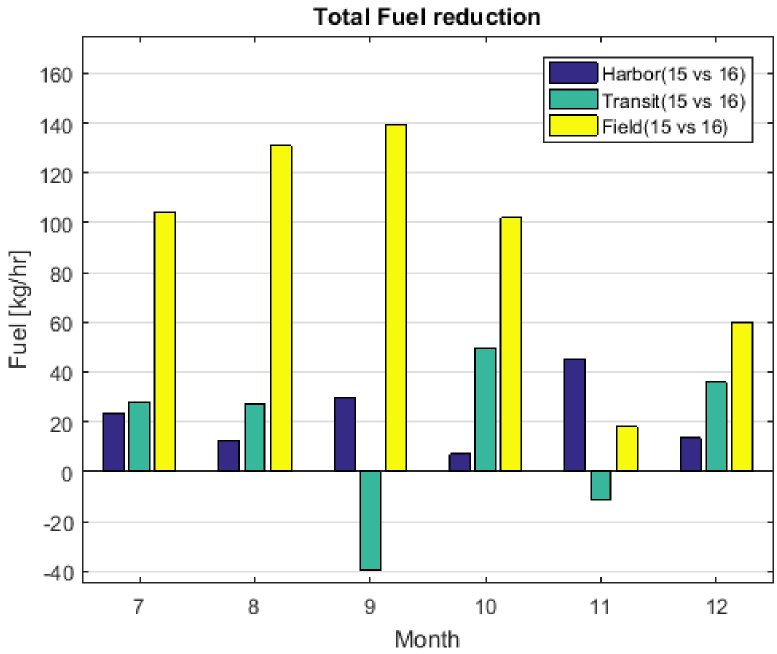


Figure 36: Monthly differential in fuel consumption between 2016 and 2015 in the respective modes.

Figure 36 shows the difference in fuel consumption in 2016 compared with 2015. The main observation is that operation at field are the highest and most stable fuel saving, compared to harbor and transit. This saving is also supported in the same range when taking the difference from 2012-2015 and 2016 data, which is not the case for harbor and transit. This means that the fuel saving related to the vessel operating in harbor and transit has more uncertainty compared to when operating at field. The monthly difference in fuel consumption from 2012-2015 and 2016 can be found in Appendix B.

Saving in transit and harbor vary more from month to month. The inconsistent reduction in consumption makes it challenging to conclude with a rate of reduction related to these modes. In addition, the difference when comparing to 2012-2015 gives indications of higher saving than when comparing to the 2015 data, and increases the uncertainties to the numbers. The harbor mode indicates saving all months, but is highly variating from month to month in the figure. The transit has in average close to no significant saving. Data that includes start-stop mode may reveal further potential for fuel reduction in these modes with the HBS.

Based on these data and Figure 36 results in the following reduction rates: harbor, 20%; transit HI & LO, 3%; and DP & Standby 26%. In the sampling period the vessel operated close to no time in Transit HI and Standby, because of that the reduction rates for these modes is found from the mode related average SFOC and is shown in Appendix B. The following reduction rates is found: harbor, 19%; transit LO, 3%; and DP, 32%. These reduction rates give enough information to calculate the unknown reduction rates. This resulted in the following reduction rates: Harbor, 20%; Transit HI, 3%; transit LO, 3%; DP, 32%; and Standby, 20%.

Table 9 contains the calculated annual reduction in fuel consumption for each moth with the HBS. The calculations are based on the fuel reduction rates, from known average fuel consumption for each mode and the time the vessel operated in each mode. The operation distribution profile for the vessel in this table is based on data from 2012 to 2015. This resulted in an annual fuel reduction of 473.1 ton and corresponded to 17% overall fuel reduction. This will be referred to as Scenario 1. The overall fuel reduction consists of 370.5 ton LNG and 102.6 ton MGO.

The theoretical calculation method done in last section was based on the same operation distribution profile as Scenario 1. The fuel reduction in each mode corresponded acceptable with the reduction rates found based reduction rates from the sampling period and is shown in Table 9. Despites many assumptions the theoretical calculation method resulted in 14% overall fuel reduction included start-stop, peak shaving and spinning reserve. To comparison, Scenario 1 gave an overall fuel reduction of 17%. This is higher than expected from the theoretical calculation method, despite the sampling period does not including start stop mode. The theoretical is concluded to give good and conservative indications of what range of reduction in fuel consumption a vessel can expect, based on this comparison. This shows the importance of performing calculations before investing in HBS. Because scenario 1 is based on operation profile from 2012 to 2015 the reduction of 17% overall fuel reduction is most likely the result of the HBS in a long perspective.

Table 9: Scenario 1 is estimated reduction in fuel consumed based on the operation profile from 2012 to 2015, reduction rates from comparing 2015 to 2016 and average fuel consumption related to each mode.

Mode	Distribution profile 2012-15		Reduction rate 2015		Reduction (ton)	
Harbor	29 %		20 %		72.0	
Transit HI & LO	1 %	28 %	3 %	3 %	38.2	
DP & Standby	41 %	2 %	32 %	20 %	362.9	
			Red fuel		17 %	473.1

Table 10 contains the calculated reduction in fuel consumption with the HBS based on the operation profile in the defined sampling period from July to December 2016. This resulted in a total reduction in annual fuel consumption of 353.2 ton and corresponded to 13% overall reduction. This will be referred to as Scenario 2. The total reduction of fuel consist of 276.8 ton LNG and 76.4 ton MGO.

Table 10: Scenario 2 is estimated reduction in fuel consumed based on the operation profile from July to December2016, reduction rates from comparing 2015 to 2016 and average fuel consumption related to each mode.

Mode	Distribution Profile 07-12.16		Reduction rate 2015		Reduction (ton)	
Harbor	39 %		20 %		94.3	
Transit HI & LO	0 %	37 %	3 %	3 %	49.7	
DP & Standby	24 %	0 %	32 %	20 %	209.3	
			Red fuel		13 %	353.2

Comparing the two scenarios, the time distribution profile of the vessel deviates significantly and is the reason for the low fuel reduction in Scenario 2 and the reduction rates from the sampling period. The time spent in harbor goes from 29% to 39%, and estimated reduction increases to 94.3 ton. Time spent in operating in DP & Standby decreases from 43% to 24%, which results in less fuel saving. Since these modes contributes to significant fuel saving, the total fuel saved decreases from 362.9 ton to 209.3 ton.

The fuel reduction found from Scenario 1 is the expected from the HBS in a longer perspective because it is based on three years of the vessels operation history. The overall saving fuel reduction found in Scenario 2 is the actual reduction in the period where the HBS has been operative. This is found to be in the range of 13% and 353.2 ton overall annual fuel reduction. This provided a lower result than expected mainly due to a lower portion of DP mode in the sampling period. Scenario 2 is the concluded annual fuel reduction of the HBS from the sampling period from July to December 2016. The data shows clear reduction in fuel consumption, even though the sampling period only covers six months of fully utilized HBS. And the scenarios show that the saving potential would be higher on average, given a more beneficial operation profile. If the vessel operates a larger portion of operation in DP mode, HBS provides a higher saving.

The contribution of fuel saving whilst the vessel is engaged in start-stop mode remains unknown as there is no available data for quantifying the effect of this mode yet.

7.5.2. Weather impact on consumption

The vessel is operating in an environment where they regularly are exposed to loads due to wind, currents and waves. This section will be looking for possible correlation between the vessel fuel consumption and the wave and wind that the vessel is operating in before and after applying the HBS. Weather data has been obtained for three locations considered to be representative for the vessels operations at field, transit and harbor. Figure 37 shows the area and path of operation for the vessel during 2016 and the three considered weather locations. Information about geographical locations for working operations, is obtained from AIS data received from Norwegian Costal Administration [64]. Figure 29, Figure 31 and Figure 32 shows similar density plots of operation for Viking Energy from 2012 to 2016.The field location shown in Figure 37 is located near Gullfaks, Stadtfjord and other oil fields the vessel has been frequently operating. This weather location represents the vessels operations in DP & Standby. The transit location is selected between the field and shore and represents the vessel operating in transit. The harbor location is selected close to shore outside Mongstad. The wind speed and significant wave height is generated for each of the three locations for 2015 and 2016. The weather data are based on high-resolution Hindcast data named NORA 10 and are considered to have good correspondence with real weather in the North Sea [65]. The weather data are provided by Norwegian Meteorological Institute [60]. Coordinates and more descriptions on how the weather data has been obtained are provided in Appendix C and Appendix D.

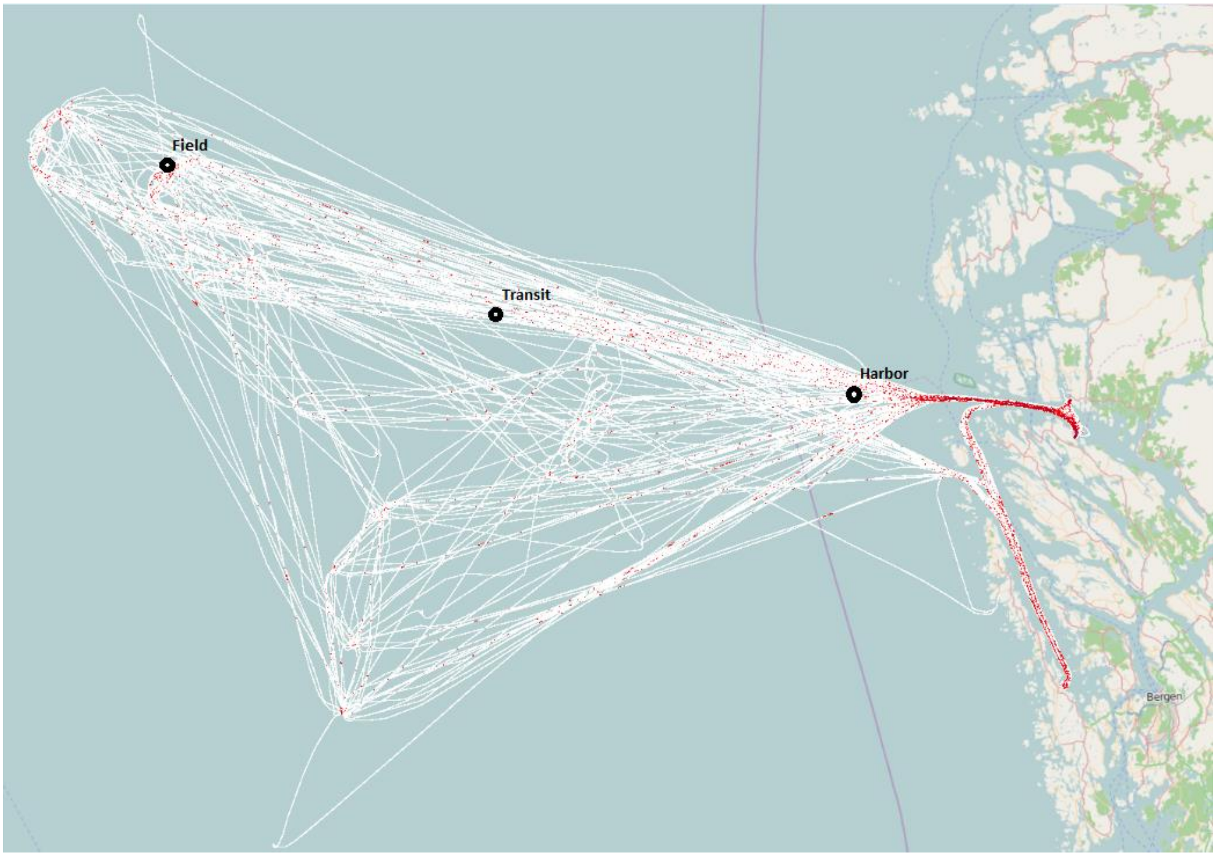


Figure 37: The density plot of the vessel for 2016 including the representative locations for each operation category [64].

Waves and wind are known to add resistance for ships due to pressure difference. In calm weather, added resistance from waves and currents can account for 15-30% of the total resistance [66]. Wind are known to increase drag for to the vessel with respect to the projected area perpendicular to the wind direction, and the relative wind speed [67]. In this thesis, the actual weather is represented statistically by average significant wave height and wind speed. Wind and wave headings are not considered as the vessel travel between shore and the same fields. This ensure that the vessel experience the same amount of fore as aft wind and wave headings during transit.

Weather data and validation

The fuel consumption data from 2015 and 2016 will be compared in the months where the HBS is considered to be fully operated. Consumption for a general vessel tends to be higher during the winter months and significant lower during the summer season [63]. Before the fuel consumption are compared with the weather related to the data set, the data set is compared to the historical trend. Figure 38 shows the historical average wave height and wind speed from 1958 to 2012 together with 2015 and 2016 from July to December. This give information about how the weather was during 2015 and 2016 and possible variations compared to the historical expected.

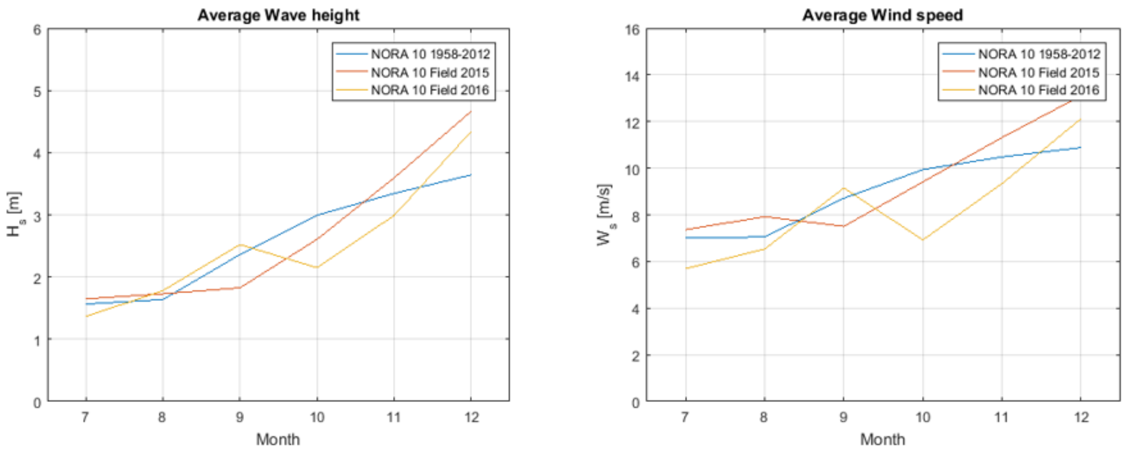


Figure 38: Average monthly wave height and wind speed at field location from 1958-2012, 2015 and 2016 generated from Hindcast NORA 10 model.

The location of field is plotted because the weather was found to have insignificant variations between the locations. For 2016, the average wave height is lower in October and November and higher in December, compared to the historical average. The other months corresponds well with the historical average. The average wind speed is lower in July, August, October and November than the historical average. There is more wind in September and December than in the historical average.

The average wave height is close to expected for all months in 2015. The exception is in September and October the average wave height is slightly lower and in December the average wave height is significantly higher compared to historical average. The average wind speed corresponds well with the average historical wind speed except for September and December is slightly lower and higher respectively.

Summing it up it appears to better weather during 2016 than in 2015 compared to the historical average weather based on historical average. This means that the vessel have slightly less environmental loading in the period where the HBS is applied than in the previous year. This may give a slightly better condition for fuel reduction of the HBS than if the weather was closer to historical average and 2015.

Weather based consumption

This section presents and discusses the fuel consumption of the vessel in relation to average wave and wind values for each mode of operation. Figure 39 presents fuel consumption in 2015 and 2016 on the left and right side respectively. The fuel consumption for both periods is compared to significant wave height and wind speed, all which are given in monthly average values in harbor mode. The fuel consumption in 2015 shows no sign of correlation with both average wind speed and average wave height. However, it can be observed great variations on fuel consumption from month to month, while wave height and wind speed increases steadily towards the winter.

The fuel consumption in 2016 indicates slightly to be affected by the weather variations. This is not observed from the 2015 fuel consumption data and might be an effect of applying the HBS. In addition, the fuel consumption in 2015 is maintained at a different and higher overall level compared to the consumption in 2016. It is challenging to explain a possible reason for why the harbor mode indicates to be affected by the weather. The fuel consumption for each mode is logged by hand. What mode the vessel is operating in is a subjective decision made by the operator, and will increase the uncertainty of the modes and numbers [16]. This mode is considered to have little correlation with the weather based on these data presented.

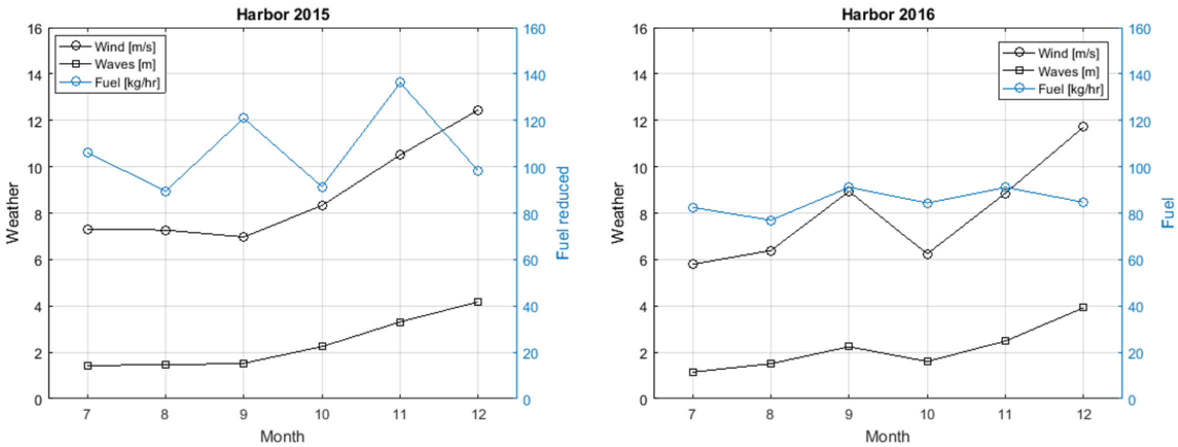


Figure 39: Fuel consumption in 2015 and 2016 compared to wind and waves in the selected Harbor point.

Figure 40 shows the fuel consumption by the blue line in 2015 and 2016 on the left and right side respectively. The average fuel consumption, average significant wave height and wind speed are plotted, all which are given in monthly average values in Transit HI & LO mode. The wave height and the wind speed in 2015 are very close to historical expected trend, which is a slow and steady increase towards the winter as discussed earlier. The fuel consumption looks to be of random values and indicates no link to the weather. The highest fuel consumption can be observed in July, which is the month with the lowest average wind speed and wave height.

The fuel consumption in 2016 is also be observed to be in the highest range in July, in a month of low average wave height and wind speed. The fuel consumption appears to be in the same range in September and November, which both are associated with high average wind speed and wave height. The fuel consumed looks to be slightly affected by the weather in transit mode, with July and December as an exception. The overall fuel consumption appears in a slightly lower level in 2016 than in 2015, this may be a result from an overall better weather in 2016 than in 2015. Despite the fuel consumption level, the fuel consumption looks to be slightly more correlated by weather after installation of the HBS. That is if September, October and November fuel consumption is observed with wind and wave values in 2016.

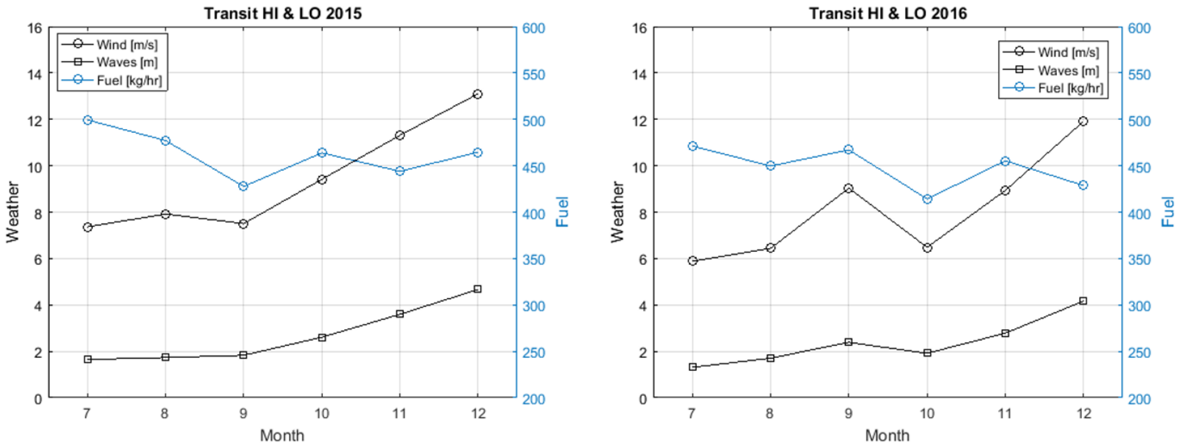


Figure 40: Fuel consumption in 2015 and 2016 compared to wind and waves in the selected Transit point.

In harsh weather in transit mode the vessel reduces the speed to maintain control of the vessel motions. This can be a possible explanation of why the fuel consumption per hour is lower in December, despite higher average wind speed and wave height. The fuel consumption is considered to be slightly correlated to the weather conditions in transit mode.

The modes related to work at the field, DP and Standby are shown in Figure 41 for 2015 and 2016 at left and right side. The average fuel consumption, average significant wave height and wind speed are plotted, all which are given in monthly average values in DP & Standby mode. The overall fuel consumption during the months in 2015 is at a considerable higher level compared to 2016. The average fuel consumption in 2015 reviles no systematic pattern in relation to significant wave height and wind speed, from month to month. The highest fuel consumption is observed in September, while the weather is benign. The lowest average fuel consumption appears in November where the average wind speed and wave height are among the highest. The fuel consumption in 2016 reveals a clear correlation with the average wave height and wind speed when operating in this mode. The fuel consumption is high in the months where the average wave height and wind speed is high and vice versa. This appears to be true for all months covered in the sampling period. A possible explanation is that when the vessel is maintaining position at open sea the environmental impact involves significant forces regardless of direction. It appears to have greater influence in station keeping compared to harbor and transit mode.

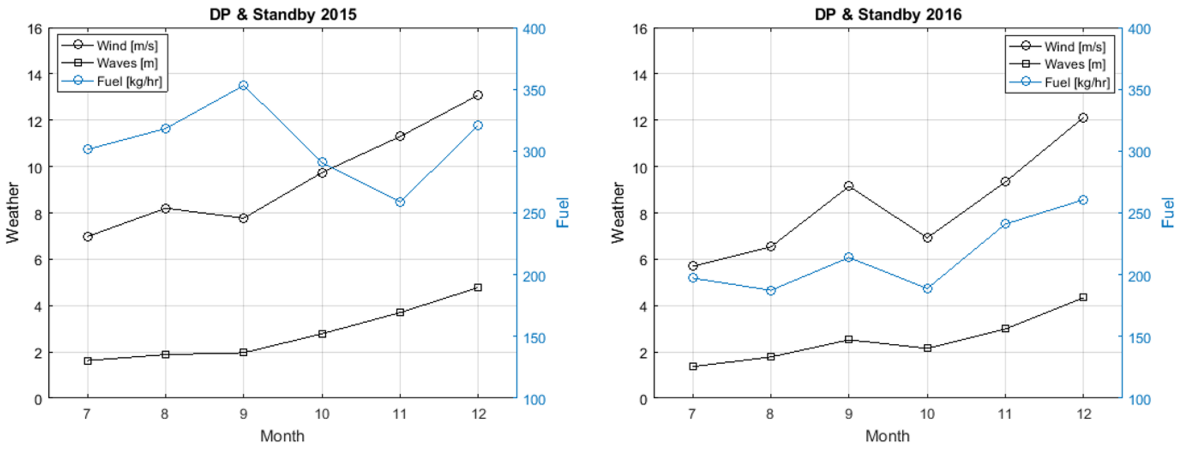


Figure 41: Fuel consumption in 2015 and 2016 compared to wind and waves in the selected Field point.

To summarize the two last sections the weather was found to be more benign in 2016 than 2015 compared to historical average wave height and wind speed. This indicates slightly favorable weather for lower fuel consumption in 2016 compared to 2015. The average wave height and wind speed was found to have little correlations with the fuel consumption when the vessel operated in harbor mode. When operating in transit the fuel consumption reveals some months of correlation with weather. The reason is likely to be wave and wind direction is varying making head wind and tail wind random. Based on the conditions the fuel consumption in 2015 was not found to be correlated with the weather conditions when operation in station keeping. When the vessel operates in station keeping with the HBS in 2016, the fuel consumption revels a clear correlation with the weather conditions. The HBS system is found to have a significant positive effect on fuel reduction in change in weather conditions when operating at field. The system particularly has a positive effect in calm weather conditions. In addition, the fuel consumption is maintained at a significant lower level in 2016 compared to 2015. The HBS adds redundancy in a passive manner, which involve less fuel wasted, more predictability in fuel consumption related to the weather conditions when operating in station keeping.

7.5.3. Economical

The economical side of the HBS is important for all parts of interest and will be discussed in the following section.

For the technology to be viable, providing reduction in fuel consumption alone is not sufficient. The reduction in fuel consumption should also seek to be in a range that defends the capital expenditure (CAPEX) related to the HBS within the intended lifetime of the system. The CAPEX of the BS involves system modifications, new components, and work execution to get the system up and running. From section 7.5.1, the fuel consumption of the vessel before and after applying the HBS has been analyzed. This resulted in two scenarios of reduction in fuel consumption based on two operation profiles for the vessel and is listed in Table 11. Scenario 1 showed 473.1 ton fuel reduction per year based on the operation profile for the vessel from 2012 to 2015. This corresponded to 370.5 ton MGO and 102.6 ton LNG. Scenario 2 showed 352.2 ton reduction in fuel consumption per year based on the vessels operation profile from July to December 2016. Which corresponds to 276.8 ton LNG and 76.4 ton MGO. Scenario 2 is considered to be the actual fuel reduction since it is based on the operation profile for the sampling period, while scenario 1 is expected in a long term.

Table 11: The two fuel reduction scenarios, from historical and sampling period operation profile respectively.

	Total reduction (ton)	LNG (ton)	MGO (ton)
Scenario 1	473.1	370.5	102.6
Scenario 2	352.2	276.8	76.4

This discussion focuses solely on cash flow related to the vessel. Incentives and funding are described in section 2.3 and are not accounted for in this economical assessment. The system includes a battery of 653 kWh, power electronic and work execution to integrate the system to the existing bus. The prices and estimations for reduction in maintenance are provided by Westcon [16]. The installation of the HBS is assumed to be executed during a scheduled yard stay, therefore cost related to the vessel of hire are not accounted for. Off hire means that the charter is not paying hire for the vessel. The estimated cost of the fuel saved are based on the current LNG and MGO price of 5.24 USD/MMBtu and 492 USD/ton [68] [69]. This corresponds to 2088.5 NOK/ton and 4172.2 NOK/ton. The currency used was 8.48 USD/NOK per 26.03.17. The initial fuel price are assumed to be constant in the estimations. The maintenance cost is estimated to be reduced by 3.0 MNOK over the lifetime of ten years due to 20% less running hours on engines [16]. Time will show if the estimate appears to be in the correct range. All numbers and estimations are provided in Appendix E.

Scenario 1

Figure 42 represents the cash flow over the intended lifetime of the HBS based on scenario 1 with a waterfall diagram. The negative red bar represents the CAPEX regarding system and execution cost and take place in year zero. The system is assumed to start with the annual saving in year one. The lifetime of the system is intended to be 10 years. The blue bars represent annual saving from reduced fuel consumption and reduced maintenance. This corresponds to 1.54 MNOK savings including 0.3 MNOK contributed from reduced maintenance. The annual income has been accounted for Net Presence Value (NPV) with an expected return rate of 3%. Based on these conditions the NPV calculations of the investment resulted in 13.13 MNOK, corresponding to a payback time of 9 years and 2 months.

Figure 42: The cash flow for scenario 1 with the current fuel price and a return rate of 3%.

This shows that the HBS provides a positive economical business case with the current fuel prices based on the vessels operation profile from 2012 to 2015. The economical outcome beyond ten years depends if it is decided to install new battery or continue operating on the original.

Figure 43 shows the calculated NPV for changes in the fuel price for scenario 1. The changes in fuel price involves the current fuel price, 20% decrease, 20% and 40% increase, which gives an NPV of 13.13, 11.01, 15.24 and 17.36 MNOK respectively. The NPV calculations involves a 10 year perspective and a rate of return of 3%. If the fuel price are assumed higher than the current, the NPV is increasingly more attractive. In case of lower fuel price, the NPV is negative according to the given conditions.

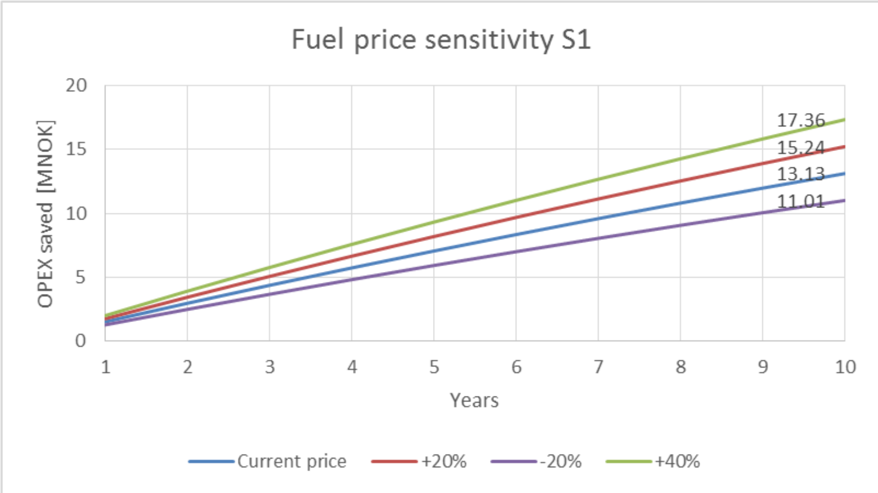


Figure 43: Sensitivity for scenario 1 of the current fuel price, ±20% and 40% price change with a rate of return of 3%.

Scenario 1 shows that the economical outcome of the investment is very dependent on the fuel price. The profit is acceptable for the current fuel price in the intended lifetime. The range is covered in high and low fuel price with 15.24 MNOK and 11.01 MNOK the payback time is 7 and 11 years to break even the initial investment based on the conditions involved in scenario 1.

Scenario 2

Figure 44 shows the NPV calculations and contains same characteristics as Figure 42 in the previous section. The difference is that this calculation is based on scenario 2 and the reduced fuel consumption related to this. The cost saved related to annual maintenance is 0.3 MNOK, and hence reduced fuel consumption is 0.9 MNOK each year. This gives an annual saving of 1.2 MNOK based on the current LNG and MGO price. The rate of return is set to 3% and gives a NPV of 10.44 MNOK of the investment with a 10 year perspective, which corresponds to a payback time of 11 years and 10 months.

Figure 44: The cash flow for scenario 2 with the current fuel price and a return rate of 3%.

The current condition gives a negative NPV of 1.56 MNOK of the investment, which again means that the operation profile from the sampling period in 2016 is not optimal for the HBS to give economical profit of the investment. Figure 45 shows the calculated NPV for various changes in the fuel price for scenario 2. This involves the current fuel price, 20% decrease, 20% and 40% increase results in an NPV of 10.44, 8.87, 12.02 and 13.60 MNOK respectively. This involves a 10 year perspective and a rate of return of 3%. If the fuel price is assumed higher than the current, the calculated NPV is marginally positive for 20% increase and positive for 40% increase. In the case of lower fuel price, the NPV is even lower than the current fuel price in the given conditions.

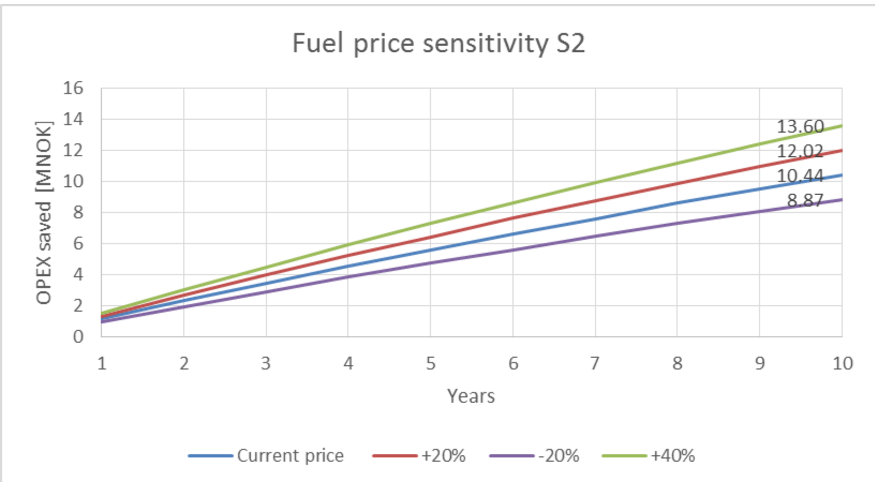


Figure 45: Sensitivity of change in fuel price for scenario 2 with the current, $\pm$20% and 40%.

Summed together, the economical calculations show that the business case related to the HBS is highly dependent on the fuel price. With the current fuel prices, the result from scenario 1 and scenario 2 was 13.13MNOK and 10.44MNOK, respectively in a 10-year perspective.

Scenario 1 is the expected outcome in a longer perspective and is based on the operation profile from 2012 to 2015. It gave a positive NPV of 1.13 MOK when compared to the CAPEX of 12 MNOK if the fuel price remains on the same level. Resulting in a payback time of 9 years and 2 months. Scenario 2 is considered to be the actual reduction in fuel consumption for this vessel, as this is directly the operation profile during the sampling period. This gave a negative NPV of 1.56 MOK when compared to the CAPEX of 12 MNOK if the fuel price remains on the same level. Corresponding to a payback time of 11 years and 10 months.

Based on linear interpolation between the scenarios this vessel is found to maintain a minimum overall fuel reduction of 15% to break even the initial investment in a 10-year perspective. The operation profile of the vessel in the sampling period included 24% of the time in DP mode and gave a negative economic result for scenario 2. The operation profile of the vessel from 2012 to 2015 the vessel was operating 41% of the time in DP mode and gave scenario 1 a positive economic result. Assuming linear fuel saving and that fuel saving are only a function of the time spent in DP mode, linear interpolation gave a minimum threshold of 34% operation time in DP mode for a vessel to meet the overall fuel reduction of 15%.

After the lifetime of the battery is reached, the battery must either be replaced or continue to be utilized. If the battery is continued to be utilized, the capacity of the battery might be insufficient to be used as a spinning reserve and the fuel reduction will be lower. If the battery is replaced, in the current case the battery cost represents roughly half of the CAPEX. Based on section 5.5 the batteries predicted on the market 10 years ahead are most likely to be cheaper. Probably this can result in a more attractive business case seen in a perspective beyond 10 years.

7.6. Other important benefits

The next two sections will be assessing the reduction of environmental impact and possible reduction of maintenance as an effect of the HBS.

7.6.1. Environmental

When assessing the environmental impact, there is mainly two areas of interest. First, the reduced emission to air as a result of the HBS. Second, the environmental impact caused by production of the battery and power electronics.

Emission to air

When the HBS is applied to the vessels power system, it results in less fuel consumed as found in section 7.5.1. This again leads to reduced environmental impact as the numbers of engine running are reduced, and the remaining engines operate on a more efficient level. The amount of emission for a combustion engine is a function of the engines load level, and the most reliable estimations are found by the power demand and the current SFOC. This is a bottom up approach. This method is not applicable to this case as data covering the power demand and the SFOC for the case is not obtained. For this case, the environmental impact saved by the HBS will be estimated based on the amount of fuel saved. This is a top down approach.

The annual fuel reduction based on scenario 2 which again is based on the operation profile of the sampling period corresponded to 276.8 ton LNG and 76.4 ton MGO. The heating value of LNG and MGO is 13 kWh/kg and 42.7 MJ/kg corresponding to 11.86 kWh/kg, respectively [70] [71]. The reduced LNG are assumed to be consumed at high loads corresponding to an efficiency of 0.44 [39]. The reduced MGO are assumed to be consumed at low loads, and a corresponding efficiency of 0.22 [41]. This is because the dual fuel (DF) engines are designed to switch over to MGO at low loads as described in section 4.4.3.

Section 3.2 obtained emission factors in g/kWh for each substance with a Global Warming Potential (GWP) related to MGO and LNG consumed at high and low loads. When the amount of pollutant is estimated, the GWP factors are multiplied to reflect the CO_2-eqivalent.

The emission of CH_4 is very dependent on the load level when operating on LNG. The methane leakage is high if the DF engine operate on LNG at low loads [39]. Methane contributes to 25 time's greater environmental impact than CO_2. Thus, if the vessel operates at low loads in LNG, the emission factors for methane presented in section 3.2 should be adjusted up. All numbers and calculations obtained for emission to air for both scenarios is provided in Appendix F.

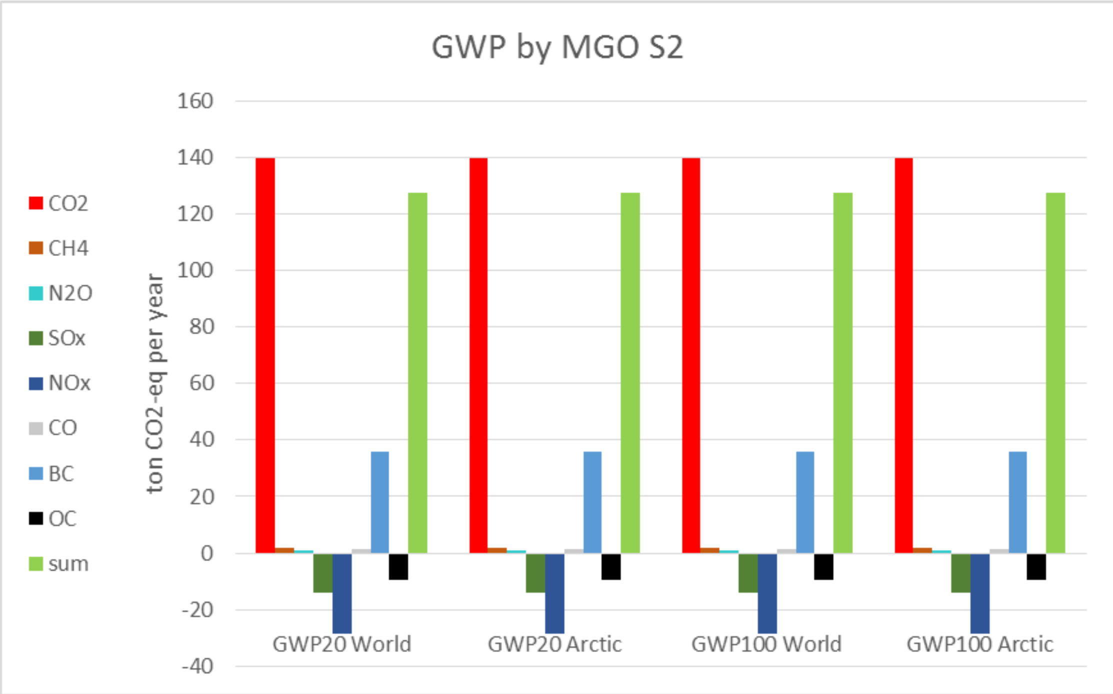


Figure 46: GWP reduced based on fuel saved in 20 and 100 years perspective for non-Artic and Arctic regions.

Figure 46 shows the result of the saved GWP by operating with the HBS. This estimation is based on the fuel saving from scenario 2. The GWP are calculated according to Arctic and Global factors in 20 and 100 years perspective.

The world factors is an average value from the four world regions: East Asia, Europe, North Africa, North America and South Asia and is considered to be representative emissions located in the North Sea. And the Arctic factor is considered to be representative for emissions located in the Barents Sea [9].

The positive bars represents pollutants with a warming effect, and the negative bars represents pollutants with a cooling effect. Each bar shows the ton CO_2-eq saved from each pollutant, and the light green shows the total reduced GWP for each region and time perspective. The total reduction in GWP for 20 years world and Arctic, respectively, are 1299 ton CO_2-eq and 1334 ton CO_2-eq per year. The total reduction in GWP for 100 years World and Arctic, respectively, are 1020 ton CO_2-eq and 1001 ton CO_2-eq per year. The most common unit to provide the GWP in, is a 100-year perspective with World specific factors according to IPCC 2013 report [28].

As the vessel of the case operates on the west coast of Norway, the World factors are considered to be representative for this case. The emission reduction as a result of the HBS is concluded to be 1020 ton CO_2-eq per year based on the fuel saved in scenario 2. This is the saved environmental impact of the HBS.

There will probably be a saved cost for the shipping company due to reduced emission taxes, but this has not been considered in this assessment

Emission by battery system

This section will discuss the environmental footprint concerning the production of the battery system involving the battery and the main power electronics. Producing batteries involves metals with environmental concerns and production processes that require great energy.

The analysis is based on numbers provided by [72] study involving cradle to gate life cycle assessment regarding emission from battery production, battery specifications by Westcon P&A [10] and study done by [48]. The study from [72] analyzed the amount of CO2-eq during production of NCM lithium-ion battery pack corresponding to an electric car. This chemistry is the same as used in the vessel of the case. Batteries for cars and marine applications will be different considering internal design, packing etc. this is not taken into account for this case. They found the global warming impact ranged from 172 to 487 kg CO2-eq/kWh where lowest and highest value reflects best and worst case of production. The typical battery installed in the case is 653 kWh and gives the total CO2-eq of 320 ton CO2-eq based on worst case of production and a 100 year GWP perspective. Compared to [48] study they found battery for the PSV only contributes to 285 kg CO_2-eq/kWh. The batteries for this case is produced in South Korea, the worst case of production, 487 kg CO_2-eq/kWh from [72] will be used. From [48] the power electronics for a PSV was found to represent 30% of the GWP from the battery, this is assumed in this estimation.

According to Scenario 2 in section 7.5.1 the annual fuel reduced by 276.9 ton LNG and 75.4 ton MGO. Pervious section concluded this to reduce the environmental impact by 1020.0 ton CO_2-eq per year according to World factors in a 100-year perspective. Hence 10200 ton CO_2-eq over the intended lifetime of the HBS. Figure 47 represents the reduced environmental impact due to fuel saved compared with the impact from production of the battery and the power electronics. Over ten years of operation the impact saved due to fuel reduction is 10 200 ton CO_2-eq. The GWP caused by production of battery and power electronics is payed back after 4.9 month of operation with the HBS.

It becomes clear that the impact related to production are very small when related to the impact reduced by operation of the HBS. For further details and scenario 1 see Appendix G. The environmental impact from production of the battery and power electronics are concluded to be negligible compared to the fuel savings from utilizing the HBS.

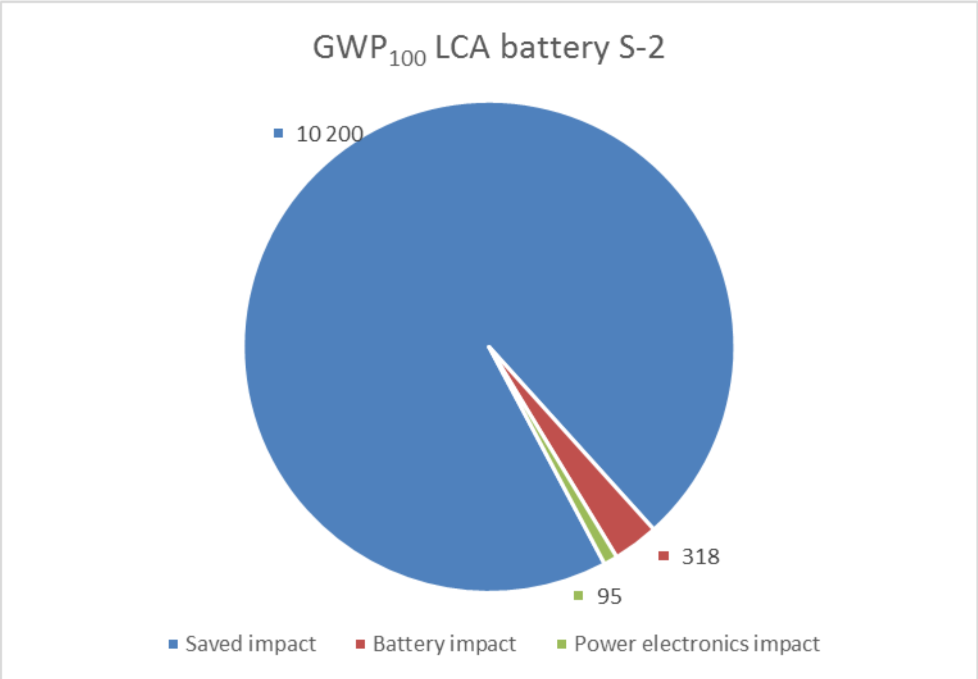


Figure 47: Impact by production of the battery system compared with saved due to fuel reduction in scenario 2 during 10 years of operation, in ton CO_2-eq.

7.6.2. Maintenance

Maintenance and overhauls of machinery are done in time intervals, which are provided by the manufacturers. A software logs online hours and when certain numbers of online hours are reached, the technicians are informed that maintenance must be done. Online hours are here defined as the number of engine running hours. If four engines operate in one hour, the result is four online hours.

Figure 48 indicates a reduction in online hours, calculated to be 12%, before and after the battery system was installed, from 2015 to 2016. The online hours provided comes from June to October, June deviates from the defined sampling period from July to December, but that is the data available and the battery was operative. The vessel was operative 3455 hrs. in 2016 and 3572 hrs. in 2015 in the considered period, corresponding to 3% less operative time in 2016. Assuming a linear reduction in online hours with operating time, the average reduction of online hours is 9% (12%-3%) after introducing the hybrid battery system.

The data gives good indications of reduction. With more comprehensive data the reduction can be stated with higher certainty. There may also be data from more vessels. If the time reveals greater reduction, this will increase the economic benefits.

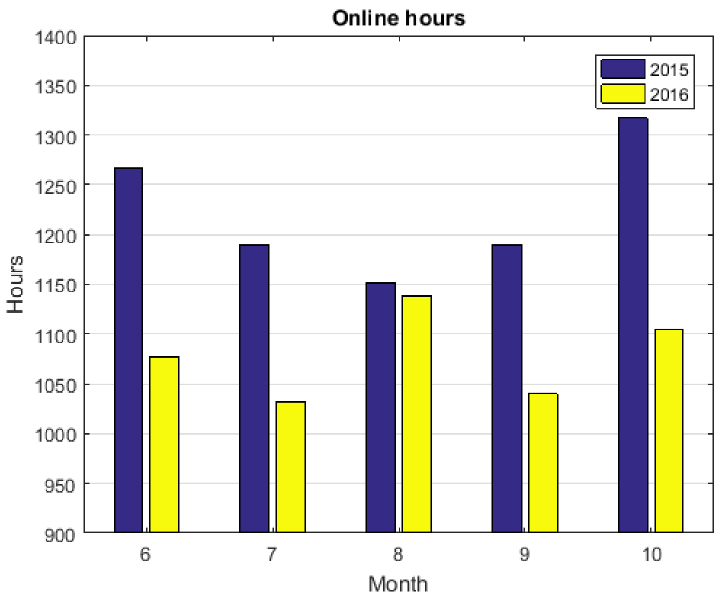


Figure 48: Online hours of the four engines from each month in 2015 and 2016 [59].

7.7. Other important challenges

The following section will describe challenges related to the HBS of the case and in general. This involves crew training, performance reduction of the battery and generation development of engine efficiency.

7.7.1. Crew experience

The general preferred work practice within a shipping company is to a large extent defined and enforced by the onshore department. When introducing new technology onboard the vessel it is highly important to maintain actual work the same as preferred work practices. The shipping company must aim to standardize the preferred work so that it is well known by the crew and is reflected in the company policy [73]. The fact that preferred and actual work differs may be a result of the effect Snook described like this "Over time, globally designed by locally impractical procedures lose out to practical action when no one complains. Gradually, locally efficient behavior becomes accepted practice" [74].

Set in a vessels perspective the crew can be regarded as an isolated community, and may contribute to a slow and steady drift of local practice from written procedures [73]. The battery system has been operative for more than one year. The battery system requires new procedures and a new and different area of crew competence compared to traditional machinery.

The system is designed to have similar interface as a conventional generator. Still the crew must learn how to react to alarms, signals and symptoms from the HBS. During the time of operation there have been several occasions, indicating lack of knowledge of the HBS procedures and behavior. The consequence can affect the battery performance negatively immediately and in a long term perspective. Due to exposure to temperatures, SOC, humidity and so on outside of the set values. This can be a challenge when new technology is introduced, and it is recommended as an area of focus to secure optimal operation and performance of the system. In order to maintain the fuel consumption and battery system functionality it is important to prioritize training of the crew and information about the best work practice. This will assure good knowledge, ownership and interest. Giving the foremen and the team authority to adjust the procedures according to experience and changes in work situation, have been successful in the nuclear power plant industry. The work force supported the procedures and the procedures became self-corrected [75]. This strategy could be suitable in the shipping industry related to HBS and also for the conventional system within the vessel.

A visit on the vessel in February 2016 gave the impression that the crew was positive to the new technology. A captain stated that maneuvering the vessel is "Like driving a Tesla" [1]. This gives good indication of the agile and response properties of the 95m long vessel.

More specific work and data must be done to assure good quality on this field. This could be to log systematically every occasion of alarm from the system, and followed up by short explanation. It is important to maintain focus on crew training to avoid that procedures and normative behavior drift away from the standards provided by the supplier of the respective systems. And the recommendation is to maintain an active focus on this area. Some ship owners claim to gained good profit from increased focus on this area [76].

7.7.2. Performance reduction

In terms of battery performance, there will be degradation as times goes, due to aging and various cyclic loading. The battery cycle life is defined as the time or the numbers of cycles before the battery capacity falls below 80% on initial capacity. Predicting the performance development involve extensive simulation based on experience of performance degradation for similar chemistries. Figure 49 shows the result of the simulations done by the battery supplier. It predicts a remaining capacity of 84%, after 10 years of operating in the profile given in Table 12. The battery is then stated to have a cycle life of 10 years [50].

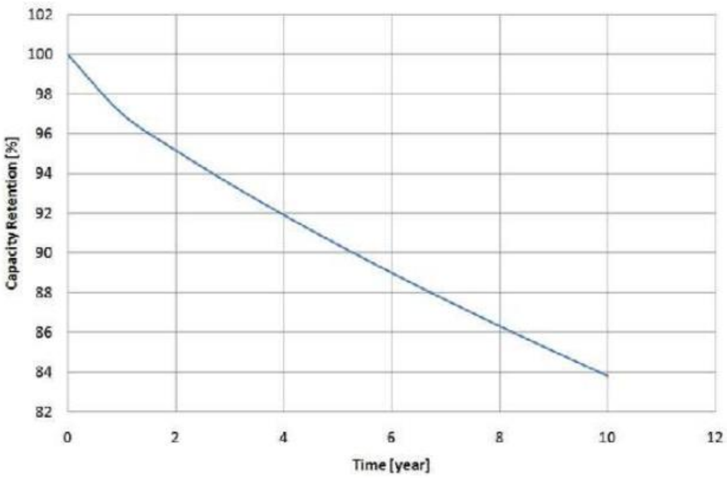


Figure 49: The curve of capacity degradation for the battery over the lifetime, simulated [50].

Table 12: Operation profile for the vessel assumed in the simulations, ON/OFF refers to start stop [50].

Battery Load Profile	% of time
Transit	19.0%
DP- Bad Weather	15.5%
DP - Good Weather	46.5%
ON / OFF	19.0%

Little experience is sustained related to operate a battery of this size with this kind of operational pattern involving peak shaving, spinning reserve and start-stop mode. Therefore, there is excitement connected to how the capacity will degradant due to loading and aging [16]. A capacity test of the battery is required to be executed annually to determine the State of Health (SOH). The first test was done in April 2016 and gave a result of 102% and the next test will be done during 2017.

$$\left(\frac{648\ kWh \cdot 0.8^2 - 648\ kWh \cdot 0.1^2}{1600\ kW}\right) \cdot 60 = 15.3\ minutes \qquad (7.2)$$

If the aging prediction mentioned above reveals to be true after 10-years, the case of abandonment in a critical situation the battery can provide the system with power in 15.3 minutes as calculated in equation (7.2). If so, the maximum abortion time of 7 minutes will still be fulfilled with a good margin. More years of operation must be obtained to form a good basis for evaluation and conclusion at this area.

7.7.3. Generation development

The hybrid battery technology mainly provides reduction in fuel consumption as a function of how many online engines can be reduced. Further making the residual engines operate at higher MCR resulting in more optimal consumption. Therefore, the fuel reduction is a consequence of less fuel consumed per kilowatt produced and less running engines. As the vessel of the case was among the first LNG fueled PSV, over a decade of engine development have improved overall efficiency, engine control and monitoring [39]. Figure 50 shows the engine profile corresponding to the case, as the first generation, and the state of the art LNG engine. Improvements to the whole power range can be observed. The greatest improvement has been at loads below 40%. This will affect the potential for fuel reduction associated with installing a battery hybrid system.

Note that these graphs come from testing in ideal temperatures, new lubrication and no ship motions [39]. In real operation environment, both curves will probably be higher.

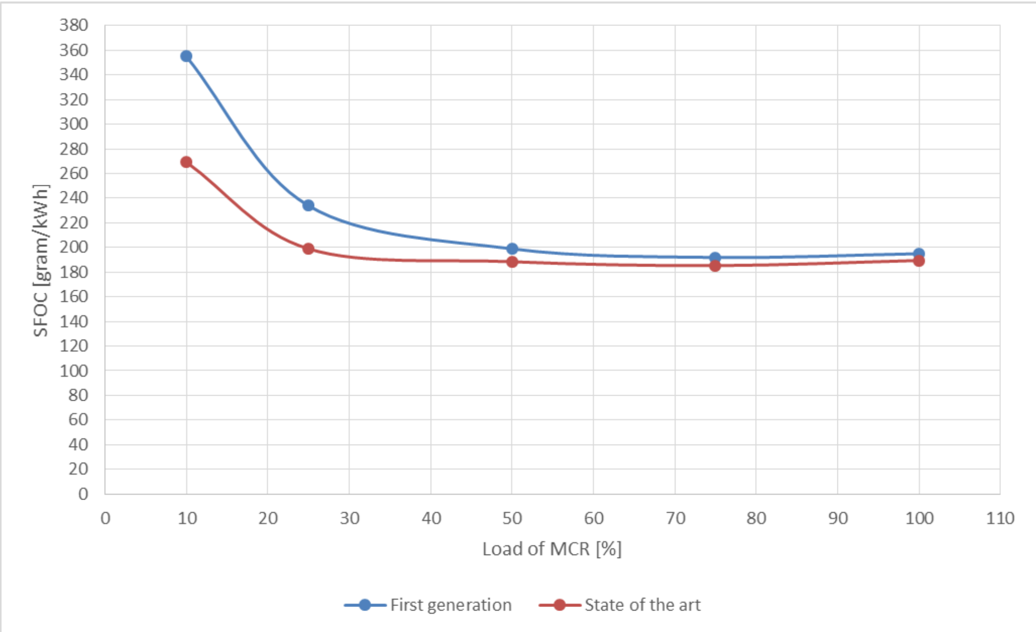


Figure 50: Generation comparison of LNG Dual Fuel from 2003 and 2015 respectively both engines in size range of 2000

Based on the SFOC curve to the state of the art engine and the theoretical calculation method of the fuel reduction, an estimate of the potential by applying a HBS is carried out.

The result is shown in Table 13 and is the same calculation method as in the start of section 7.5.1. The last generation LNG engine was estimated to provide an overall fuel reduction of 8% based on the operational profile from 2012 to 2015, and the same conditions and assumptions as in section 7.5.1.

This indicates that the potential for fuel reduction by installing a HBS can be expected to be lower for a vessel with state of the art power system.

*Table 13: Fuel reduction with the theoretical calculation method and four generators of 2010 kW each before and after implementing the HBS. Based on SFOC for the state of the art DF engine and the operation profile from 2012 to 2015. *improved 3% due to peak shaving mode, ** SFOC set to sweet spot due to start stop mode.*

Conventional setup										
Mode	Hrs./yr.	G_N (kW)	MCR (%)	Total (kW)	No. G	MCR (%)	SFOC (g/kWh)	ton/hr.	ton/yr.	% red.
Transit HI	88	1065	52	4260	4	53	189	0.80514	70.53	
Transit LO	2453	900	44	1800	2	45	190	0.34200	838.86	
DP	3592	300	15	900	3	15	240	0.21600	775.79	
Standby	175	450	22	900	2	22	213	0.19170	33.59	
Harbor	2540	500	24	500	1	25	199	0.09950	252.77	
Sum									1 971.53	
Hybrid setup										
Transit HI	88	1420	69	4260	3	71	191 *	0.78925	66.97	6.4
Transit LO	2453	1800	88	1800	2	45	192 *	0.33523	813.69	6.9
DP	3592	900	22	900	2	22	255 *	0.22262	661.58	18.6
Standby	175	900	44	900	1	45	200 *	0.17460	29.06	23.9
Harbor(start/stop)	2540	500	24	500	1	25	192 **	0.09600	235.43	18.3
Sum									1806.7	
Total reduction									164.8	8.4

8. Conclusion

The prime objective for this thesis has been to analyze and quantify the effect of implementing a Hybrid Battery System (HBS) to a Platform Support Vessel (PSV) by using the battery to optimize the original power system.

The main advantages of implementing a HBS to a vessel is the reduction in fuel consumption and exhaust gas emission. When the load demand changes during an operation, the battery system gives instant access to power while a combustion engine takes time to change. To compensate for the time delay, the combustion engine operates at a higher load than required causing a waste of energy. In general, vessels that spend significant time in station keeping, have the greatest benefit of HBS. This is due to unfavorable loading of the engines to fulfill the redundancy requirements in this mode. In addition, vessels with a wide power demand, meaning vessels with varying load demand such as icebreakers and tugboats can expect to save significant fuel by introducing a HBS system.

The case analysis of Viking Energy gave an annual reduction in fuel of 13% comparing the sampling period with historical data given the same operation time distribution for the vessel. Normalizing both to actual distribution over a three-year operation period gives a calculated reduction of 17% due to a more favorable distribution. The difference is mainly due to a higher portion of Dynamic Positioning (DP) mode in the historical data. The economical evaluation concluded that the minimum threshold for overall fuel reduction to be 15% for the investment to break even in a ten-year perspective. Based on the few months of data the reduction in engine online hours is found to be 9% relative to the online hours for the same month the previous year. The potential for fuel reduction by the HBS is dependent on the efficiency of the original engines. This is because more modern engines operate with a lower specific fuel consumption at medium to low loads. The HBS system was found to have a significant positive effect on fuel consumption in change in weather conditions when operating in DP. The system particularly has a positive effect in calm weather conditions.

The hybrid battery technology definitely gives significant fuel reduction, given the right operation profile for the vessel. This is due to reduced numbers of online engines and more optimal loading. It is recommended to install this type of HBS for vessels that operate in DP for more than 34% of the total time or a mode providing a similar level of fuel saving to meet an overall reduction of 15%.

9. Recommendation for further work

This thesis has been focusing on quantifying the effect of applying a Hybrid Battery System (HBS) on a Platform Support Vessel (PSV) by using the battery to optimize the original power system. This is done based on a HBS retrofitted to the PSV of the case.

More data

As time goes a longer period of operational data will be available and probably from more vessels. A study covering data from numbers of systems and a longer period of operational data will contribute to a further quantification of the effect.

New build

The HBS in this thesis is retrofitted on the vessel. So an interesting study would be to assess the economic benefits and the potential for fuel saving when implementing the HBS as the original power system.

Other vessels and vessels types

The author assesses briefly other vessels that are considered to have a potential benefit of the HBS. A more detailed study assessing the feasibility for other vessels that PSV for the HBS.

System optimization

The ship of the case is built, and the main bus distributes AC. Further work could be done to investigate the effect of hybrid battery system in vessels equipped with DC grid or other system related actions that can contribute to higher efficiency of the battery system.

Detailed weather impact

In this thesis the fuel consumption data is presented in a monthly average. To study of the fuel consumption data on a daily basis compared to AIS data and weather conditions could provide a more detailed relation between the weather and the fuel saving from the HBS. This in combination with optimal crew practice can provide greater total fuel reduction.

Climate impact

This thesis evaluated the reduced climate effect from the HBS at the vessel of the case. An interesting studying could investigate the potential saving related to more vessels implementing the technology.

10. References

[1] T. Stensvold, "Teknisk Ukeblad," 11 October 2016. [Online]. Available: https://www.tu.no/artikler/forste-i-verden-her-skal-batterier-erstatte-motor-i-kritiske-situasjoner/359157. [Accessed 15 February 2017].

[2] G. Flaaten, "Sysla," 03 May 2016. [Online]. Available: http://sysla.no/2016/05/03/maritim/denne-containeren-sikret-toarskontrakt-med-statoil_99610/. [Accessed 24 February 2017].

[3] OPEC, "Statista," 2 January 2017. [Online]. Available: https://www.statista.com/statistics/262858/change-in-opec-crude-oil-prices-since-1960/. [Accessed 2 Mars 2017].

[4] Norwegian Petroleum Directorate, 10 July 2013. [Online]. Available: http://www.npd.no/en/Publications/Reports/Utslipp-av-NOx-fra-petroleumsvirksomheten-pa-norsk-sokkel/5-virkemidler-for-a-redusere-NOx-utslipp/. [Accessed 2 Mars 2017].

[5] H. Såtendal, *Insentiver for fuelbesparelse,* Battery Forum Gardermoen: Watts Up 2017, Statoil.

[6] C. Aadland, "Sysla Grønn," 19 January 2015. [Online]. Available: http://maritime.no/nyheter/krever-utslippsfrie-ferger-i-hordaland/. [Accessed 2 Mars 2017].

[7] "Global trends in renewable energy investment 2016," United Nations Enironment Programme, Bloomberg New Energy Finance, Frankfurt Scool of Finance & Management, 2016.

[8] DNV GL; ZEM; Grenland Energy, *DNV GL Handbook for maritime and offshore battery systems,* 2016.

[9] H. E. Lindstad, G. S. Eskeland and A. Rialland, "Batteries in offshore support vessels - Pollution, climate impact and economics," *Transportation Research Part D: Transport and Environment,* Vols. 50, https://doi.org/10.1016/j.trd.2016.11.023, pp. 409-417, 2017.

[10] Westcon P&A, *Internal document, Westcon P&A,* 2017.

[11] M. R. Patel, Shipboard electrical power systems, CRC Press, 2012.

[12] International Association of Classification Societies, Mars 2011. [Online]. Available: http://www.iacs.org.uk/document/public/explained/class_whatwhy&how.pdf. [Accessed 8 Mars 2017].

[13] DNV GL, "Rules for classification Ships: Part 6 Addititonal class notations Chapter 2 Propulsion, power generation and auxiliary system," 2017.

[14] DNV GL, Rules for classification Ships: Part 6 Additional class notations Chapter 3 Navigation, Manoeuvring and position keeping, 2017.

[15] ZEM; Grenland Energy; DNV GL, "DNV GL Guideline for large Maritime Battery System," 2014.

[16] Westcon P&A, *Personal communication,* 2017.

[17] G. Mjølhus, Interviewee, *HSEQ Manager, Solstad.* [Interview]. 10 Mars 2017.

[18] Eidesvik Offshore ASA, "ENOVA," [Online]. Available: https://www.enova.no/om-enova/om-organisasjonen/teknologiportefoljen/batterihybrid-installasjon-i-forsyningsfartoyet-viking-energy/. [Accessed 6 April 2017].

[19] European Commission, [Online]. Available: http://ec.europa.eu/environment/funding/intro_en.htm. [Accessed 16 February 2017].

[20] International Maritime Organization, "Second IMO GHG Study 2009".

[21] H. E. Lindstad and I. Sandaas, "Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology," *Journal of Ship Production and Design,* vol. 32, no. 4, http://dx.doi.org/10.5957/JSPD.32.4.150006, pp. 195-205, 2016.

[22] DNV GL, "Alternative fuels for shipping," 2014.

[23] DNV GL Research and development, "Hybrid ships," DNV GL, 2013.

[24] International Maritime Organization, Marpol Annex VI And NTC 2008 with guidelines for implementation, 2013.

[25] J. J. Corbett and P. Fischbeck, "Emissions from Ships," *Science,* vol. 287, no. 5339, http://science.sciencemag.org/content/278/5339/823, pp. 823-824, 1997.

[26] M. Brander and G. Davis, "Greenhouse Gases, CO2, CO2e, and Carbon: What Do All These Terms Mean?," Ecometrica, https://ecometrica.com/white-papers/greenhouse-gases-co2-co2e-and-carbon-what-do-all-these-terms-mean, 2012.

[27] M. Sand, T. K. Berntsen, Ø. Seland and J. E. Kristjanson, "Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes," *Journal of geophysical research - Atmospheres,* vol. 118, no. 14, http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50613/abstract, pp. 7788-7798, 2013.

[28] Intergovernmental Panel on Climate Change, "Climate Change 2013 - The Physical Science Basis," Cambridge University Press, 2013.

[29] DNV GL, "Reduksjon av klimagassutslipp norsk innenriks skipsfart," 2016.

[30] J. F. Hansen and F. Wendt, "History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends," *IEEE,* vol. 103, no. 12, http://ieeexplore.ieee.org/document/7272043/, pp. 2229-2242, 2015.

[31] "Dynamic positioning basic principles," Kongsberg, [Online]. Available: https://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/BD306BBB3E7DA73FC1256DAB00353083?OpenDocument. [Accessed 3 Mars 2017].

[32] "IMO DP Classification," Kongsbeg, [Online]. Available: https://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/D9479D5DB35FCA01C1256A4C004A876E?OpenDocument. [Accessed 3 Mars 2017].

[33] E. K. Denes, D. A. Hudson and S. R. Turnock, "Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping," *Energy Policy,* Vols. 40, https://doi.org/10.1016/j.enpol.2011.09.046, pp. 204-218, 2011.

[34] S. Bengtsson, K. Andersson and E. Fridell, "A comparative life cycle assessment of marine fuels," *Proceedings of the Institution of Mechanical Engineers, Part M, Journal of Engineering for the Maritime Environment,* vol. 225, no. 2, http://journals.sagepub.com/doi/abs/10.1177/1475090211402136, pp. 97-110, 2011.

[35] P. Schnack and M. Krüger, "LNG as Ship Fuel," DNV-GL, 2015.

[36] D. Woodyard, Pounder's Marine Diesel Engines and Gas Turbines, Elsevier Science, 2009.

[37] S. Brynolf, E. Fridell and K. Andersson, "Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol," *Journal of Cleaner Production,* vol. 74, no. https://doi.org/10.1016/j.jclepro.2014.03.052, pp. 86-95, 2014.

[38] Royal academy of engineering, "Future Ship powering options; Exploring alternative methods of shipping propulsion," 2013.

[39] H. E. Lindstad, Interviewee, *Senior Research Scientist.* [Interview]. 30 january 2017.

[40] Xtronics, "Fuel Volumetric and Gravimetric Energy Density compared," [Online]. Available: https://xtronics.com/wiki/Energy_density.html. [Accessed 13 June 2017].

[41] B. J. Vartdal, "Hybrid Ships - Technology for the future?," 2013.

[42] C. Zhang and J. Jiang, Fundamentals and application of Lithium-Ion Batteries in Electric Drive Vehicles, John Wiley & Sons, Incorporated, 2015.

[43] M. Brain, "How Lithium-ion Batteries Work," How Stuff Works, 14 November 2006. [Online]. Available: http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm> 12 June 2017. [Accessed 12 June 2017].

[44] L. O. Valøen, "Battery technology and challenges," Grenland Energy, Skien, 2016.

[45] Electropaedia Battery and Energy Technologies, "Rechargeable Lithium Batteries," Woodbank Communications Ltd, 2015. [Online]. Available: http://www.mpoweruk.com/lithiumS.htm. [Accessed 15 May 2017].

[46] "Types of Lithium-ion," Battery University, 30 November 2016. [Online]. Available: http://batteryuniversity.com/learn/article/types_of_lithium_ion. [Accessed 6 Mars 2017].

[47] DNV GL Strategic R&I, Revolt Report Transnova, 2015.

[48] S. Lasselle, L. O. Valøen and B. Gundersen, "Life cycle analysis of batteries in maritime sector," Maritime Battery Forum, https://www.nho.no/siteassets/nhos-filer-og-bilder/filer-og-dokumenter/nox-fondet/dette-er-nox-fondet/presentasjoner-og-rapporter/life-cycle-analysis-for-batteries-in-maritime-sector_final_v_0.1.pdf, 2016.

[49] ZEM, G. Energy and DNV-GL, "DNV GL Guideline for large maritime battery systems," 2013.

[50] Egil, Mollestad, "Energy Storage Offer to Westcon for Eidesvik Viking Energ [Internal]," Zero Emission Energy For the Maritime Sector, Høvik, 2015.

[51] M. Egil, *Bærekraftige batterier for tyngre transporter Zero-seminar,* 2016.

[52] A. K. Ådnanes, Maritime Electrical Installations And Diesek Electric Propulsion, ABB AS Marine, http://img1.eworldship.com/2012/0913/20120913041849123.pdf, 2003.

[53] DNV GL, *In focus - The future is hybrid,* 2015.

[54] LG Chem, *Batteries in Global Perspective,* 2016.

[55] H. Russel, J. Newman and M. Rogers, "McKinsey&Company Sustainability & Resource Productivity," July 2012. [Online]. Available: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/battery-technology-charges-ahead. [Accessed 14 May 2017].

[56] S. D. Breucker, E. Peeters and J. Driesen, "Possible applications of Plug-in Hybrid Electric Ships," in *Electric Ship Technologies Symposium*, Baltimore, 2009.

[57] E. Ona, O. R. Godø, N. O. Handegard, V. Hjellvik, R. Patel and R. Pedersen, "Silent research vessels are not quiet," *Acoustical Society of America,* Vols. 121, 4, no. http://dx.doi.org/10.1121/1.2710741, 2007.

[58] B. Zahedi, L. E. Norum and K. B. Ludvigsen, "Optimized efficiency of all-electric ships by dc hybrid power systems," 2014.

[59] ENOVA, "Sluttrapport, Batterihybrid Installasjon - Viking Energy (Internal)," 2017.

[60] Norwegian Meteorological Institute , *Personal communication,* 2017.

[61] H. Sverre Kristian, Interviewee, *First Amanuensis.* [Interview]. 26 April 2017.

[62] J. O. Wikkums and E. Mollestad, "Status of Battery Technology and future developments," in *Solenergidagen 2016*, Oslo, 2016.

[63] H. Såtendal, Interviewee, *Principal Consultant Supply chain management Marine operations.* [Interview]. 29 March 2017.

[64] Norwegian Costal Administration, *Personal Communication,* 2017.

[65] M. Reistad, Ø. Breivik, H. Haajenstad, O. J. Aarnes, B. R. Furevik and J. Bidlot, "A high resolution hindcast of wind and waves for the North Sea, the Norwegian Sea and the Barents Sea," *Journal of Geophysical research, Oceans,* vol. 116, 2011.

[66] T. Tezdogan, A. Incecik, O. Turan and P. Kellett, "Assessing the Impact of a Slow Steaming Approach on Reducing the Fuel Consumption of a Containership Advancing in Head Seas," *Transportation Research,* vol. 6, no. 14, 2016.

[67] A. F. Molland, S. R. Turnock and D. A. Hudson, Ship Resistance and Propulsion, Cambridge University Press, 2011.

[68] "European Union Natural Gas Import Price," YCHARTS, 30 April 2017. [Online]. Available: https://ycharts.com/indicators/europe_natural_gas_price. [Accessed 5 June 2017].

[69] "Ship and Bunker North and Western Europe," 2 June 2017. [Online]. Available: https://shipandbunker.com/prices/emea/nwe. [Accessed 5 June 2017].

[70] Gasnor, "Noen typiske data for energibærere," [Online]. Available: http://gasnor.no/naturgass/typiske-data-energi/. [Accessed 05 June 2017].

[71] H. O. Kristensen, "Energy demand and exhaust gas emissions of marine engines," Technical University of Denmark, 2012.

[72] L. A.-W. Ellingsen, G. Maheau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen and A. H. Strømman, "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack," *Jornal of Industrial Ecology,* vol. 18, no. 1, pp. 113-124, 2014.

[73] G. M. Lamvik, A. M. Wahl and M. P. Buvik, "Professional culture, work practice and reliable operaions in shipping," in *Reliability, Risk and Safety: Theory and Applications - Bris*, London, 2010.

[74] S. A. Snook, Frendly Fire: The Accidental Shootdown of U.S. Black Hawks over Nprthern Iraq, New Jersey: Princeton University Press, 2000.

[75] M. Bourrier, "The Contribution of Organizational Design to Safety," *European Management Journal,* vol. 23, no. 1, https://doi.org/10.1016/j.emj.2004.12.014, pp. 98-104, 2005.

[76] T. Stensvold, "Teknisk Ukeblad," 24 August 2010. [Online]. Available: https://www.tu.no/artikler/gjor-skipene-klimanoytrale/242008. [Accessed 5 June 2017].

Appendix A

Table 14 Qualitative assessment of vessels applicability for the HBS.

	SR	PS	EDP	SS	CI
Platform Support Vessel	Applicable	Applicable	Applicable	Applicable	Applicable
Rigs and FPSO	Applicable	Applicable	Applicable	Feasible	Applicable
Special vessels	Applicable	Applicable	Applicable	Applicable	Applicable
Tugboats	Applicable	Feasible	Applicable	Applicable	Applicable
Ferries	Not applicable	Applicable	Applicable	Feasible	Applicable
Icebreakers	Not applicable	Feasible	Applicable	Feasible	Applicable
Lifting vessels	Applicable	Applicable	Applicable	Feasible	Applicable
Research vessels	Feasible	Applicable	Applicable	Feasible	Applicable

SR= Spinning reserve, PS=Peak Shaving, EDP=Enhanced Dynamic Performance, SS=Start-Stop, CI=Cold Ironing.

Applicable = (green)

Feasible = (yellow)

Not applicable = (red)

Appendix B

The monthly difference from the 2012-2015 and 2016 data in the months involved in the sampling period.

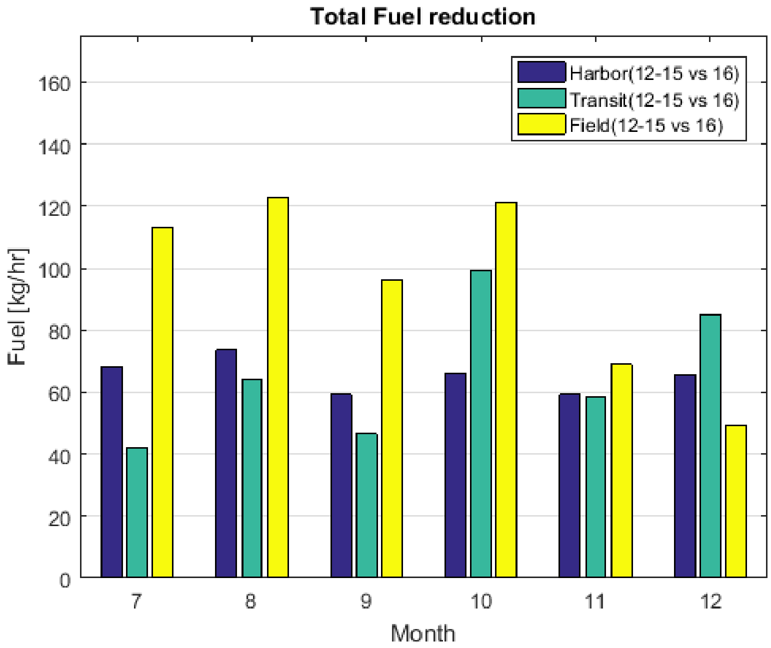


Figure 51: Monthly differential in the respective months between 2016 and 2012-2015 data.

The reduction in the SFOC (g/kWh) related to each mode before and after operating with the hybrid battery system. This is used to find the unknown fuel reduction rates of Transit HI and Standby in section 7.5.1.

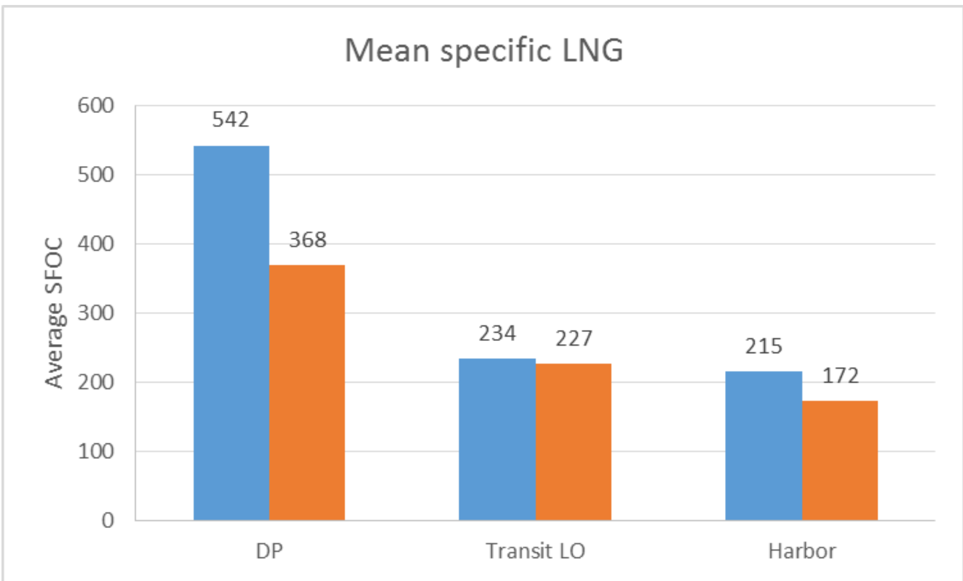


Figure 52: Mean SFOC based on fuel consumption data from 2015 to 2016.

Table 15: Reduction rate found from SFOC reduction related to each mode.

	DP	Transit LO	Harbor
Reduction rate (%)	32	3	19

Appendix C

Figure 53 is a comparison between Hindcast NORA 10 data and measurements in the North Sea. It can be observed to correspond good with the measurements.

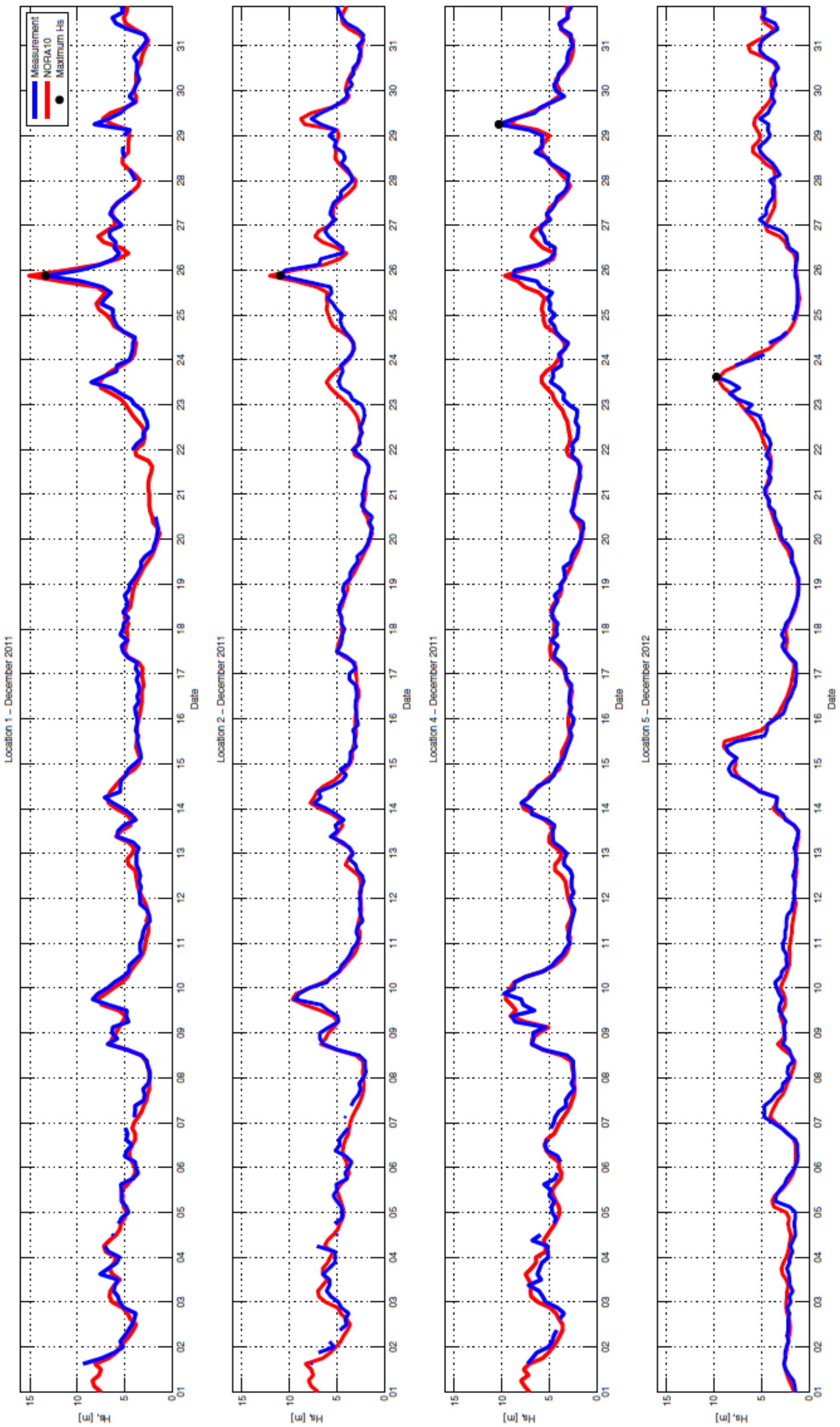


Figure 53: Time series of Nora 10 and measured H_s for representative timeframe [65].

The NORA 10 data was provided with values each 3 hour, thus 8 measurements each twenty-four hour. Each moth has been calculated for an average value. This has been done both for significant wave height (H_S) and wind speed (W_S). This was to validate if the weather in the sampling period was according to historical expectance. The wind and wave monthly average are plotted for each year from 1958 to 2012, July to December. Then the average of all these years on a monthly basis are plotted together with the monthly average corresponding to the sampling period in 2016, 2015 and 2012 to 2015. It can be observed that July, October, and November have smaller waves than the historical average. Further, December is found to have larger waves. The wind speed has much the same trend as waves with below expected in July, August, October, and November. And with wind speed higher than expected in September and December. The geographical point called Historical is used as a historical reference to validate weather data on the other locations. Figure 54 shows all geographical points of interests.

The Hindcast model has generated a wind speed and wave height value for every 3-hour corresponding to 8 values every 24 hours.

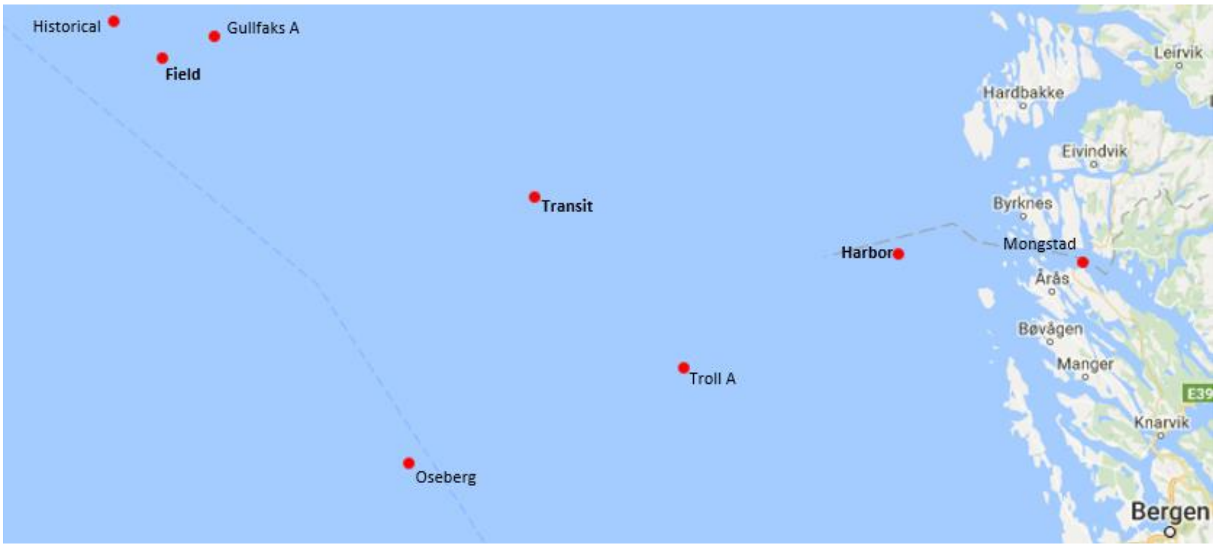


Figure 54: Map of the representative data points for each operation category

Table 16 presents the coordinates behind the map in Figure 37 and Figure 54.

Table 16: Coordinates of key points

Point	Coordinates (DD)
Gullfax A	61.176106, 2.189150
Oseberg A	60.491864, 2.827314
Troll A	60.645639, 3.726494
Field	60.645639, 3.726494
Transit	60.92,03.24
Harbor	60.83,04.43
Historical (1956-2012)	61.20,01.86
Mongstad	60.814792, 5.036756

Appendix D

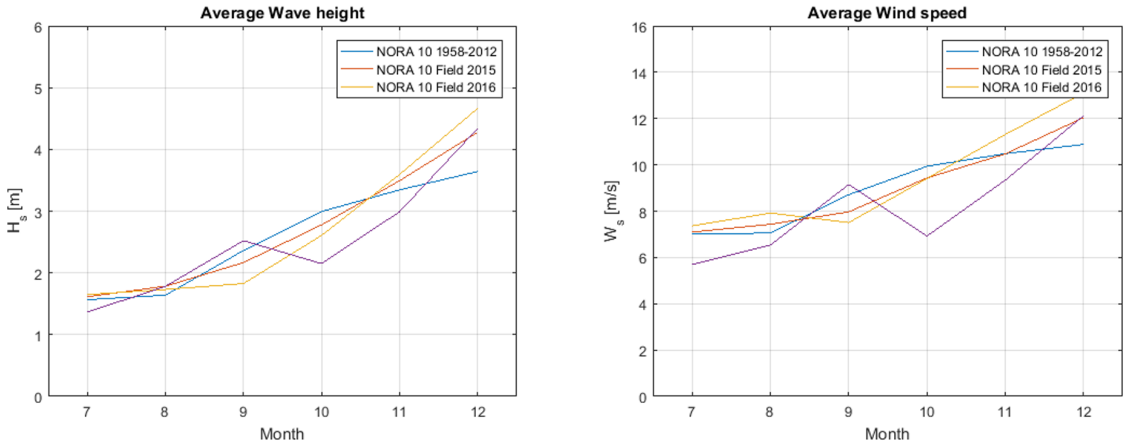


Figure 55 Wave height and Wind speed left and right. Comparing Hindcast NORA 10 data from 1958-2012, 2012-2015, 2015 and 2016 in a monthly average value.

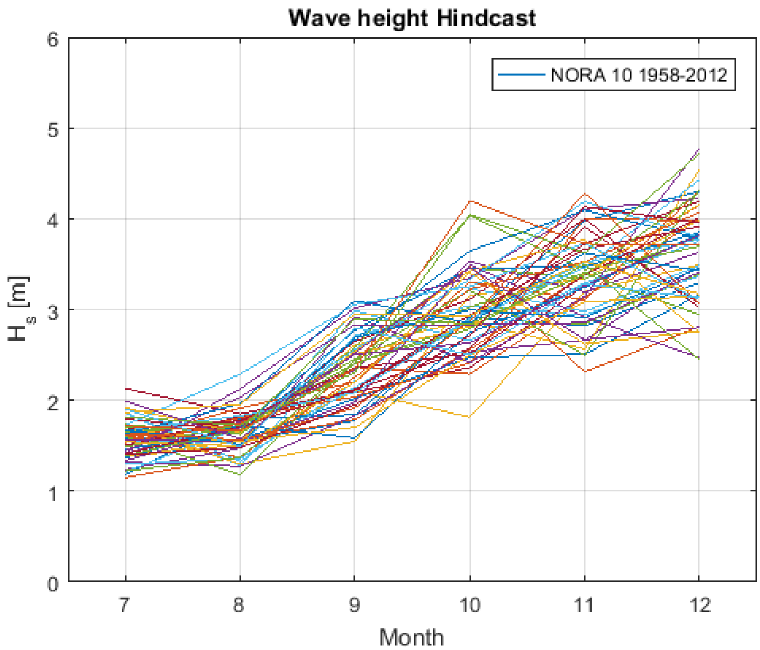


Figure 56: Historical monthly average H_S from 1958 to 2012.

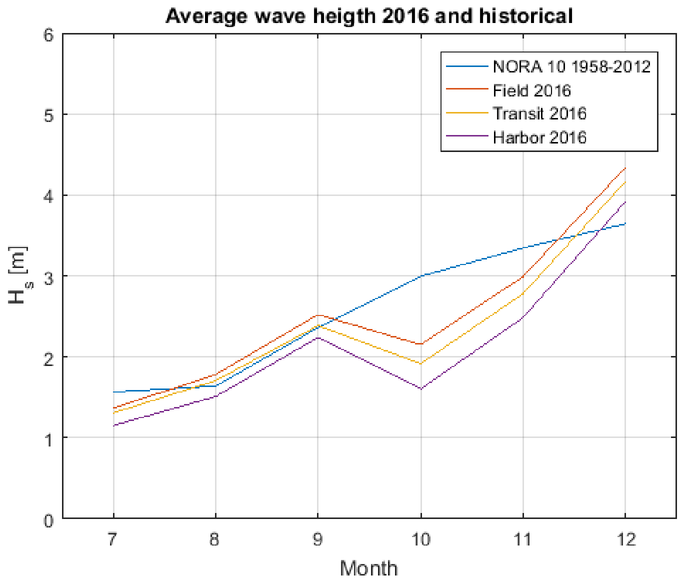


Figure 57: Monthly average H_S from historical data compared to 2016 in respective months.

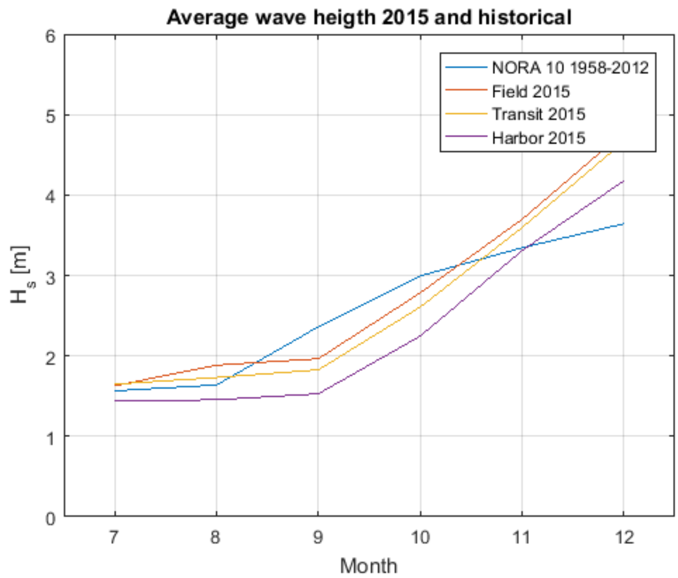


Figure 58: Monthly average H_S from historical data compared to 2015 in respective months.

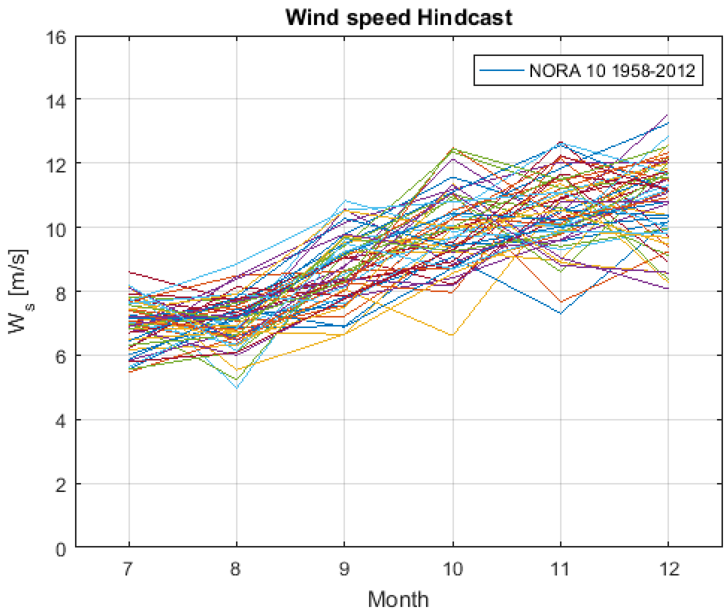


Figure 59 Historical monthly average W_s from 1958 to 2012.

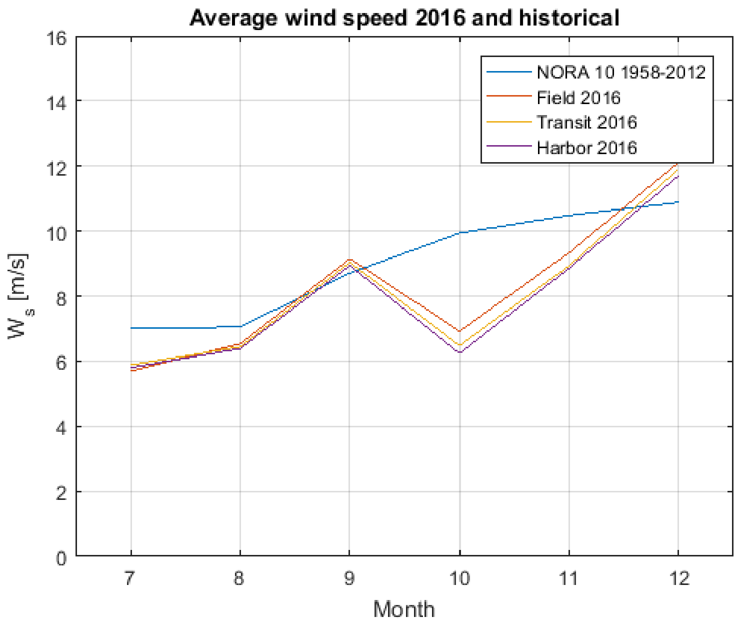


Figure 60: Monthly average W_s from historical data compared to 2016 in respective months.

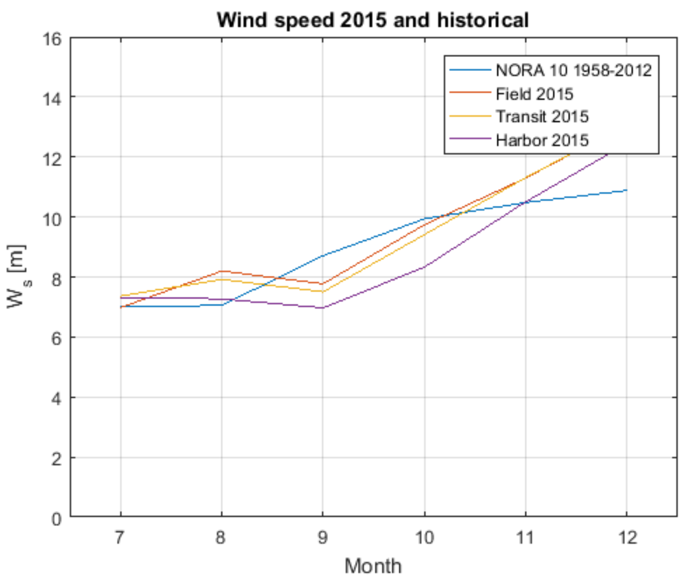


Figure 61: Monthly average W_s from historical data compared to 2015 in respective months.

Appendix E

Scenario 1

Cash flow with fuel price change

Fuel saved	370.50	102.60
Fuel saved (NOK/yr.)	1239008.3	
OPEX (NOK/yr.)	300000	
USD to NOK	8.48	per 26.03.17
mmbtu to ton	0.0203013	

CAPEX	-12000000
Rate of return (RR)	3 %

	-20 %	Current	20 %	40 %
LNG (USD/mmbtu)	4.192	5.24	6.288	7.336
LNG (NOK/ton)	1751.0277	2188.7846	2626.541516	3064.298435
MGO (USD/mt)	393.6	492	590.4	688.8
MGO (NOK/ton)	3337.728	4172.16	5006.592	5841.024
LNG red. ton pr yr	370.50			
MGO red. ton pr yr	102.60			
Cost saved pr yr	991206.65	1239008.3	1486809.971	1734611.633
Cost saved incl. OPEX	1291206.6	1539008.3	1786809.971	2034611.633
		NPV		
Year (n)	-20 %	cuurent (C_n)	20 %	40 %
0	0	0	0	0
1	1253598.7	1494182.8	1734766.962	1975351.1
2	1217086.1	1450662.9	1684239.769	1917816.602
3	1181637	1408410.6	1635184.242	1861957.866
4	1147220.4	1367388.9	1587557.516	1807726.083
5	1113806.2	1327562.1	1541317.977	1755073.867
6	1081365.2	1288895.2	1496425.22	1703955.211
7	1049869.2	1251354.6	1452840.02	1654325.447
8	1019290.5	1214907.4	1410524.291	1606141.211
9	989602.38	1179521.7	1369441.059	1559360.399
10	960779.01	1145166.7	1329554.426	1513942.135
11	932795.15	1111812.3	1290829.54	1469846.733
12	905626.36	1079429.5	1253232.563	1427035.663

$$NPV = \sum_{n=1} \frac{C_n}{(1+RR)^n}$$

Scenario 1
Cash flow with fuel price change

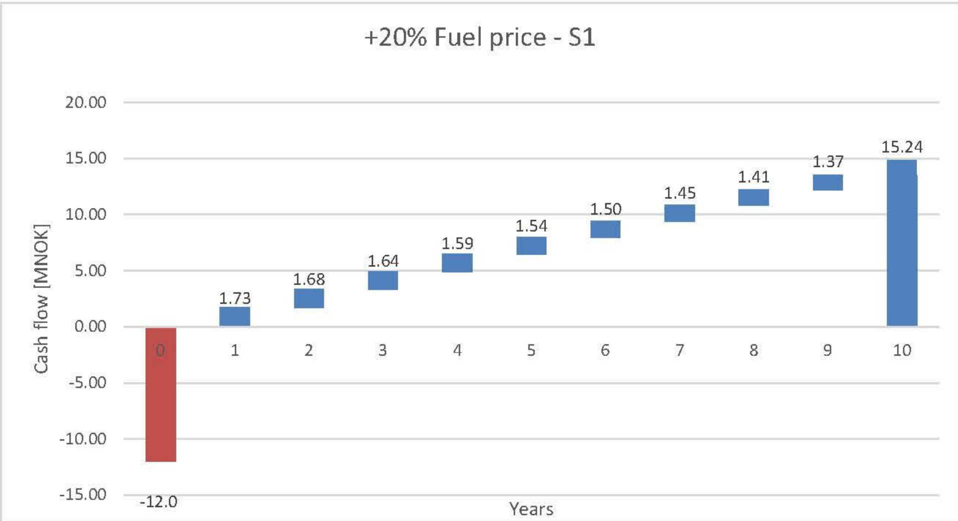
	Current price			Accumulated		
	baseline	positive	negative	Current price		
0	0	0	-12000000	0		
1	0	1494182.8	0	1494182.824		
2	1450662.9	1450662.9	0	2944845.761		
3	2859073.6	1408410.6	0	4353256.378		
4	4226462.5	1367388.9	0	5720645.328		
5	5554024.6	1327562.1	0	7048207.414		
6	6842919.8	1288895.2	0	8337102.644		
7	8094274.4	1251354.6	0	9588457.236		
8	9309181.8	1214907.4	0	10803364.61		
9	10488704	1179521.7	0	11982886.33		
10	11633870	1145166.7	0	13128053.04		
					years	moths
				payback	9.14	1.7

Scenario 1

Cash flow with fuel price change

	+ 20% LNG and MGO			Accumulated
	baseline	positive	negative	+20%
0	0	0	-12000000	0
1	0	1734767	0	1734766.962
2	1684239.8	1684239.8	0	3419006.731
3	3319424	1635184.2	0	5054190.973
4	4906981.5	1587557.5	0	6641748.489
5	6448299.5	1541318	0	8183066.466
6	7944724.7	1496425.2	0	9679491.686
7	9397564.7	1452840	0	11132331.71
8	10808089	1410524.3	0	12542856
9	12177530	1369441.1	0	13912297.06
10	13507085	1329554.4	0	15241851.48

	years	moths
payback	7.7	8

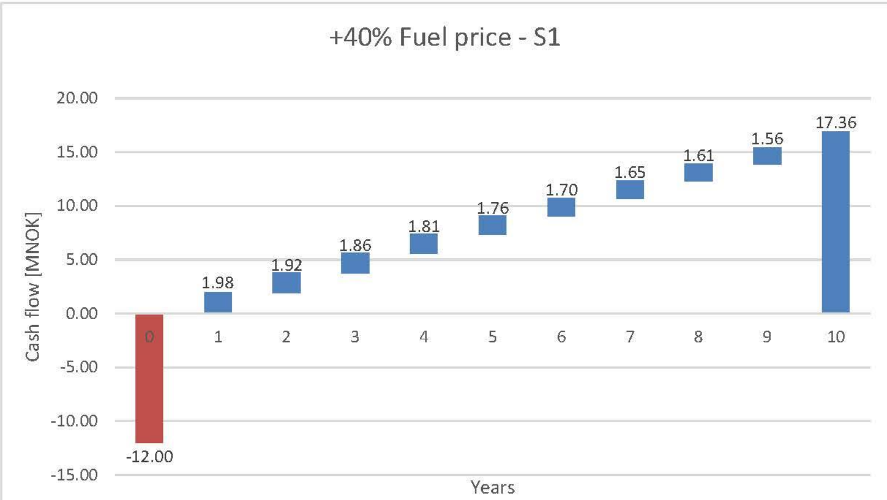


Scenario 1

Cash flow with fuel price change

	+40% LNG and MGO			Accumulated
	baseline	positive	negative	+40%
0	0	0	-12000000	0
1	0	1975351	0	1975351.1
2	1917817	1917817	0	3893167.7
3	3779774	1861958	0	5755125.57
4	5587501	1807726	0	7562851.65
5	7342574	1755074	0	9317925.52
6	9046530	1703955	0	11021880.7
7	10700855	1654325	0	12676206.2
8	12306996	1606141	0	14282347.4
9	13866357	1559360	0	15841707.8
10	15380299	1513942	0	17355649.9

	years	moths
payback	6.63	7.5

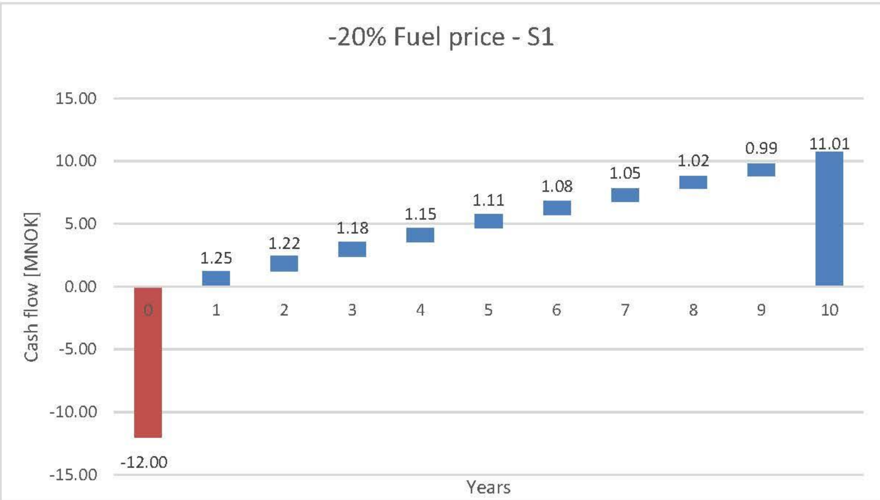


Scenario 1

Cash flow with fuel price change

	-20% LNG and MGO			Accumulated
	baseline	positive	negative	-20%
0	0	0	-12000000	0
1	0	1253599	0	1253598.69
2	1217086	1217086	0	2470684.79
3	2398723	1181637	0	3652321.78
4	3545943	1147220	0	4799542.17
5	4659750	1113806	0	5913348.36
6	5741115	1081365	0	6994713.6
7	6790984	1049869	0	8044582.77
8	7810275	1019290	0	9063873.22
9	8799877	989602.4	0	10053475.6
10	9760656	960779	0	11014254.6
11	10693451	932795.2	0	11947049.8
12	11599077	905626.4	0	12852676.1

	years	moths
payback	11.20	2.4



Scenario 2

Cash Flow with fuel price change

Fuel saved	276.80	76.36
Fuel saved (NOK/yr.)	924441.7	
OPEX save	300000	
USD to NOK	8.48	per 26.03.17
mmbtu to ton	0.020301	

CAPEX	-12000000
Rate of return	3 %

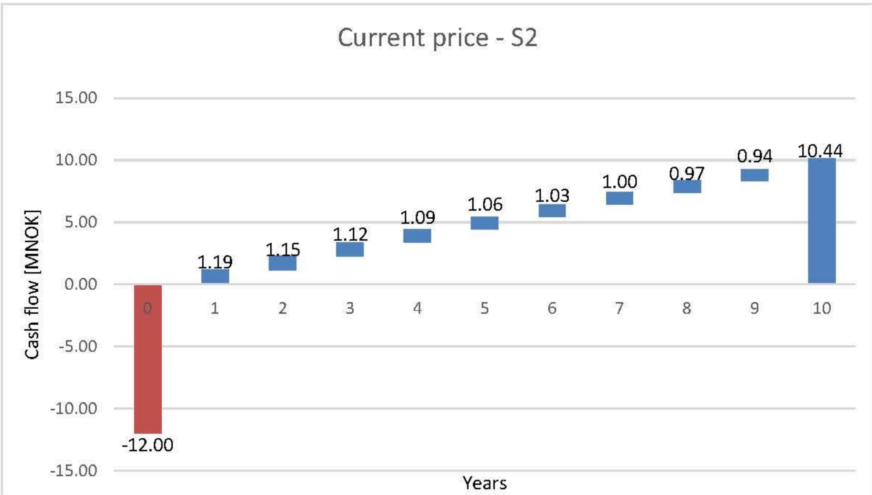
	-20 %	Current	20 %	40 %
LNG (USD/mmbtu)	4.192	5.24	6.288	7.336
LNG (NOK/ton)	1751.028	2188.784597	2626.541516	3064.298435
MGO (USD/mt)	393.6	492	590.4	688.8
MGO (NOK/ton)	3337.728	4172.16	5006.592	5841.024
LNG red. ton pr yr	276.80			
MGO red. ton pr yr	76.36			
Cost saved pr yr	739553.4	924441.714	1109330.057	1294218.4
LNG and MGO price	-20 %	cuurent	20 %	40 %
0	0	0	0	0
Cost saved incl. OPEX	1039553	1224441.714	1409330.057	1594218.4
		NPV		
Year (n)	-20 %	cuurent (C_n)	20 %	40 %
0	0	0	0	0
1	1009275	1188778.363	1368281.609	1547784.854
2	979878.8	1154153.751	1328428.746	1502703.742
3	951338.6	1120537.622	1289736.647	1458935.672
4	923629.7	1087900.604	1252171.502	1416442.4
5	896727.9	1056214.178	1215700.487	1375186.796
6	870609.6	1025450.659	1180291.735	1335132.811
7	845252	995583.1638	1145914.306	1296245.448
8	820633	966585.5959	1112538.161	1258490.726
9	796731.1	938432.6174	1080134.137	1221835.656
10	773525.3	911099.6285	1048673.919	1186248.21
11	750995.5	884562.7461	1018130.019	1151697.291
12	729121.8	858798.7826	988475.7464	1118152.71
13	707885.3	833785.2259	959685.1906	1085585.155
14	687267.2	809500.2193	931733.1948	1053966.17
15	667249.8	785922.543	904595.3348	1023268.127

$$NPV = \sum_{n=1} \frac{C_n}{(1+RR)^n}$$

Scenario 2
Cash Flow with fuel price change

	Current price			Accumulated
	baseline	positive	negative	Current price
0	0	0	-12000000	0
1	0	1188778.363	0	1188778.363
2	1154154	1154153.751	0	2342932.114
3	2274691	1120537.622	0	3463469.736
4	3362592	1087900.604	0	4551370.339
5	4418806	1056214.178	0	5607584.518
6	5444257	1025450.659	0	6633035.176
7	6439840	995583.1638	0	7628618.34
8	7406426	966585.5959	0	8595203.936
9	8344858	938432.6174	0	9533636.553
10	9255958	911099.6285	0	10444736.18
11	10140521	884562.7461	0	11329298.93
12	10999319	858798.7826	0	12188097.71
13	11833105	833785.2259	0	13021882.94

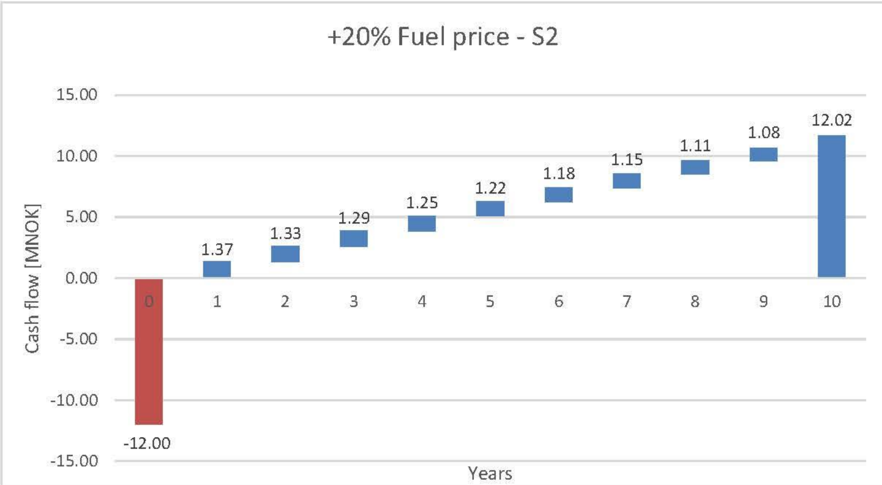
	Years	Months
Payback	11.81	10



Scenario 2

Cash Flow with fuel price change

	+20% LNG and MGO			Accumulated	
	baseline	positive	negative	+20%	
0	0	0	-12000000	0	
1	0	1368281.609	0	1368281.609	
2	1328429	1328428.746	0	2696710.355	
3	2618165	1289736.647	0	3986447.001	
4	3870337	1252171.502	0	5238618.503	
5	5086037	1215700.487	0	6454318.99	
6	6266329	1180291.735	0	7634610.725	
7	7412243	1145914.306	0	8780525.031	
8	8524782	1112538.161	0	9893063.192	
9	9604916	1080134.137	0	10973197.33	
10	10653590	1048673.919	0	12021871.25	
11	11671720	1018130.019	0	13040001.27	
				Year	Monts
			Payback	9.982	11.8

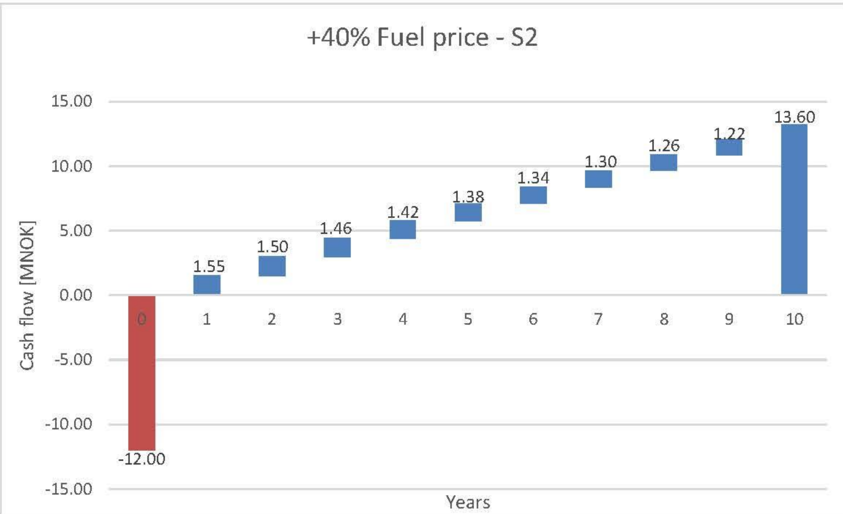


Scenario 2

Cash Flow with fuel price change

	+40% LNG and MGO			Accumulated
	baseline	positive	negative	+40%
0	0	0	-12000000	0
1	0	1547785	0	1547784.85
2	1502703.74	1502704	0	3050488.6
3	2961639.41	1458936	0	4509424.27
4	4378081.81	1416442	0	5925866.67
5	5753268.61	1375187	0	7301053.46
6	7088401.42	1335133	0	8636186.27
7	8384646.87	1296245	0	9932431.72
8	9643137.59	1258491	0	11190922.4
9	10864973.3	1221836	0	12412758.1
10	12051221.5	1186248	0	13599006.3

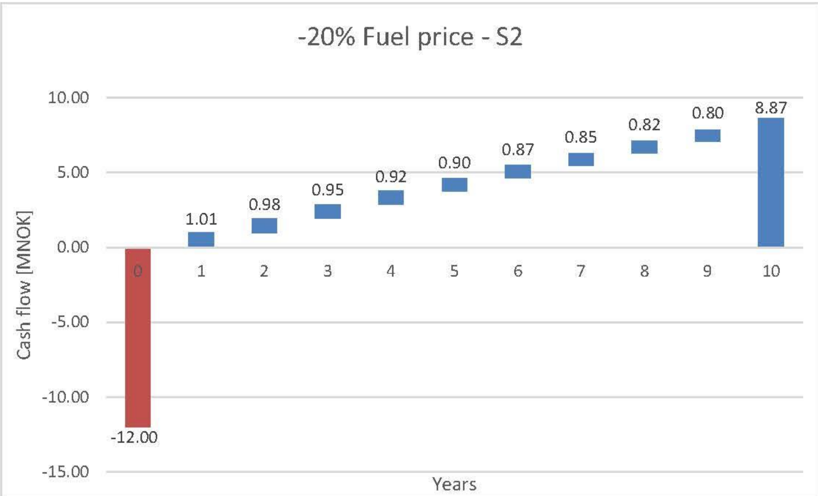
	Years	Months
Payback	8.70	8



Scenario 2
Cash Flow with fuel price change

	-20% LNG and MGO down			Accumulated
	baseline	positive	negative	-20%
0	0	0	-12000000	0
1	0	1009275	0	1009275.12
2	979878.755	979878.8	0	1989153.87
3	1931217.35	951338.6	0	2940492.47
4	2854847.06	923629.7	0	3864122.18
5	3751574.93	896727.9	0	4760850.05
6	4622184.51	870609.6	0	5631459.63
7	5467436.53	845252	0	6476711.65
8	6288069.56	820633	0	7297344.68
9	7084800.66	796731.1	0	8094075.78
10	7858326	773525.3	0	8867601.12
11	8609321.47	750995.5	0	9618596.59
12	9338443.29	729121.8	0	10347718.4
13	10046328.6	707885.3	0	11055603.7
14	10733595.8	687267.2	0	11742870.9
15	11400845.5	667249.8	0	12410120.7

	Years	Months
Payback time	14.50	6.1



Linear interpolation to estimate the threshold in minimum time spent in dynamic positioning in order to gain economical profit.

$$24 + \frac{0 - (-1.56)}{1.13 - (-1.56)}(41 - 24) = 33.9\%$$

Figure 62: Linear interpolation finding the minimum time spent in DP for the vessel to gain profit of the HBS.

Linear interpolation to estimate the threshold in minimum overall fuel reduction to break even the initial investment.

$$13 + \frac{0 - (-1.56)}{1.13 - (-1.56)}(17 - 13) = 15.3\%$$

Figure 63: Linear interpolation finding the minimum threshold for overall fuel saving for the vessel to break even the investment of the HBS.

Appendix F

Scenario 1
Reduced environmental impact

	Annual time	Hours	LNG(ton/yr)	Energy	MGO(ton/yr)	Energy
Transit LO	28 %	2427.396	30.65	175 318.00	6.25	16 307.50
DP	41 %	3567.072	278.23	1 591 475.60	77.52	202 265.18
Standby	2 %	152.424	5.53	31 631.60	1.64	4 279.09
Transit HI	1 %	58.692	1.12	6 406.40	0.15	391.38
Harbor	29 %	2554.416	54.92	314 142.40	17.03	44 434.68
		red. ton/yr.	370.45		102.59	
			red. kWh/yr.	2118974		267677.83

$$Fuel(ton/yr) \cdot C_v(kWh/kg) \cdot \eta = Energy(kWh/yr)$$

	C_v (kWh/kg)	η
LNG	13.00	0.44
MGO	11.86	0.22

$$K_p(g/kWh) * Energy = P_e\ (ton/yr)$$

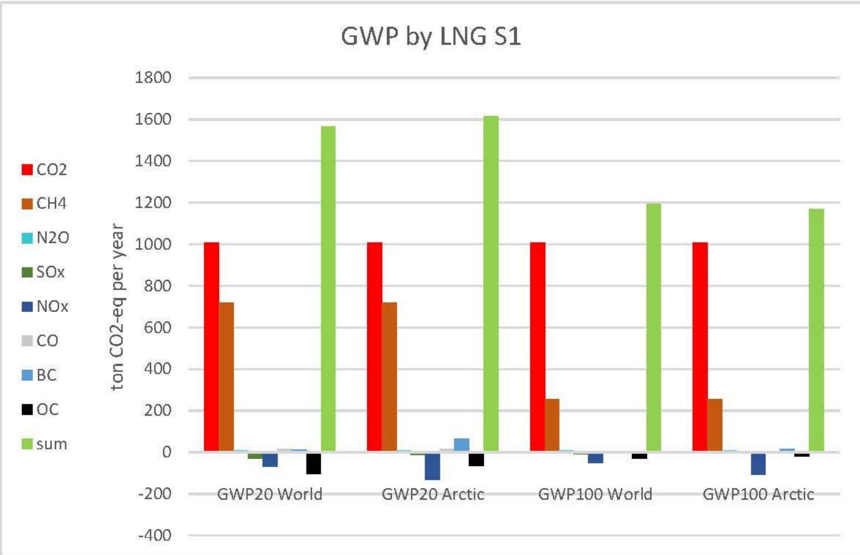
	LNG High load		MGO Low load	
Emission	K_p(g/kWh)	P_e(ton/yr)	K_p(g/kwh)	P_e(ton/yr)
CO2	475.00	1006.51265	700	187.3744796
CH4	4.00	8.475896	0.1	0.026767783
N2O	0.02	0.04237948	0.02	0.005353557
SOx	0.10	0.2118974	0.5	0.133838914
NOx	2.00	4.237948	9	2.409100452
CO	1.40	2.9665636	1.4	0.374748959
BC	0.005	0.01059487	0.15	0.040151674
OC	0.20	0.4237948	0.2	0.053535566

	GWP_{20} World	GWP_{20} Arctic	GWP_{100} world	GWP_{100} Arctic
CO_2	1	1	1	1
CH_4	85	85	30	30
N_2O	264	264	265	265
SO_x	-141	-47	-38	-13
NO_x	-15.9	-31	-11.6	-25
CO	5.4	5.4	1.8	1.8
BC	1200	6200	345	1700
OC	-240	-151	-69	-43

Scenario 1

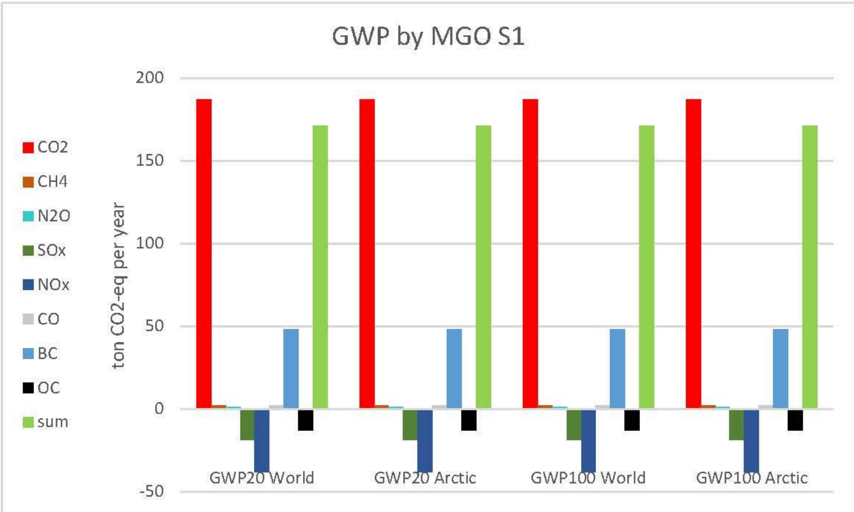
Reduced environmental impact

LNG				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	1006.51265	1006.51265	1006.51265	1006.51265
CH_4	720.45116	720.45116	254.27688	254.27688
N_2O	11.1881827	11.1881827	11.2305622	11.2305622
SO_x	-29.8775334	-9.9591778	-8.0521012	-2.7546662
NO_x	-67.3833732	-131.376388	-49.1601968	-105.9487
CO	16.0194434	16.0194434	5.33981448	5.33981448
BC	12.713844	65.688194	3.65523015	18.011279
OC	-101.710752	-63.9930148	-29.2418412	-18.2231764
sum	1567.91362	1614.53105	1194.560998	1168.444643



Scenario 1
Reduced environmental impact

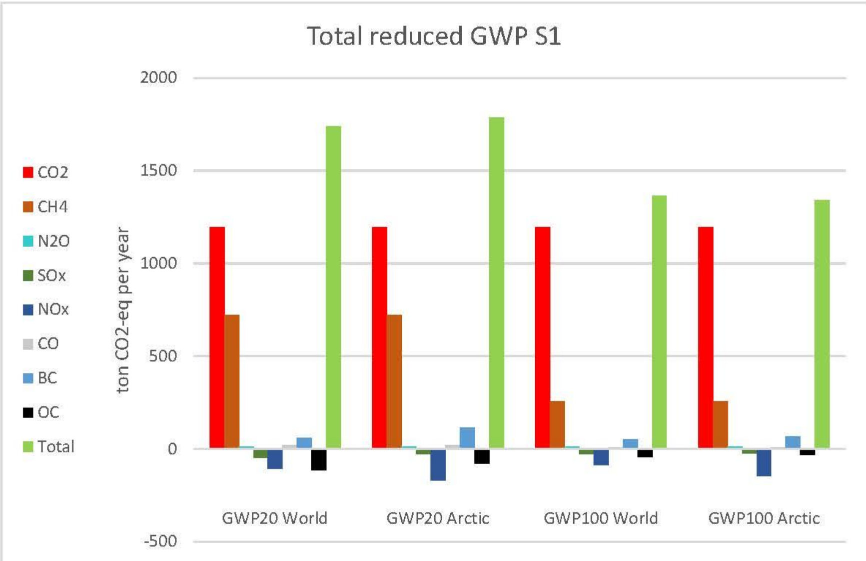
MGO				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	187.3744796	187.37448	187.3744796	187.3744796
CH_4	2.275261538	2.27526154	2.275261538	2.275261538
N_2O	1.413338932	1.41333893	1.413338932	1.413338932
SO_x	-18.87128687	-18.871287	-18.8712869	-18.8712869
NO_x	-38.30469719	-38.304697	-38.3046972	-38.3046972
CO	2.02364438	2.02364438	2.02364438	2.02364438
BC	48.18200904	48.182009	48.18200904	48.18200904
OC	-12.84853574	-12.848536	-12.8485357	-12.8485357
sum	171.2442137	171.244214	171.2442137	171.2442137



Scenario 1

Reduced environmental impact

MGO and LNG				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	1193.88713	1193.88713	1193.88713	1193.88713
CH_4	722.7264215	722.726422	256.5521415	256.5521415
N_2O	12.60152165	12.6015217	12.64390113	12.64390113
SO_x	-48.74882027	-28.830465	-26.9233881	-21.6259531
NO_x	-105.6880704	-169.68109	-87.464894	-144.253397
CO	18.04308782	18.0430878	7.36345886	7.36345886
BC	60.89585304	113.870203	51.83723919	66.19328804
OC	-114.5592877	-76.841551	-42.0903769	-31.0717121
Total	1739.157835	1785.77526	1365.805211	1339.688857



Scenario 2

Reduced environmental impact

	Annual time	Hours	LNG(ton/yr)	Energy	MGO(ton/yr)	Energy
Transit LO	37 %	3266.604	41.24	235 892.80	8.41	21 943.37
DP	24 %	2078.748	162.14	927 440.80	45.18	117 883.66
Standby	0 %	0	0	-	0	-
Transit HI	0 %	0	0	-	0	-
Harbor	39 %	3414.648	73.41	419 905.20	22.76	59 385.39
		red. ton/yr.	276.79		76.35	
			red. kWh/yr.	1583238.8		199212.42

$$Fuel(ton/yr) \cdot C_v(kWh/kg) \cdot \eta = Energy(kWh/yr)$$

	C_v (kWh/kg)	η
LNG	13.00	0.44
MGO	11.86	0.22

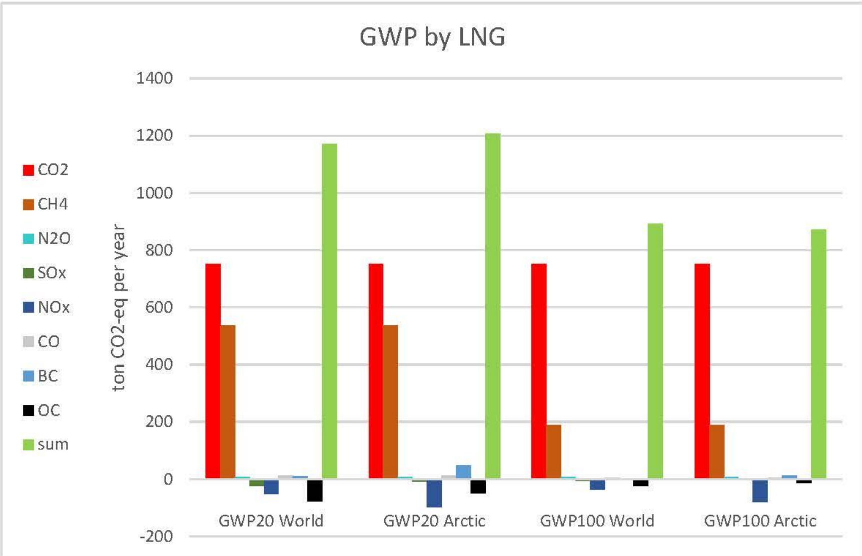
$$K_p(g/kWh) * Energy = P_e\ (ton/yr)$$

	LNG High load		MGO Low load	
Emission	K_p(g/kWh)	P_e(ton/yr)	K_p(g/kwh)	P_e(ton/yr)
CO2	475.00	752.03843	700	139.448694
CH4	4.00	6.3329552	0.1	0.019921242
N2O	0.02	0.03166478	0.02	0.003984248
SOx	0.10	0.15832388	0.5	0.09960621
NOx	2.00	3.1664776	9	1.79291178
CO	1.40	2.21653432	1.4	0.278897388
BC	0.005	0.00791619	0.15	0.029881863
OC	0.20	0.31664776	0.2	0.039842484

	GWP_{20} World	GWP_{20} Arctic	GWP_{100} world	GWP_{100} Arctic
CO_2	1	1	1	1
CH_4	85	85	30	30
N_2O	264	264	265	265
SO_x	-141	-47	-38	-13
NO_x	-15.9	-31	-11.6	-25
CO	5.4	5.4	1.8	1.8
BC	1200	6200	345	1700
OC	-240	-151	-69	-43

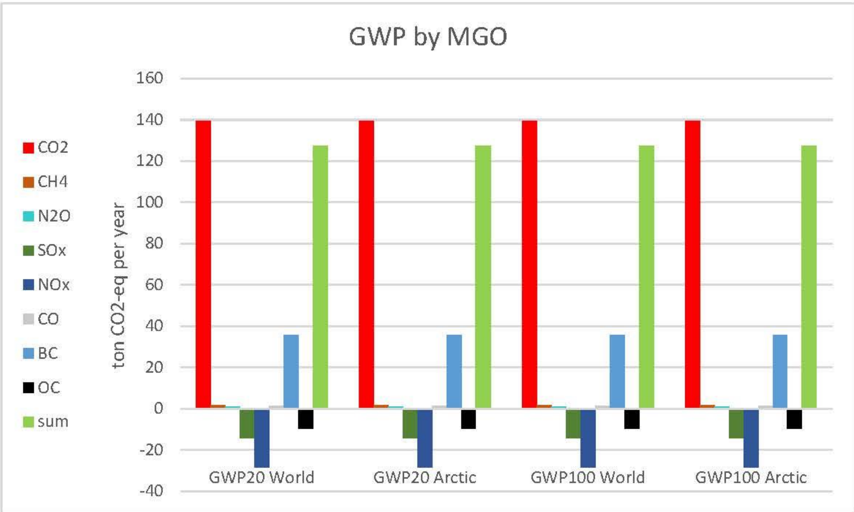
Scenario 2
Reduced environmental impact

LNG				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	752.03843	752.03843	752.03843	752.03843
CH_4	538.301192	538.301192	189.988656	189.988656
N_2O	8.35950086	8.35950086	8.39116564	8.39116564
SO_x	-22.3236671	-7.44122236	-6.01630744	-2.05821044
NO_x	-50.3469938	-98.1608056	-36.7311402	-79.16194
CO	11.9692853	11.9692853	3.989761776	3.989761776
BC	9.4994328	49.0804028	2.73108693	13.4575298
OC	-75.9954624	-47.8138118	-21.8486954	-13.61585368
sum	1171.50172	1206.33297	892.5429573	873.0295391



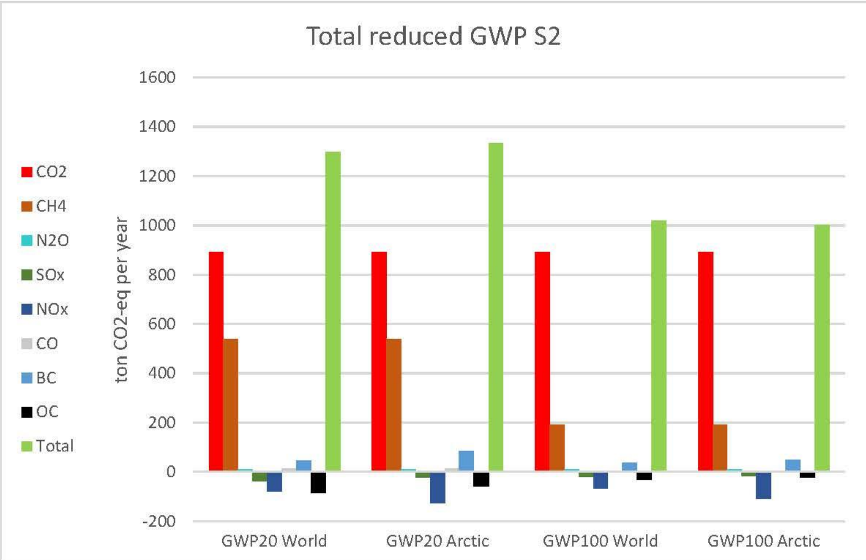
Scenario 2
Reduced environmental impact

MGO				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	139.448694	139.448694	139.448694	139.448694
CH_4	1.69330557	1.69330557	1.69330557	1.69330557
N_2O	1.051841578	1.05184158	1.051841578	1.051841578
SO_x	-14.04447561	-14.044476	-14.0444756	-14.0444756
NO_x	-28.5072973	-28.507297	-28.5072973	-28.5072973
CO	1.506045895	1.5060459	1.506045895	1.506045895
BC	35.8582356	35.8582356	35.8582356	35.8582356
OC	-9.56219616	-9.5621962	-9.56219616	-9.56219616
sum	127.4441536	127.444154	127.4441536	127.4441536



Scenario 2
Reduced environmental impact

MGO and LNG				
	GWP_{20} World	GWP_{20} Arctic	GWP_{100} World	GWP_{100} Arctic
CO_2	891.487124	891.487124	891.487124	891.487124
CH_4	539.9944976	539.994498	191.6819616	191.6819616
N_2O	9.411342442	9.41134244	9.443007218	9.443007218
SO_x	-36.36814269	-21.485698	-20.0607831	-16.1026861
NO_x	-78.85429114	-126.6681	-65.2384375	-107.669237
CO	13.47533122	13.4753312	5.495807671	5.495807671
BC	45.3576684	84.9386384	38.58932253	49.3157654
OC	-85.55765856	-57.376008	-31.4108916	-23.1780498
Total	1298.945871	1333.77712	1019.987111	1000.473693



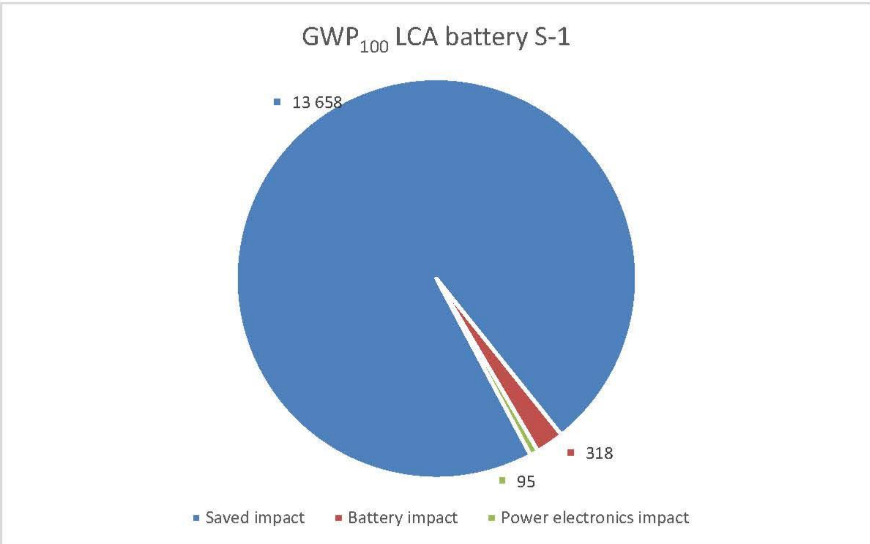
Appendix G

Impact of battery production compared to saved fuel in Scenario 1

Scenario 1				
Red. fuel/yr.	370.5	102.6	473.1	4731
ton CO2 eq/yr.	1194.561	171.2442137	1365.805	13658.05

Plot data	
Saved impact	13658.05
Battery impact	318.011
Power electron	95.4033

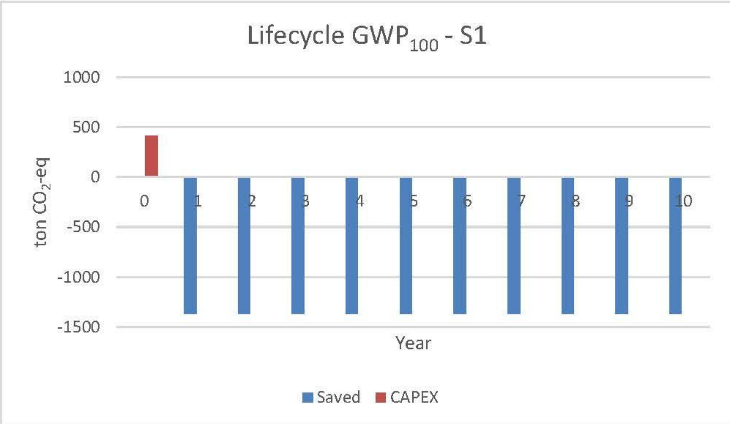
Battery Size	653	kWh	
Emission LBV	172	kg CO2 eq/kWh	GWP 100
Emission AVV	487	kg CO2 eq/kWh	GWP 101
Battery impact			
LBV	112.316	ton CO2 eq	
AVV	318.011	ton CO2 eq	
Power Electronics			
LBV	33.6948		
AVV	95.4033		



Impact of battery production compared to saved fuel in Scenario 1

	Months	Days
Payback time	3.632269	18.96806277

	Saved	CAPEX
0	0	413.4143
1	-1365.81	0
2	-1365.81	0
3	-1365.81	0
4	-1365.81	0
5	-1365.81	0
6	-1365.81	0
7	-1365.81	0
8	-1365.81	0
9	-1365.81	0
10	-1365.81	0

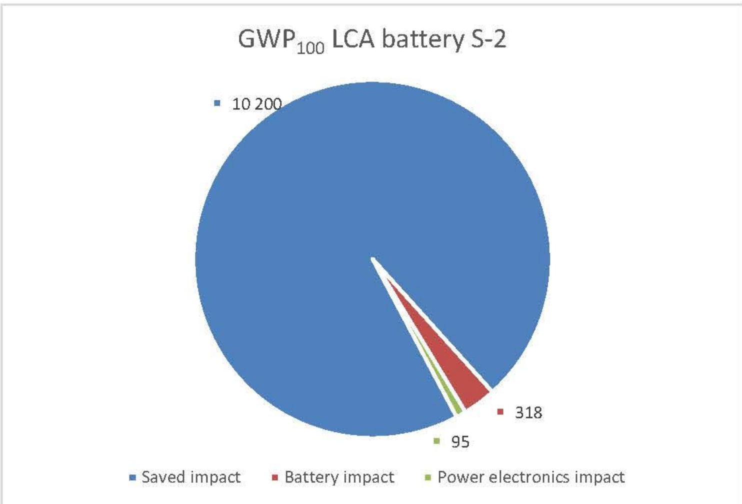


Impact of battery production compared to saved fuel in Scenario 2

Scenario 2				
Red. fuel/yr.	276.8	76.4	353.2	3532
ton CO2 eq/yr.	892.543	127.4441536	1019.987	10199.87

Plot data	
Saved impact	10199.87
Battery impact	318.011
Power electron	95.4033

Battery Size	653	kWh	
Emission LBV	172	kg CO2 eq/kWh	GWP 100
Emission AVV	487	kg CO2 eq/kWh	GWP 100
Battery impact			
LBV	112.316	ton CO2 eq	
AVV	318.011	ton CO2 eq	
Power Electronics			
LBV	33.6948		
AVV	95.4033		



Impact of battery production compared to saved fuel in Scenario 2

	Months	Days
Payback time	4.863759	25.91277322

	Saved	CAPEX
0	0	413.4143
1	-1019.99	0
2	-1019.99	0
3	-1019.99	0
4	-1019.99	0
5	-1019.99	0
6	-1019.99	0
7	-1019.99	0
8	-1019.99	0
9	-1019.99	0
10	-1019.99	0