OMB6 Student Project: Hybrid Marine Vessel

TEK5380 - Project on Renewable Energy

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ABSTRACT:

This is a report of a student project for the course TEK5380 Project on Renewable Energy at the University of Oslo. The goal of the project is for students to learn about and gain experience in systems engineering and project work as well as learning about renewable energy systems. Along with Sintef, IFE, Havila and Corvus, Equinor is conducting a project with the goal of increasing benefits of battery use on hybrid marine power systems called OMB6. As a preliminary study Equinor has assigned a group of students at UiO to analyse power data from an existing hybrid powered vessel to explore improvement ideas. As well as data analysis, a case study is conducted for four different scenarios; vessel with solely diesel powered system, vessel with hybrid system, vessel with hybrid system and charging from onshore external power supply in port and vessel with hybrid system and charging from offshore and offshore external power supply. Data analysis showed that the hybrid power system's main purpose, spinning reserve capacity, operates as intended most of the time but that there is still room for improvement in the operational strategy. The case study proved that spinning reserve capacity is the main contributor of the battery system for reduced fuel consumption. Furthermore, the scenario in with on- and offshore charging reduced the fuel consumption and CO_2 emissions from the vessel in the highest degree.

Contents

1 Introduction

1.1 Background

The marine industry is a large contributor to the world-wide greenhouse gas emissions. In 2018 the International Maritime Organization adopted mandatory measures to create incentive to reduce emissions[14]. Therefore, the marine industry is developing strategies in order to reduce emissions from marine vessels. The strategies that have been adopted include the design of the hull, the power and propulsion system of the vessel, alternative fuels, alternative energy sources and operation[2]. Some examples of measures are hybrid power systems, biofuels, carbon capture and lightweight materials.

Equinor has a large amount of marine operations and have ambitions to reduce their total emissions by 40% by 2030[4]. One measure Equinor has adopted is hybrid power systems on marine vessels. From 2021 Equinor will collaborate with Sintef, IFE, Havila and Corvus on a project named OMB6[15]. In this project, 6 years of operational data from hybrid marine vessels will be analysed with the goal of increasing the benefit of the hybrid system by 5-10%. As a preliminary study, Equinor has issued a student project based on real data from one of the vessels analysed in the OMB6 project. The power system of the vessel consists of four diesel generators and a marine battery to supply the onboard loads such as propulsion engines and hotel load.

1.2 Aim and Objectives

The group has received one week of operational data from Equinor. This data is to be analysed mainly to explore the possible benefits of battery charging from an external energy source. Four different operation scenarios for the vessel have been introduced and will be analysed with the goal of increasing the utilization of the marine battery installed on the vessel.

The aim of this project is;

Explore improvement ideas for battery utilization on marine vessels in order to reduce CO2 emissions.

The following objectives will be explored;

1. To review relevant literature for hybrid vessels.
2. To review and analyse energy data from a hybrid vessel during three offshore trips.
3. To conduct a case study:
    - Base case 1: The power generation on the vessel without battery.

- Base case 2: The power generation on the vessel with battery and no external power source for charging.
- Case 1: The power generation on the vessel with battery system with onshore external power source for charging and onboard supply.
- Case 2: The power generation on the vessel with battery system onshore and offshore external power source for charging and onboard supply.

4. Explore alternative strategies for optimizing battery utilization

1.3 Organization

The group consists of four students from the Renewable Energy Systems master programme at the Institution of Technology Systems at the University of Oslo. The students have backgrounds from Material technology, electrical engineering, renewable energy and mechanical engineering.

The proposed progress plan can be found in fig. 1. Throughout this project the students work mainly together. Two students are mainly responsible to handle the data for analysis and the other two are mainly responsible for literature study and documenting findings. Observations are discussed with the group as a whole before reaching conclusions or assumptions.

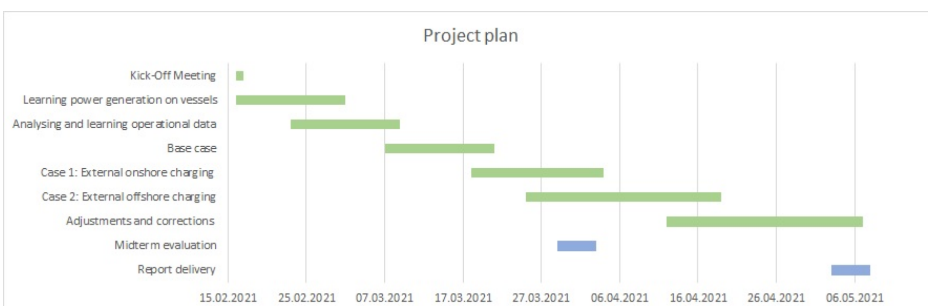


Figure 1: Progress plan

1.4 Report Structure

First, a description of the system and relevant literature are reviewed in Chapter 2 ***Background***. This chapter consists of system configuration, different components that are important for the vessel, and for further analysis of the operation onboard. Then, a literature survey is performed, where relevant projects and papers are described. Secondly, the result and observations from analysing the provided data are presented in Chapter 3 ***System Analysis Part 1***. The real data from the dataset is used to analyse how the hybrid vessel presently operates. Different operational strategies and notable observations are given and the calculation for fuel efficiency and emissions. The data analysis will then be used to conduct a case study in Chapter 4 ***System Analysis Part 2***, which focuses on four cases. The cases will explore the different opportunities with battery and charging. The results will follow in Chapter 4 ***System Analysis Part 1*** where the necessary calculations are displayed. A discussion in Chapter 5 ***Discussion*** will bring forward the process this student project has been through and the changes along the way. Lastly, Chapter 6 ***Conclusion*** will draw the conclusion and highlight suggestions for the way forward in the wake of this study.

2 Background

2.1 System Description

The aim of the project is to reduce emissions from a single marine vessel with a hybrid power system. Therefore, the system is confined to the vessel power system as a microgrid. Within the system, there are several components. All components that are not generation, storage, or propulsion on the system are defined as the hotel load. The system components are:

- Four Diesel Generators
- Battery Subsystem
- Hotel Load
- Electric Thruster and Propulsion Motors

2.1.1 System configuration

The system boundary is the power system on the vessel. External sources as shore power and diesel are in the surrounding environment and are only considered as inputs to the system. Furthermore, the battery system is considered a gray box. The energy in and out of the battery is considered, but due to limited information, detailed battery operation is not included. Hotel Load is only an energy consumer, therefore considered as a black box. The four diesel generators are considered as gray boxes. Power, fuel consumption, and efficiency are the generator properties used. Lastly, only the power demand from the electric thruster and propulsion engines are used, thus this subsystem is considered as a black box.

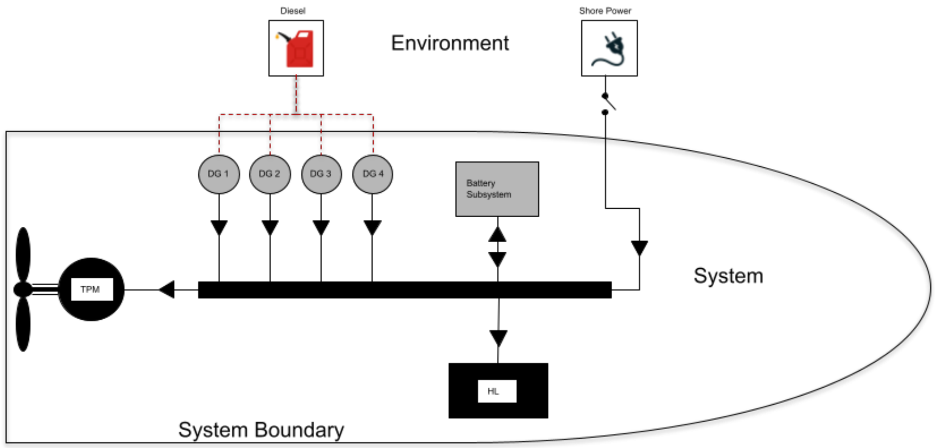


Figure 2: System Illustration

Label	Component	Capacity
DG1	Diesel Generator 1	2100 kW
DG2	Diesel Generator 2	2100 kW
DG3	Diesel Generator 3	2100 kW
DG4	Diesel Generator 4	2100 kW
Battery Subsystem	Battery Subsystem	620 kWh
HL	Hotel Load	
TPM	Thruster and Propulsion Motors	
Shore Power	External Power Source	

Table 1: System Components

2.1.2 Power flow

The data provided by Equinor and Sintef consists of battery power, propulsion power, hotel load, shore power, generator power, and generator fuel consumption. The diesel generators and shore power are the two energy inputs of the system. All power consumed within the microgrid is supplied either by one to four diesel generators or energy from shore. In the dataset, shore power has supplied the vessel to cover the hotel load while docked, and all other components are shut off. The stored power in the battery comes from either shore or generator. In the dataset, the battery is charged by the shore power while docked; otherwise, the generators charge the battery. For Base Case, the shore power will only supply the hotel load. In Case 1 and 2, the shore power is charging the battery as well as supplying hotel load.

2.1.3 Operation modes

The vessel has several different operation modes, which indicate the operational status of the power system. Generation and load profiles may differ between operation modes. Therefore, the data is tagged with an operation ID which indicates what operation the vessel is in at each timeframe.

Operation ID	Operation Mode
0	Other
1	Port
2	Maneuver
3	Transit Eco
4	Transit
5	Transit Fast
6	Port + Shore Connection
7	Standby
8	Port Battery
100	DP Standby
101	DP Class 2
102	DP Gangway
103	DP Maneuver

Table 2: Operation Modes

The main purpose of the battery system is to operate as spinning reserve during dynamic positioning. Because spinning reserve is not required during all operation modes, the battery is also used for peak shaving in other operation modes. While the battery is used as spinning reserve, it is expected to have high state of charge and not deliver much power to the system. If a generator fails or shuts down during DP-mode, the battery must be able to instantly replace the faulty generator with the same power, thus the battery is assumed to be able to deliver 2100 kW. Data from each operation mode will be isolated and analysed to explore where fuel consumption of diesel generators can be minimized.

2.1.4 Fidelity of system

This is a severely simplified model of a hybrid powered marine vessel. The system is designed according to the data provided, along with some assumptions. Factors such as metocean data, fluid dynamics, system temperatures, and lifecycle greenhouse gas emissions of shore power are not considered in the system. The main goal of the project is for the participants of OMB6 to get an indication of the potential improvements of plug-in hybrid marine systems by alternative charging schemes.

2.2 Literature Survey

2.2.1 Reference projects

Offshore supply vessels have been designed, traditionally, to guarantee that they can perform their jobs almost at any sea state. Through multiple engines and advanced dynamic positioning systems [10], this has been accomplished. But to achieve a reduction of emission and fuel consumption, hybrid technologies need to be introduced. After the electrification of automotive transportation, it became more feasible to use batteries in the maritime sector. Today, the marine sector has begun to insert batteries into their vessels and utilize them in different ways. Batteries are used in addition to the diesel generator to reduce fuel consumption or as a substitute for a generator. Today's challenges are to guarantee that batteries can store and deliver enough power to ensure the onboard power requirements as well as defining a sufficient operation strategy. Some Offshore Supply Vessels projects are described below in table 3. There are other hybrid projects on marine vessels like ferries, cruise ships, fishing vessels, shipping vessels and more.

Firm	Vessel	Description	Year
Eidesvik Offshore	Viking Energy	[5] Converting the vessel into a sea-going plug-in battery hybrid with technology from Westcon and Kongsberg Maritime. The first vessel to install a 653 kWh/1600 kW battery on a supply vessel for propulsion.	2016
Solstad Farstad	Normand Server and Normand Supporter	[3] 560 kWh battery is replacing 1 of 4 diesel generators. Westcon Power and Automation are providing the batteries, and the sister company Westcon Yards are carrying out the conversion. Same system as Viking Energy.	2019

Firm	Vessel	Description	Year
Island Offshore	Island Crusade, Island contender and Island Commander	[9] Kongsberg Maritime are supplying the hybrid battery solutions, they are combining conventional LNG or diesel engines with its SAVe Energy battery system.	2020
Harvey Gulf International Marine	Harvey Energy	[7] The technology group Wärtilä will carry out the conversion, with a 1450 kW battery hybrid solution. The first dual-fuel PSV in North America.	September 2020
CBO	Flamengo	[13] Will be the first vessel in Latin America to be fitted with a battery pack for hybrid propulsion. The technology group Wärtsilä will carry out the conversion.	Equipment is scheduled for April 2021
Harvey Gulf International Marine	Harvey Power, Harvey Liberty, Harvey Freedom and Harvey America.	[17] The technology group Wärtsilä will carry out the conversion, with a 746 kWh batteries.	Start 2021 and completed in early 2022.

Table 3: Reference projects (past, current, and planned)

The hybrid vessel Viking Energy has been active since 2015. The battery pack is used for peak shaving; it absorbs peak power loads during transit and contributes to additional power when needed instantly during demanding operations [5]. The biggest news from this project is that the battery pack replaced one of the main engines when the vessel was operating in dynamic positioning (DP) mode, and it was here the most significant energy saving was. From 2018 the owners could tell that, on average, fuel consumption has been reduced by 16-17 percent, and in dynamic positioning mode, the fuel consumption reduction has been as high as 28 percent. The hybrid battery installation enables diesel engines to function up to 20 percent more efficiently and will, therefore, reduce operating costs. Because of the even supply of power from the batteries and that the batteries take over much of the generators' load, this results in a reduced need for maintenance and gives a more stable operation.

The other projects mentioned above have not been active long and have some expectations for the hybridization of the vessels when it comes to emissions, fuel costs savings, and use. The [3] [12] hybridization is expected to reduce emissions by 15-20 percent, and [15] to have an overall fuel cost savings in the range of 10-20 percent. These numbers correlate well with the results from the Viking Energy vessels. The use of the battery pack will be very similar to the Viking Energy vessel.

2.2.2 Relevant theoretical research projects

In [8] a study on GHG emission on hybrid vessels was done. In this paper, the authors created an optimization model in order to find a plug-in hybrid vessel configuration and strategy with minimized GHG emission. In their model lifecycle, GHG emissions from electricity from coal power plants were used, which resulted in high emissions from larger battery capacities. However, it was found that the strategy with maximum amount of battery modules and most shore charging gave the lowest on-board fuel consumption. This indicates that the scenarios proposed in section 1 will have lower fuel consumption.

Researchers from Delft University of Technology and Harbin Engineering University have researched the impact of hybrid propulsion on large cargo ships during port approaches [16]. A case study with three cases was conducted. The base case considered a conventional power system where all propulsion was provided by a diesel engine. The second case, auxiliary diesel engines provide electricity for an electric propulsion engine while the vessel is in coastal waters. In the third case, a battery powers an electric engine for propulsion in coastal waters. However, while on open sea, the auxiliary engines charge the battery while the main engine provides propulsion. The results of this study were that when approaching port, the battery powered system (case 3) had the highest accumulated fuel consumption. Even though the local emissions of GHG were lower in coastal areas were zero, the total GHG emissions were higher than that of a conventional power system. The research in [16] however, differs from the OMB6 student project on some critical areas. Firstly the round-trip fuel consumption is not considered and most open-water operation is neglected. Furthermore, battery charging from external sources is not considered, which could greatly lower the fuel consumption of the vessel used for this study.

In [6] a machine learning algorithm was used to predict the load profile of a hybrid vessel. The power system of the vessel used in [6] is very similar to that of the OMB6 student research. Using machine learning to predict the load profile resulted in a 9.6% reduction of fuel consumption and 24% increase in endurance. These results are well within the goal of the OMB6 project and we believe that fuel economy can be further improved with the addition of external charging of the battery.

2.3 Revised Scope of work

Based on the research presented, there is strong belief that hybridization of marine vessels can reduce fuel consumption and GHG emissions. Results from both similar vessels and theoretical models show the potential of such a power system in the maritime sector.

The goal of OMB6 is to improve existing marine hybrid power systems. Using the data provided for this project, the group expects to find that the battery is used for both peak shaving as well as spinning reserve during operation, resulting in a considerable reduction in fuel consumption. Furthermore, during the analysis, better use of the battery system such that fuel consumption can be further reduced may be found.

Conducting a case study using observations made during data analysis will indicate how the benefits of marine hybrid power systems may be improved. Assuming that all energy provided from external sources used in Case 1 and Case 2 is considered renewable, GHG emissions should be lowest in the scenario with most external energy provided.

3 System Analysis Part 1

In this section, the results and observations from analysing the provided data are presented. The real data from the dataset is used to analyse how the hybrid vessel presently operates, which will be used to conduct a case study. The analysis is done in Python.

During data analysis, it became more and more clear that the hybrid system from which the data is extracted is not optimal. There is reason to believe that the battery causes strange behavior of the power system in some instances. However, there are also instances where the battery is operating as intended for peak shaving or spinning reserve, preventing additional diesel generators to start up. These observations are further discussed later in this section.

3.1 Data Overview

The data provided is one week of data in one second resolution, i.e., over 600000 rows of data. Therefore there is not much accurate analysis that can be done by analysing the whole dataset at once. However, to get an idea of how the vessel operates, it is useful to study the whole dataset. To begin, the power profile for the week shows peak loads, peak battery in- and output, as well as when the vessel is at port.

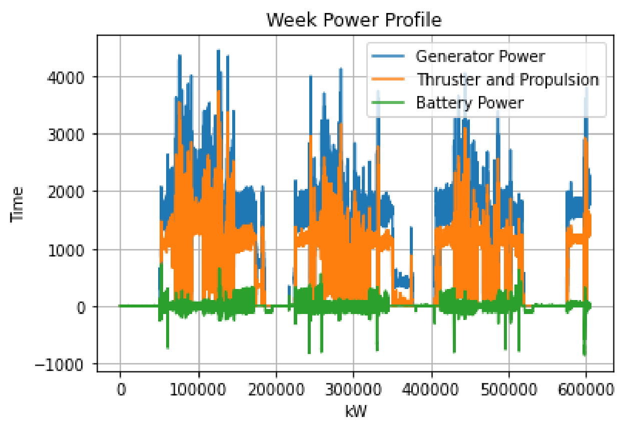
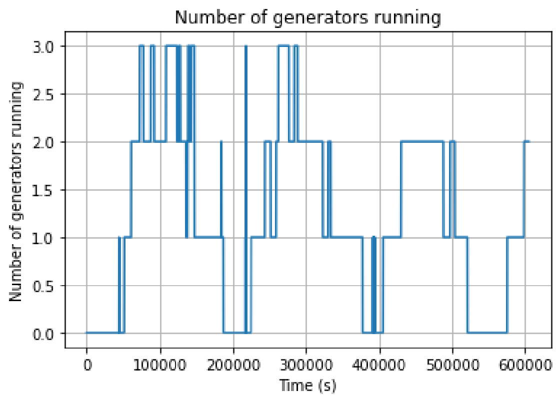
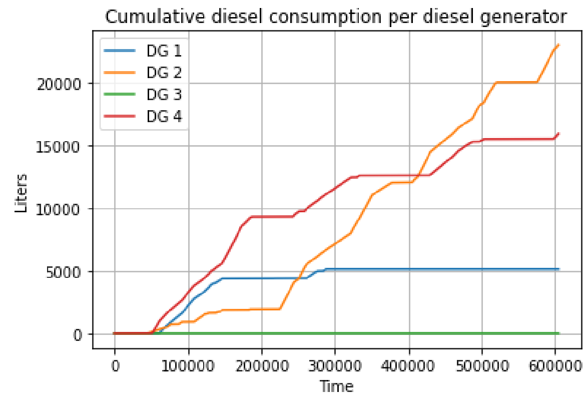


Figure 3: Generator, thruster and propulsion and battery outputs throughout week

In fig. 3, it is shown that the vessel sails three stretches between ports and begins the fourth sail at the end of the week. The battery power output is represented in green. Positive battery output is power delivered by battery to the system (discharge), and negative battery output is power from system into battery (recharge). The peak demand for the thruster and propulsion system is a little less than 4000 kW. In theory, with 2100 kW diesel generators, this demand could be met by only two diesel generators. As can be seen in fig. 4a, demand is mostly met by one or two diesel generators. At times with three generators running, the third generator is mostly used as spinning reserve due to rules and regulations. In fig. 4b the cumulative fuel consumption of the diesel generators is presented. Generators 2 and 4 are the main generators supplying energy to the vessel. Generator 1 is used some, but mostly for spinning reserve. Lastly, generator 3 is never used and is considered a redundant diesel generator.



(a) Number of generators running



(b) Cumulative fuel consumption per generator

Figure 4

To analyse the battery operation, it is useful to find what vessel operation in which the battery is most used. This investigation also revealed that not all operation ID's are used in the data. In table 4, the operation ID's found in the data is listed. In fig. 5 the time series battery output is plotted along with operation ID. From this graph, it is clear that the battery has the highest output during operation ID 3 Transit Eco, in which the vessel is in about one-third of the week's operation. Furthermore, the graph shows that the battery also contributes during operation ID 100 (10 in figure) DP-mode but to a lower degree.

Operation ID in use	Operation Mode
1	Port
3	Transit Eco
5	Transit Fast
6	Port Shore Connection
7	Standby
100	DP

Table 4: Operation ID's used

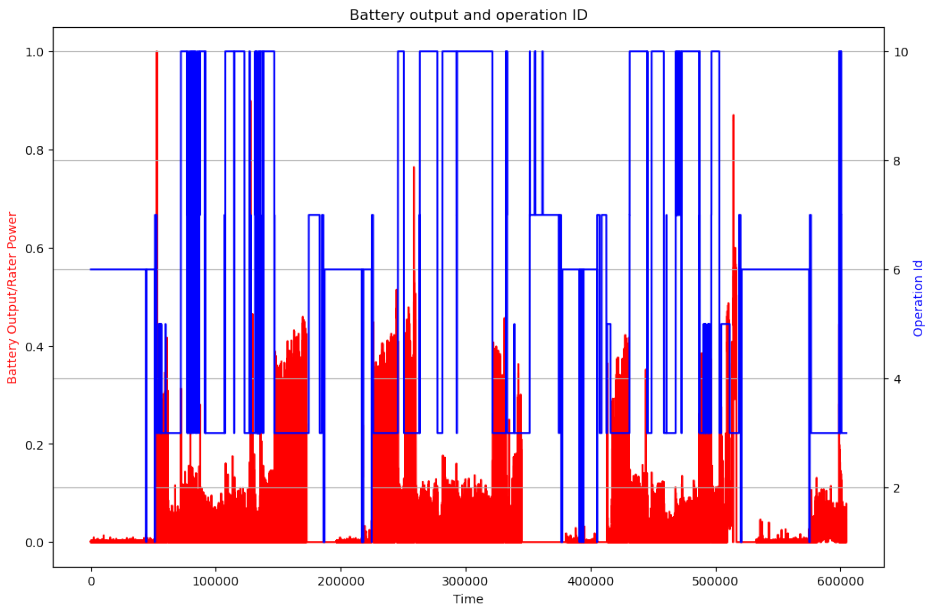


Figure 5: Operation ID and battery output (Operation ID 100 adjusted to 10 for this graph)

3.2 Fuel Consumption And Fuel Efficiency

3.2.1 Generator fuel consumption and efficiency by output

Using the real data, the fuel consumption and fuel efficiency of the generators can be found. Fuel consumption per kW provided and the efficiency of the diesel generators will be used in the case study to calculate GHG emissions and increase the efficiency of the system.

The fuel consumption of each diesel generator is provided in the dataset as l/h. Fuel consumption is used to calculate the energy efficiency of each generator. Fuel consumption is provided as (l/h) and power output as (kW), and using these values, the fuel and efficiency curves are generated. The rated power of the generators is 2100kW, and the fuel efficiency is a value of kWh/l. Calculating the energy generated by generators in kWh and the volume of diesel consumption in l and the resulting efficiency, the following steps were made.

P_i = power (kW) in timestep i $(1s)$
$\dot{V}_i$ = fuel consumption (l/h) in timestep i $(1s)$
E_i = energy (kWh) in timestep i $(1s)$
V_i = volume (l) in timestep i $(1s)$
η_f = fuel efficiency (kWh/l)

$E_i = \frac{P_i}{3600}$
$V_i = \frac{\dot{V}_1}{3600}$

$\eta_{fi} = \frac{E_i}{V_i}$

The resulting fuel consumption and efficiency curves are:

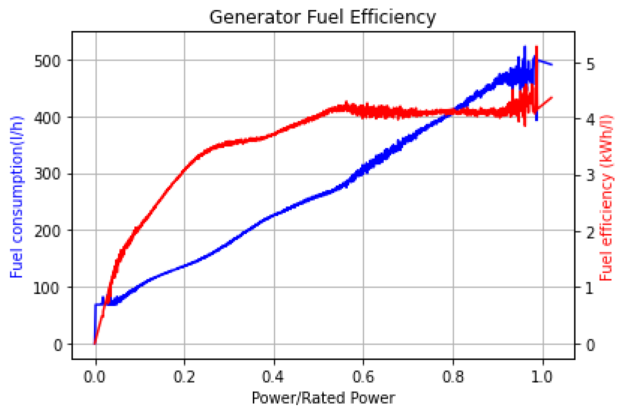


Figure 6: Diesel generator fuel consumption and efficiency

As can be seen in fig. 6, generator fuel consumption at maximum power output is close to 500 l/h. The generator efficiency between 50% and 100% power is almost flat. Any generator operation below 50% power is considered a suboptimal operation and should be avoided as much as possible. Furthermore, the fuel consumption is considered linear with coefficients 445 as the slope and 47 as the y-intercept using normalised power outputs.

3.2.2 Cumulative fuel consumption and emissions

To reduce the CO_2 emissions of this system, emissions in the reference data must be known. Since fuel consumption is provided per time-step in the data, the cumulative fuel consumption can be calculated. Sources on the amount of CO_2 per liter of diesel vary by a few grams, but the most commonly found is 2.68 kg [1]. The average fuel consumption, as well as cumulative consumption and emissions, are listed per operation ID and in total in table 5.

	Total time (h:m)	Avg fuel consumption (l/h)	Total fuel consumption (l)	Total emissions (kg)
OP1: Port	1:35	102	161	431
OP3: Transit Eco	59:11	428	25381	68021
OP5: Transit Fast	3:30	395	1380	3698
OP6: Port Shore	46:48	3	135	362
OP7: Standby	17:06	201	3452	9251
OP100: DP	39:51	342	13630	36528
Whole trip	168:00	262	44142	118300

Table 5: Cumulative fuel consumption and CO_2 emissions.

Transit and Dynamic Positioning (DP) are clearly the operations with the highest consumption and emissions, both cumulative and per hour. This is no surprise, as these operations are the most energy intensive. The distinction between transit eco and transit fast is not clearly seen from the data, other than in transit fast, only one diesel generator is in operation, which saves fuel and emissions.

3.3 Battery State Of Charge

The state of charge (SoC) of the battery has not been provided. Thus, it has been calculated from the data. According to Equinor, the battery capacity is 620 kWh and operates between 80% and 20% SoC. Using this information along with the battery output from the dataset, SoC has been calculated. The initial state of charge is assumed to be at 80%, which is 496 kWh and the battery efficiency is 92%. SoC is calculated by iterating through the dataset and subtracting the battery output from each timestep. Recharging the battery gives negative output, thus SoC will increase during recharge. The resulting time series plot of SoC of the battery is in fig. 7. The graph of SoC tells us a great deal about how the system is designed. It can be seen that there is one instance in which the SoC drops below 20%, which is below the allowed limit for the battery. Furthermore, the SoC shows when the battery is mainly used, with the most significant discharge around the 150000 and 500000 second marks. Shortly after discharge, the battery is recharged and ready for new discharge. Combining the state of charge time series with the position each hour of the week shows that the battery is used heavily in the transit on the way back to shore. In order to exploit the green injection into the system, which is power from shore to charge the battery, the battery is discharged as much as possible before entering the port. The data also shows the battery being used in transit on the way to platforms. Before going into DP, the battery is recharged by the diesel generators to ensure sufficient spinning reserve capacity.

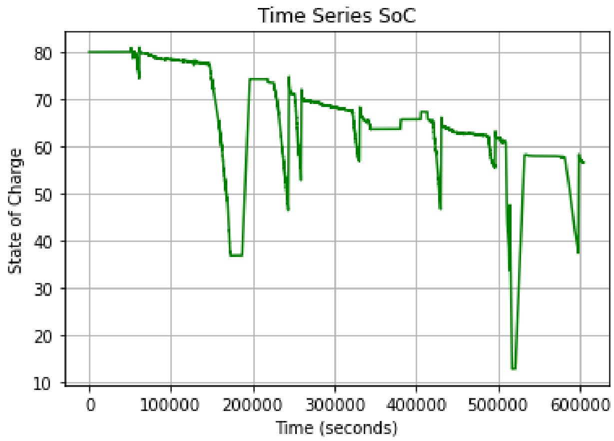


Figure 7: Calculated SoC from real data

3.4 Operational Strategy and Notable Observations

For analysis of the complete data set, two approaches were taken. First, the data were extracted and sorted into files based on their operation ID. This was done to get a better understanding of the data and relate its behavioural pattern to the operation modes. From there, the data was analysed by examining fragments. The second way was to analyse the whole week, hour by hour. The position every hour was known, so that the operation modes could be related to the position. These two approaches gave in some instances different impressions of how the battery was used according to the intended functions. Inspection of the data revealed both positive and negative usage patterns of the battery and diesel generators. On the negative side, there were generators running at low efficiency in extensive periods as well as strange oscillations in battery output. On the positive side, there was recognition of intended battery usage in terms of peak shaving and spinning reserve. These observations will be explained further in the coming sections, starting with the stated most important battery function – spinning reserve in DP-mode.

3.4.1 Dynamic positioning spinning reserve

Batteries are installed on this vessel to act as spinning reserve during dynamic positioning, which can be seen in the data. The battery will, in that case, allow for only the amount of generators to meet the load to be operating and prevent redundant generators to operate. Data from DP-mode is isolated, and times where this happened searched for. First, the number of generators running at all times in DP-mode is plotted to get an overview.

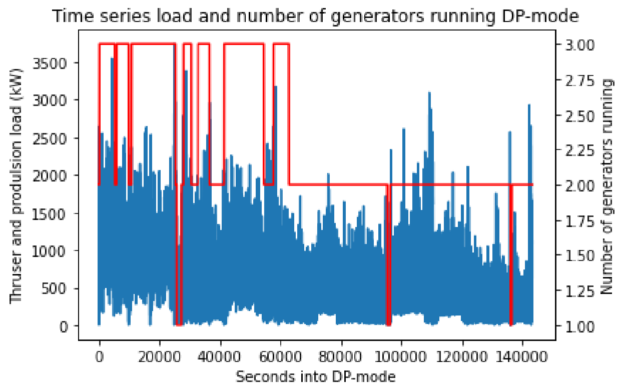
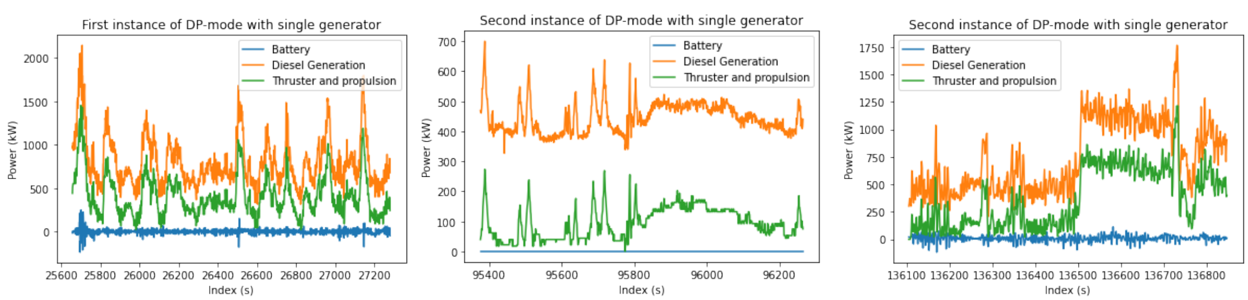


Figure 8: Number of generators running in DP-mode

In fig. 8 there are three instances where a single generator is running. Given the regulations for spinning reserve in DP-mode, this indicates that the battery is used for spinning reserve. Furthermore, these three instances are all while maneuvering in DP-mode. Also, the load is sufficient for a single generator to meet the demand. In fig. 9 the diesel generator, thruster, propulsion load, and the battery output are plotted. These are clearly periods where the battery serves as spinning reserve while the vessel is in dynamic positioning. Note that these periods of single generator operation in DP-mode are very short. The first instance is about 30 minutes, and the second and third are only about 15 minutes, accounting for about 2% of the total time in which the vessel is in DP-mode.

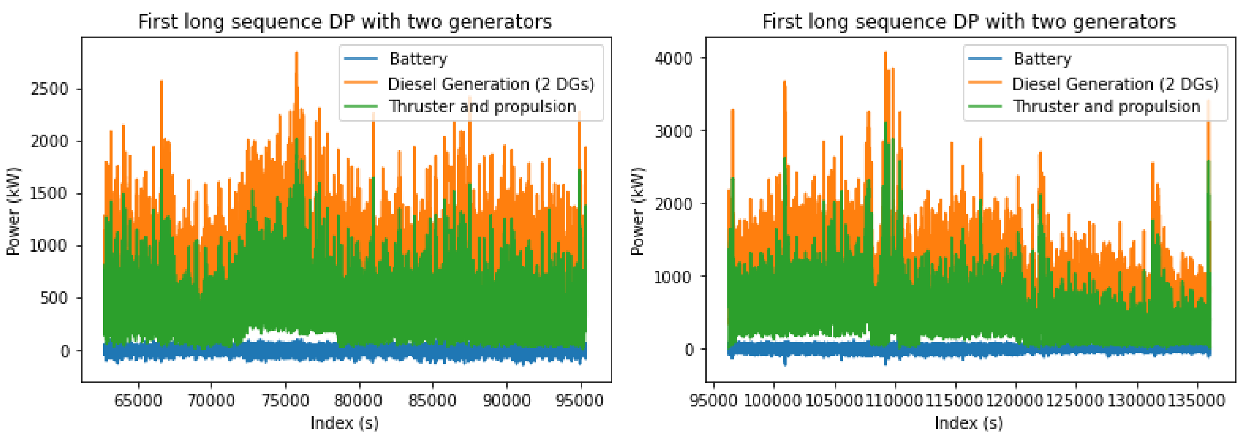


(a) First DP-Mode single generator (b) Second DP-mode single generator (c) Third DP-mode single generator

Figure 9

In fig. 10 it can be seen that the total time in DP with two generators running is majority of the time spent in DP. From the 40 hours of total time in DP, 25 of those hours are with two generators running, or 62,5% of the time. The load during this time is well below 2100 kW for the majority of the time, which means that it could be met by one generator. This indicates that it is the second diesel generator that acts as a spinning reserve for this time. However, when looking at the different segments of the trip in DP instead of just the amount of time below a certain load, a different picture emerges. fig. 11 shows a long period with

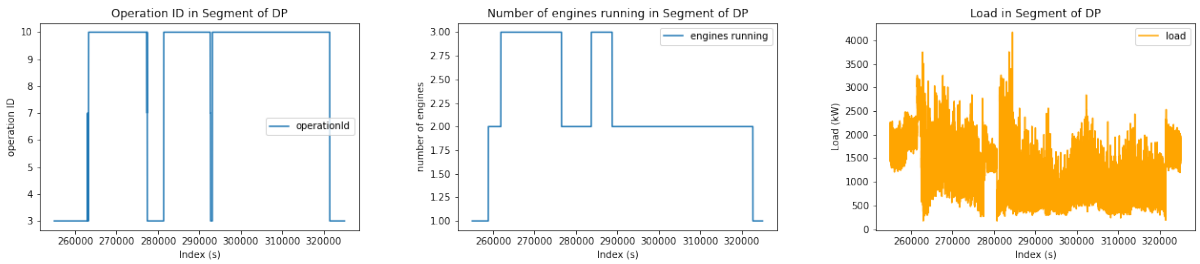
DP on day 4 of the trip. From approximately index 288000, there are two generators running. The load here is the thruster and propulsion plus the hotel load. The hotel load is, as mentioned earlier, synthesized and therefore not included in the other figures. However, it is the best indication available for the actual load, so it is included here for this purpose. Even here, the time below 2100 kW comprises the vast majority when actually looking at the numbers, but observe that peaks above this value are frequent. This means that with only one generator running, an additional generator would have to ramp up very often. This is likely not a good operation strategy, so it is assumed that two generators are required at this time only to meet the load. Without a battery, one would need a third generator as well to run as spinning reserve. This indicates that the battery serves as spinning reserve for this whole period of two operating generators. These 15 hours of DP are a good representation of the other segments of DP as well in terms of the size of the load. Given that the majority of the time in DP has two generators in operation, in addition to the reasoning in this paragraph, the conclusion is that the battery contributes significantly to a reduction of fuel consumption and, therefore, emissions through spinning reserve.



(a) (b)

Figure 10

fig. 8 shows that there are long periods with 3 generators running as well. The total time comprise about 34% of the time in DP. Looking at all the segments with three generators, the load is as expected on average higher than with two and one, but still, the load never peaks above what could be met by two generators. This leads to the conclusion that the third generator acts as spinning instead of the battery.

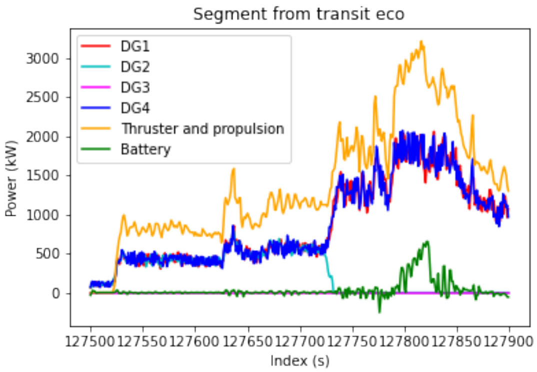


(a) (b) (c)

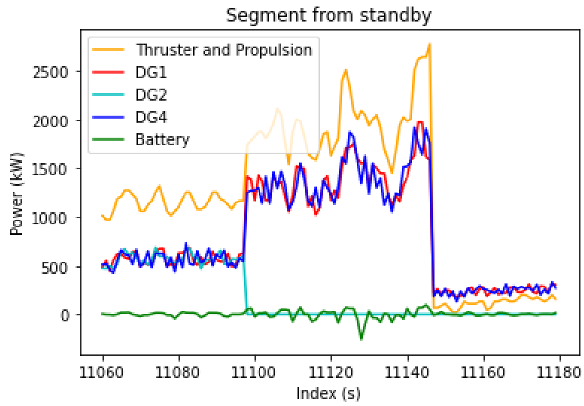
Figure 11

3.4.2 Low efficiency generator output

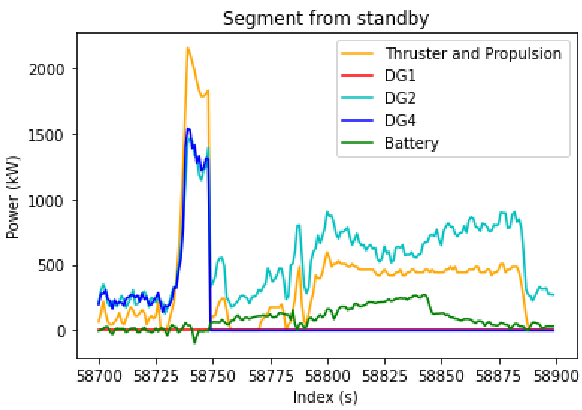
The data shows that for a considerable amount of time, multiple generators are running on low efficiency during operations other than dynamic positioning. Considering fuel consumption, this is not optimal. Other times, a generator is turned on without any indication from the load that it is necessary. In fig. 12 four instances of such operation are presented.



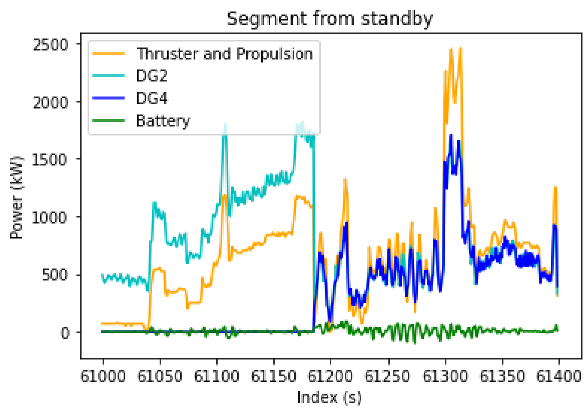
(a) OpID 3 segment



(b) OpID 7 segment



(c) OpID 7 segment



(d) OpID 7 segment

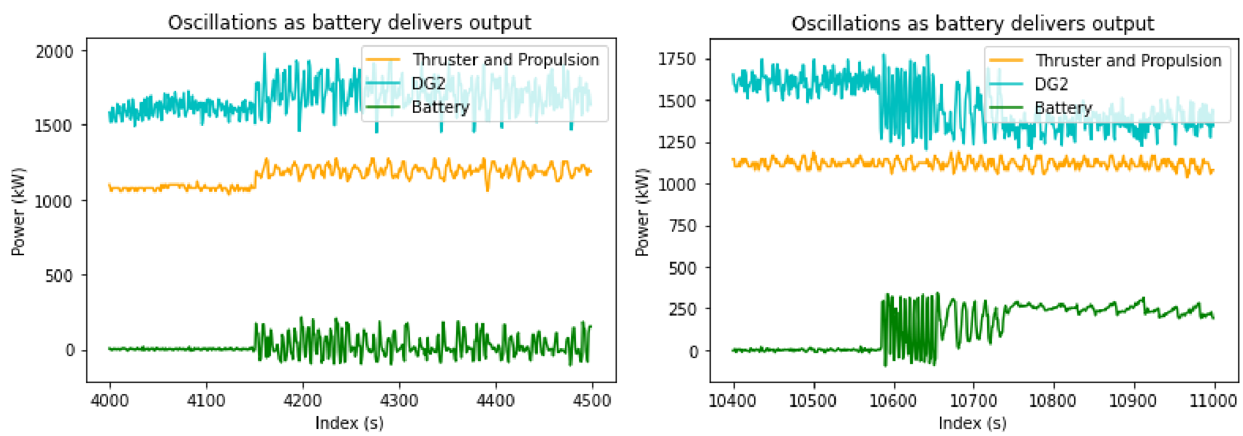
Figure 12: This is where shit goes down

In fig. 12a a segment from operation ID 3, Transit Eco, is shown. At the beginning of this segment, three generators are delivering about 500 kW to the system. Considering diesel generator efficiency, this is interpreted as suboptimal operation. Later in the segment, DG2 is shut off, and two generators meet the load demand at favorable efficiencies. Furthermore, there is a short segment in which the battery covers a load peak in order to prevent DG2 from starting up again, signs of peak shaving. In fig. 12b and fig. 12c also shows segments in which three generators are running at suboptimal efficiency before shutting a generator down and increasing the efficiency. In fig. 12d the opposite happens where a single generator is running, and another is started up.

3.4.3 Oscillations due to battery

Loads and outputs was found to be fluctuating throughout the data, and in some segments more than others. In many instances, it is observed that the most significant oscillations occur when the battery is delivering power to the system. In fig. 13 two such instances are presented. Throughout these segments of 500 and

600 seconds, the thruster and propulsion load remains fairly constant while as soon as the battery delivers power, the generator outputs start oscillating with relatively high amplitude. Many more instances like these occur within the dataset. Therefore, it is believed that the battery is the root of these fluctuations. Another observation in fig. 13b is that with constant propulsion load, DG2 is ramped down, and the battery shares the load. The generator is still operating at optimal efficiency, leading to a reduction in fuel consumption.



(a) Oscillation 1

(b) Oscillation 2

Figure 13

Investigating short segments like these is a significant contributor to understanding the operation strategy of the system. Though it is time consuming, assumptions and conclusions can be made by studying what happens around significant events like the shut-down of a generator or large discharge of the battery. Operation ID 7, Standby mode, is found to show strange behaviour of the system. It was not until late in the research that it was discovered that standby mode is mostly short segments in between DP-modes. This causes sudden changes in the operation ID 7 isolated dataset where index x and index x+1 may be hours apart in the whole dataset. Therefore fig. 12b, fig. 12c and fig. 12d have created confusion in understanding operational strategies for different operations. These figures may lead to misinformation, which the group learned at a later stage in the research.

3.4.4 Revised scope of work

Data analysis proved to be more elaborate and time consuming than first intended. Provided data and information are fairly limited to identify the vessel's operational strategy, and the group required more time to inspect data and make educated assumptions. It is concluded that the vessel does not operate optimally and, in some instances, not as intended by the operator. Undesirable operations are identified and may be useful for Equinor to further investigate in order to increase the benefits of the hybrid power system on the vessel. These factors have led to limited time and data to conduct a realistic case study. Therefore, the case study has been simplified according to the competence of the student group and the data available. The goal of the case study is then to create comparable emission data from the provided scenarios to indicate which pathways are worth investigating further in the OMB6 project.

4 System Analysis Part 2

In this section the case study has been conducted. Simple models using load data and assumed operational strategies are created and provide comparable results. Due to simplification, these results may differ from the real data and reality.

4.1 Model Description

The hotel load provided in the data is calculated as the difference between thruster and propulsion load and power generated, plus 250 kW which is assumed as base load when connected to shore and no power is provided by generators. Therefore, in the models used in this case study, the mean hotel load for each operation mode is used, resulting in a total load consisting of thruster and propulsion as well as the assumed hotel load. Spinning reserve capacity is assumed to be the capacity of a single diesel generator, 2100 kW. The battery is also assumed to have the capacity to deliver this power and has an efficiency of 92%.

Input data for models		
Mode	Hotel Load	Spinning Reserve Capacity
Transit	550 kW	0
DP-mode	500 kW	2100 kW
Standby	380 kW	0
Port	250 kW	0

Table 6: Input data for models

The models are made in Python using the Pandas library to analyse the data. For the models, the data is aggregated to 5 second resolution. This led to a handful of timesteps with arbitrary operation ID's where the hotel load is set to be 300 kW and is otherwise neglected. Calculating the power generation in the models is done by iterating through each timestep with a set of predetermined rules for the different operation modes. Fuel consumption and battery state of charge are also included in the models as presented in section 3. The models are designed so that diesel generators and battery meet the load at all times and calculates the outputs of these components. These outputs are then used to calculate fuel consumption and CO_2 emissions. When multiple generators are running in the model, the generators deliver equal power. If the battery is below 50% SoC, it is determined not sufficient to serve as spinning reserve, and an additional generator will serve this purpose.

Operational Strategies: Number of Generators Running					
Load Range	Mode	Base Case 1	Base Case 2	Case 1	Case 2
100 - 1000 kW	Transit	1	1	1	1
	DP-mode	2	1	1	1
	Standby	1	1	1	1
	Port	Shore	Shore	Shore + charge	Shore + charge
1000 - 2100 kW	Transit	1	1	1	1
	DP-mode	2	1	1	1
	Standby	1	1	1	1
2100 - 3000 kW	Transit	2	2	2	2
	DP-mode	3	2	2	2
	Standby	2	2	2	2
3000 - 4200 kW	Transit	2	2	2	2
	DP-mode	3	2	2	2
	Standby	2	2	2	2

Table 7: Operation strategies per case

4.1.1 Base Case 1

Base case 1 is a scenario of the vessel without a battery system. In this model, the generators meet the load at all times and an additional generator covers the spinning reserve capacity. This case is used as a reference case to compare reductions of fuel consumption and emissions.

4.1.2 Base Case 2

Base case 2 is a scenario of the vessel with a battery system and without external charging. In this scenario, the initial state of charge of the battery system affects the resulting fuel consumption. Therefore, the model is run with 20%, 50% and 80% initial SoC. The model for base case 2 is used for two additional subscenarios, battery used only for spinning reserve and battery used for both spinning reserve and peakshaving.

Peakshaving is modelled in two different ways:

1. Battery covers all loads over threshold of generator(s) for up to 10 seconds

2. Battery covers loads up to 900 kW above generator threshold if SoC is sufficient.

4.1.3 Case 1

Case 1 is a scenario with battery system and external charging at port. This model has the same subscenarios as Base Case 2 as well as two additional subscenarios where the battery delivers 1000 kW or 100 kW until SoC reaches 20%. These additional cases are modelled to explore alternative operation strategies.

4.1.4 Case 2

Case 2 is a scenario with battery system and external power supply and charging at port and certain offshore areas. This model has been run with the same subscenarios as Case 1. The areas with offshore charging were assumed to be at the green circles in fig. 14. The vessel is at these points for 10 hours, about 5.6% of the total week.

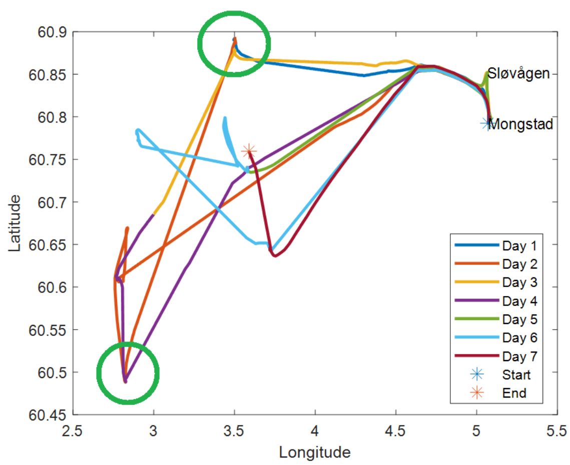


Figure 14: Vessel position throughout week. Green circles indicate where charging buoys are located

To ensure offshore charging, the model is based on a concept that consists of an offshore charging buoy. The buoy [11] will act as a charging station and a safe mooring point for the vessel as it waits to deliver goods to the platform. The power from the buoy is assumed as green electricity and will, therefore, eliminate all emissions from the vessel when connected to the buoy.

4.2 Results

The model provides generator output, battery output, and input from external power source per timestep in kW. As mentioned, in reality, many factors affect the fuel consumption of a marine vessel that is not included in these models. Therefore, the results are not comparable to real data. However, the models are comparable with one another, and these results are presented. A goal of the OMB6 project is to reduce CO_2 emissions on hybrid marine vessels. In fig. 15, the reduction of CO_2 emissions compared to Base Case 1 is presented.

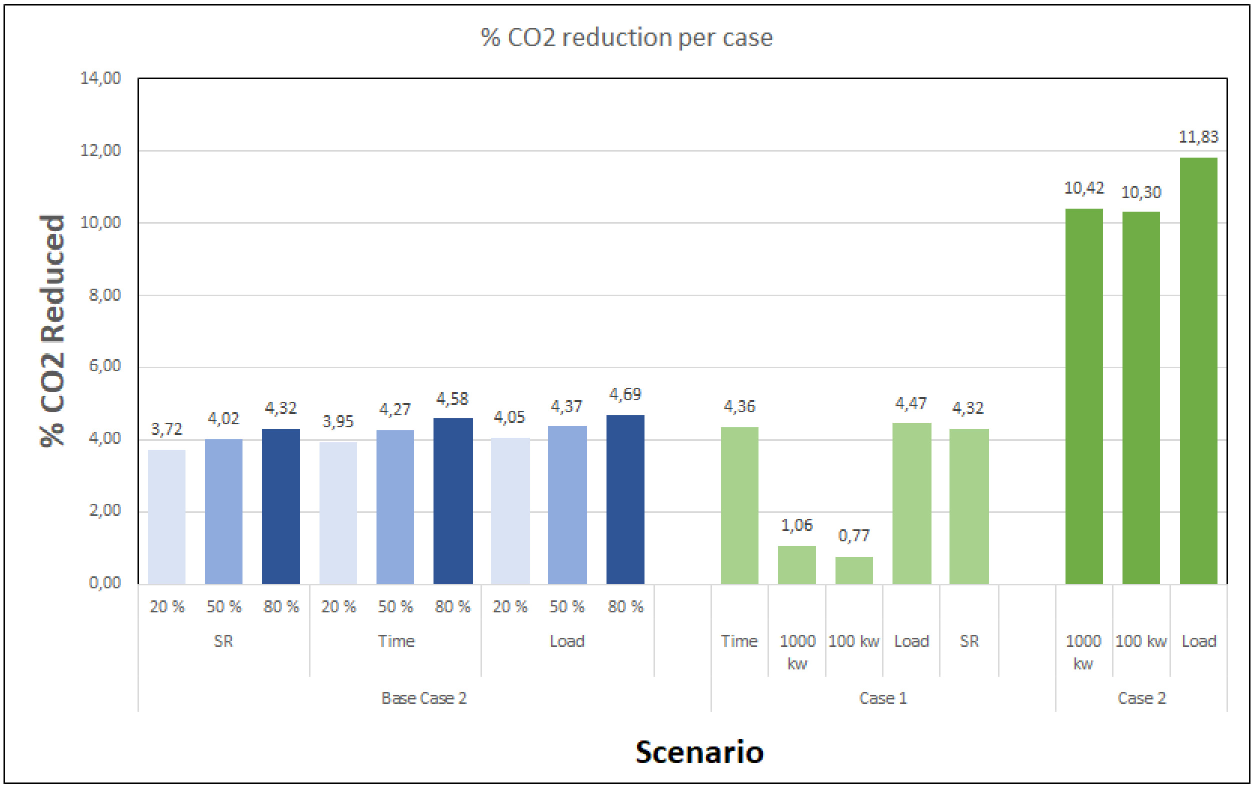


Figure 15: Percentage of emissions saved by scenario

It is clear that Case 2 has the most promising results with at least 10% reduction in emissions. Case 1, however, does not show a significant reduction in emissions compared to Base Case 2. This indicates that peak shaving account for only a fraction of emissions and that spinning reserve accounts for most of the saving. In Case 2, the cumulative load for the vessel is considerably lower due to offshore buoys not requiring standby or DP-mode as much.

To put these numbers into perspective, the cumulative fuel consumption from the data is 44142 l. Case 1 is the scenario that is most similar to the actual operation of the vessel, and Case 2 has 8% less CO_2 emissions than Case 1. This means that using these ratios found in the models, a scenario with on- and offshore power supply and charging would reduce fuel consumption by about 3500 l of diesel, or 10000 kg of CO_2 for this vessel per week.

4.2.1 Discussion of results

In all scenarios in which the battery is exclusively used as spinning reserve capacity, there is a significant reduction in emissions. Also, Base Case 2 with a fully charged battery (SR, 80%) results in identical emissions as Case 1 (SR). A reduction of about 4% of emissions can be expected as soon as a marine battery is installed. Although this is a considerable decrease in emissions, [5] obtained significantly better results at 16-17% decrease. The scenarios which include peak shaving do not have a significant reduction in emissions compared to spinning reserve. However, the battery can be better used for peak shaving in the models. The design strategy of the models limited the amount of battery output able to be implemented. If the models were created using better software or strategies, peak shaving could be improved and have more effect on the resulting emission. This is also a reason why Case 1 does not yield better results than Base Case 2. The main difference between these models is the charging of batteries, and when the batteries do not deliver substantial power, there is not substantial charging. In turn, this results in similar results for the two scenarios.

Case 2 clearly yields the best results considering fuel consumption and emissions. There are some uncertainties in this model. First of all, the times in which the vessel is connected to a buoy are only assumed to be the time periods in which the vessel is at the coordinates provided earlier. If these coordinates are at critical operation close to a platform, it is not feasible to disconnect all generators. Both the selected times and the amount of time the vessel is connected to a buoy may, and will probably, differ in actual operation. However, connecting to a buoy and receiving external power will eliminate almost all emissions from the vessel while connected.

It was desired to use the models to explore changes to more variables. The operational range of the battery system in the models is set to 20%-80% and varying the operational range could provide insight into optimal operation for the battery. In models which include degradation of components and cost of operation, the operational range of the battery system could vary its lifetime. Another variable that is not explored is the electric efficiency of the battery. Although it is expected that lower efficiency would result in less cumulative output from the battery, it is not known to which extent. Lastly, the actual operational strategy from the shipowner has not been provided, thus not investigated with the models. The main reason these variables are not explored is time.

5 Discussion

The whole project started with us receiving a data set which included 640800 excel rows, one week with one second resolution. Each individual in the group has a different background, and none were familiar working with data sets of this size. Because of this foundation we decided that we should all work together in the start to get familiar with the content and discuss the path forward as we became familiar with how to handle it. After doing some research on tools for data handling, we decided to use Python with the pandas library to organize and analyse the data.

The first step was to verify the data. Even though the data had been presented to us by a trusted partner we wanted to make sure that it matched our own estimations when it came to key values. This was to ensure that the data was not corrupt before we started to manipulate it. After running some functions on the whole data set and the results matched our expectations we went on to the next step, which was to extract it and change the resolution. In this phase we started to divide working tasks. The two people with most programming experience started to extract the data based on Operation ID's and made it into minute and hour resolution. The two other group participants started doing background study on offshore marine batteries and system designs, while taking basic python courses. All observations and discoveries during this time were discussed with the whole group before any conclusions were drawn.

The next step was to start analyzing the data. While we also saw that to complete the case studies, we needed some reference points when it came to efficiency for the generators. We wanted to present as much as possible on the midterm review so we could get as good and thorough feedback and further guidance from our partners. A good midterm review presentation was also important to get the acknowledgement that we were on the right path, especially with regard to the customer. Working towards the midterm review, we split into two pairs again, where the main focus of one pair was to analyze the data and make assumptions, while the other two were working on efficiency and fuel consumption. While we were in this phase towards the midterm review, we would always sit all four together in a zoom meeting. This way the barrier for discussion where low and the two analysts could present their finding and initiate discussion with the rest of the group. This working method worked very well for our group because it kept everyone in the loop and up to date with the latest discovery, so we were able to advance the level of discussion the more educated we got.

After the midterm review it was clear that we were onto something. The data analysis part the partners and customers would like us to dig one level deeper to further explore and understand the data. For this part we decided to divide the Operation ID's among three of us, while the last participant would be doing more background work and start to write on the final report. The now three analysts divided the Operation ID's among them and started to dig into them. We continued with our former working method where all participants where in a zoom meeting, and the analysts presented key finding which could be discussed in plenary.

This deep dive into the data made us a lot more familiar with the different Operation ID's and we started to get a thorough understanding of their behaviour. Some operation modes had strange data which made it difficult to understand what actually was happening. The Standby mode, Operation ID 7, should especially be mentioned here. This is because there was found many odd behaviour patterns within this operating id. After a long period of analyzing we sorted out the information that we thought of as important, and set up a new meeting with the respective partners to show our findings. It later came to our understanding that the strange data in isolated operation ID's was due to how the data for the operation ID's was extracted.

This meeting was very informative, and it was decided along with the supervisor and Equinor to narrow the scope of the case study. It was also during this meeting that the importance of spinning reserve capacity came to our attention. Moving forward, we would direct our focus primarily towards Operation ID 100 and emphasize this Operation ID in our case study. After this meeting, we had a group meeting where we wanted to map out a clear path towards completing the project, creating a result that would please our customer and partners. We felt that we had developed the skill set to make a decent result and started working on the scripts that would satisfy Base Case 1 & 2. This where done on a shared screen with one lead analyst and input from each of the participants along the way. While simultaneously, all the participants started working on the final report as the deadline started to approach. We had some problems adding the efficiency into the Base Case, but after a meeting with our supervisor, we were able to figure it out.

From there, we completed the Base Case and went on to Case 1 and 2. Because Case 1 and 2 were based on Base Case 1 and 2 and we had become better at working with scripts, it was faster to complete the two latter cases. After this two of us worked full time on the report while the last two participants were double checking the logical, for seeing the whole charter, and making logic assumptions based on that. These will be further explained.

The project's overall goal is to reduce CO2 emissions from a marine vessel using a battery. The framework of this project is set, so it should be easy to implement it into the existing infrastructure. This creates boundaries that must be taken into consideration when working with the data. When analyzing the data, several possibilities for improvement were found. There were a lot of inefficient use of generators and odd running patterns. On the other hand, there was discovered good use of the battery and peak shaving, which was done at high efficiency, and would contribute to using one less generator. All observation presented in this project is done without knowing the configuration of the Operation ID's and the running pattern that the owner is using. Because of this, it is not possible to conclude if the configuration and running patterns in the different Operation ID's are beneficial when it comes to reducing CO2. It has, therefore, only been presented as observations and should be viewed as speculation.

6 Conclusion

This assignment consisted of two main goals. The first is for the student group to learn about working with projects and systems engineering. Working with projects is a process and is seldom as straightforward as intended. As the group got more familiar with the assignment, the scope of work and goals were adjusted as the project went on. Five months ago, when the assignment was introduced, it was believed that the case study would be the main challenge. However, in reality, analysing the data was the most challenging task throughout the project, and this is also where most improvement ideas emerged. The second purpose was to explore improvement alternatives for battery utilization on marine vessels to reduce CO_2 emissions. Defining the system, researching relevant literature, and data analysis were necessary to finally conduct a case study. It was expected that charging the battery from an external power supply would significantly reduce the fuel consumption of the vessel. However, results from the case study proved that the charging strategy of the battery was not the main contributor for reducing emissions. The main contributor was using a buoy offshore for the vessel to connect to, which would reduce the load for an amount of time as well as charge the battery and cover hotel load. This project is a preliminary study for OMB6, and the group believes that some operational strategies with room for improvement have been identified and that the proposed scenarios are worth further investigating for the purpose of reducing the emissions from marine vessels.

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References

[1] URL: https://people.exeter.ac.uk/TWDavies/energy_conversion/Calculation20of20CO220emissions20from20 htm.

[2] Evert A. Bouman et al. “State-of-the-art technologies, measures, and potential forreducing GHG emissions from shipping – A review”. In: *View Articles published in Transportation Research Part D: Transport and Environment ISSN: 1361-9209 Transportation Research Part D: Transport and Environment* (2017). DOI: http://dx.doi.org/10.1016/j.trd.2017.03.022.

[3] Martin Ed. *Two SolstadFarstad PSVs to go hybrid 1*. May 2018. URL: https://www.rivieramm.com/news-content-hub/news-content-hub/two-solstadfarstad-psvs-to-go-hybrid-1-52967.

[4] Equinor. *Equinor med ambisjon om å kutte utslippene i Norge til nær null i 2050*. Jan. 2020. URL: https://www.equinor.com/no/news/2020-01-06-climate-ambitions-norway.html.

[5] Equinor. *This battery-hybrid ship was designed to cut emissions*. Mar. 2021. URL: https://www.equinor.com/en/magazine/battery-hybrid-supply-ship.html.

[6] Diju Gao et al. “An energy optimization strategy for hybrid power ships under load uncertainty based on load power prediction and improved nsga-ii algorithm”. In: *Energies* 11.7 (2018), p. 1699. DOI: 10.3390/en11071699.

[7] *Harvey Gulf PSV Receives Hybrid Retrofit*. Apr. 2019. URL: https://www.oedigital.com/news/464917-harvey-gulf-psv-receives-hybrid-retrofit.

[8] Zhu Jianyun et al. “Bi-objective optimal design of plug-in hybrid electric propulsion system for ships”. In: *Energy* 177 (2019), pp. 247–261. DOI: 10.1016/j.energy.2019.04.079.

[9] Bojan Lepic. *Kongsberg Maritime to convert Island Offshore PSV trio to hybrid power*. Aug. 2020. URL: https://www.offshore-energy.biz/kongsberg-maritime-to-convert-island-offshore-psv-trio-to-hybrid-power/.

[10] Elizabeth Lindstad and Inge Sandaas. “Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology”. In: *Journal of Ship Production and Design* 32.4 (Nov. 2016), pp. 195–205. DOI: 10.5957/jspd.32.2.150006.

[11] *Maersk Supply Service and Ørsted to test offshore charging buoy to reduce vessel emissions*. Sept. 2020. URL: https://orsted.com/en/media/newsroom/news/2020/09/981258233744293.

[12] Nicholas Newman. *Hybrid ships take to the high seas*. Jan. 2019. URL: https://eandt.theiet.org/content/articles/2019/01/hybrid-ships-take-to-the-high-seas/.

[13] Jasmina Ovcina. *CBO Flamengo to get Wärtsilä’s hybrid propulsion*. Nov. 2020. URL: https://www.offshore-energy.biz/cbo-flamengo-to-get-wartsilas-hybrid-propulsion/.

[14] *Reducing greenhouse gas emissions from ships.* URL: `https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx`.

[15] Sintef. *OMB6 – Optimalisert drift av maritime batterisystemer.* URL: `https://www.sintef.no/prosjekter/2021/omb6-optimalisert-drift-av-maritime-batterisystemer/`.

[16] Congbiao Sui et al. "Impact of Battery-Hybrid Cargo Ship Propulsion on Fuel Consumption and Emissions during Port Approaches". In: June 2019.

[17] *Wärtsilä upgrading four Harvey Gulf PSVs.* Oct. 2020. URL: `https://www.offshore-mag.com/rigs-vessels/article/14185650/wrtsil-upgrading-four-harvey-gulf-platform-supply-vessels`.