Real Time Simulation Study on Hybrid Marine Vessel Energy Management Systems

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***Abstract*—In line with climate goals and ambitions, the maritime industry is undergoing a technological transformation. Hybrid vessels offer the opportunity to optimize the use of the available distributed (renewable) energy resources on the grid. Hybrid Vessel Energy Management Systems need to make decisions with objectives to reduce fuel consumption, greenhouse gas emissions and maintenance expenditures during operation of the vessel. The verification of the Energy Management System is conducted by creating a Digital Twin of the hybrid vessel on the Typhoon Hardware-In-Loop platform. The model results are achieved in real time, thereby setting the foundation for Controller HIL (C-HIL) projects.**

***Index Terms*—Hybrid Vessels, Energy Management System, Real Time Simulation, Digital Twin, Typhoon HIL**

I. Introduction

The maritime sector is the key driving force of global trade and commerce, with its influence dating back several centuries. With globalisation and technological advancements, the maritime sector today is viewed as the backbone of the world economy [1]. The International Maritime Organization (IMO) values global maritime fuel consumption to be 300 million tonnes each year. This large scale fuel consumption increases greenhouse gas (GHG) emissions on an unprecedented scale. The Fourth IMO Greenhouse Gas Study 2020 finds the GHG emissions to have increased by 9.6% from their previous study conducted in 2012 [2]. The resulting consequence of this trend is an increased rate of climate change, that can have catastrophic implications to life and property.

With the intention to limit GHG emissions and fossil fuel consumption, the IMO adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships [3]. The strategy sets a framework to guide member nations on their approach to decarbonize their vessels, fully considering short- and long-term implications. Furthermore, there are two main objectives part of this framework. The first is to limit carbon intensity globally to 40% by 2030. The second is to integrate zero or near zero GHG emission fuels and technologies at a target of 5% to 10% by 2030 [3]. These developments have made hybrid ships an attractive option for improved performance and reduced fuel consumption and GHG emissions, as the sector begins to decarbonize.

This paper makes use of the Typhoon Hardware-In-Loop (HIL) platform to verify the designed Energy Management System (EMS) in real time. The digital twin can give insights into the EMS's robustness and performance in different operational scenarios. The developed model is based on a proposed hybrid solution for a cable laying vessel and manufacturer specific parameters have been implemented wherever feasible. The results from the real time simulation help calculate fuel savings, GHG emissions and saved maintenance expenditures with the hybrid solution.

II. Vessel Specifications and Operations Analysis

Details into the existing vessel configuration are discussed. The optimization of diesel generator maintenance schedules and fuel consumption are also discussed. The section culminates with data analysis into the vessel's operation in the DP2 mode.

A. Vessel Specifications

The single line diagram of the cable laying vessel in this study is depicted by Figure 1. The vessel consists of 5 diesel generators (DGs), connected to the 690V AC bus. The bus is subdivided into 3 busbars using tie breakers TB-1 and TB-2. The connection and disconnection of the tie breakers determine the operational mode of the vessel. Based on available data, a significant portion of this vessel's operation is in the Dynamic Positioning 2 (DP2) mode. Therefore, the scope of this paper will be limited to the DP2 operation mode, more specifically to the port side. This mode implies that TB-1 and TB-2 are open, which results in the Port Side (PS) and Starboard Side (SB) operating as identical island grids.

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The PS consists of DG1 and DG2 while the SB consists of DG3 and DG4 as energy providers. This vessel comprises of two propulsion thrusters rated at 2100kW and three bow thrusters rated at 1000kW respectively. The thrusters play a key role in the DP2 mode to reposition the vessel in response to environmental forces. The cranes on this vessel are rated at 560kW and the service loads of this vessel operate at 440V AC. DG5 may be used to power the 1000 kW bow thruster if required by the vessel for additional assistance. DG5 is often used in tandem with the other DGs during different operating modes when one or more tie breakers are closed. The details into the ratings of the DGs of this vessel can be found on Table I.

TABLE I
DIESEL GENERATOR POWER RATING

DG Number	Rating (kW)
Diesel Generator 1 (DG1)	1912
Diesel Generator 2 (DG2)	2560
Diesel Generator 3 (DG3)	2560
Diesel Generator 4 (DG4)	1912
Diesel Generator 5 (DG5)	1360

For vessel operations in deep waters, regulations do not permit the use of anchors to maintain the vessel's position [4]. The thrusters in the vessel are used by the Dynamic Positioning system to immediately reposition the vessel to its intended coordinates, in response to environmental disturbances. The DP2 mode is a high redundancy operation mode that requires continued vessel operation, even in the event of failure of any one of the generators or thrusters.

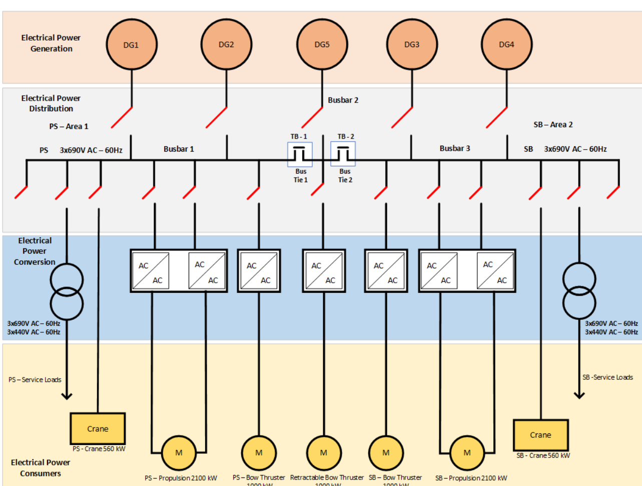

Fig. 1. Single Line Diagram of Cable Laying Vessel

B. Diesel Generator Maintenance and Fuel Consumption Optimization

Diesel Generators serve as an integral part of the electrical grid for marine vessels. Nowadays, more than 90% of large commercial vessels employ diesel generators as prime movers and for propulsion. This is due to the ability of DGs to meet high power demands, make use of low grade fuel oil and their technology is relatively mature. These reasons make DGs more reliable and durable for long duration operations as required by the maritime sector [5].

When designing shipboard power systems, an electrical load analysis is first conducted. A comprehensive study on the different loads, the critical equipment onboard and operational modes is made, such that the ideal combination of generators are selected for a specific vessel [6]. Furthermore, engineers need to consider power line losses, load limits and financial constraints when making design decisions [6]. However, a consequence of this approach is that there can be instances when the DGs are underutilized with respect to their power capacities. This is due to sea and weather conditions continuously changing, which can change the load demand.

The continued operation of DGs at low load factors results in a poor fuel consumption efficiency and exorbitant maintenance costs. At low load factors, the DGs experience incomplete combustion of fuel oil. During combustion of the air-fuel mixture, the mix will contain more parts of air than fuel [7], [8]. The outcome of this event is that the fuel is not burnt completely. This unburnt fuel will then condense to form carbon deposits all over the engine. This phenomena is termed as wet-stacking [7], [8]. The partial burning of fuel oil outputs a large coefficient of CO_2, resulting in higher greenhouse emissions [7], [8]. It is estimated that the emissions at a high load factor of about 75% is two to three times lower than at a low load factor of about 25% [7]. Finally, the effect of fouling due to the unburnt fuel leads to damage and need for replacement of engine components [9].

Evidently, the phenomena of wet-stacking is undesirable and will require corrective maintenance to continue operations. Maintenance procedures for DGs can account for hundreds of thousand of euros for each vessel. The corrective maintenance procedure is viewed as critical to ensure reliability of operation of the DG and in extension the vessel [10]. The corrective maintenance costs of the DG depends on its size, load profile and order of dispatch priority set by the vessel operator. From the work of the authors of [10], it was possible to estimate the Minimum Time Before Overhaul (MTBO) based on the load factor of the DG shown by Equation 1. The MTBO is an estimate of how long the DG may be operated before needing to undergo corrective maintenance.

$$MTBO = \sum_{i=1}^{8} b_i * \theta^i \quad (1)$$

The coefficient θ^i corresponds to the DG loading factor, whereas the the value of b_i, is detailed by Table II. The MTBO is derived based on two assumptions as made by the authors of [10]. The first assumption is that the MTBO is dependent on the average load factor. The second assumption is that the cost of overhaul is roughly 50% the cost of investment

TABLE II
MTBO Curve Coefficients [10]

b_n	Value
b_0	1040.898
b_1	3.429×10^4
b_2	1.660×10^4
b_3	4.971×10^4
b_4	-3.226×10^5
b_5	-5.504×10^5
b_6	2.803×10^6
b_7	-3.714×10^6
b_8	1.152×10^6

into the DG. From these assumptions, the cost of corrective maintenance C_{CM} is given by Equation 2. N_h represents the daily operation hours, C_{DG} represents the cost of the diesel generator and MTBO(ϕ) represents the MTBO at the average load factor (ϕ).

$$C_{\text{CM}} = \frac{365 \cdot N_h \cdot 0.5 \cdot C_{\text{DG}}}{1.3 \cdot \text{MTBO}(\phi)} \quad (2)$$

Figure 2 depicts the expected Minimum Time Before Overhaul for the DGs in this study. At low load factors less than 50% of the rated capacity of the DG, there is a reduced number of available operational hours. At load factors between 50% and 80%, the MTBO curve is almost linear. However, at load factors greater than 80%, there is again a decrease in the MTBO. This decrease can be the result of wear and tear experienced by engine components at consistently high loads.

The Specific Fuel Oil Consumption (SFOC) is a measure of fuel consumption per unit of energy delivered by the DG. The SFOC data was provided by the vessel owner. The SFOC curves for DG1, DG2, DG3 and DG4 are found to be similar. The SFOC curve can be seen on Figure 2 as well. It can be noted that at low load factors, the specific fuel oil consumption is quite high. Increasing the load factor brings down the specific fuel oil consumption. Similar to the MTBO curve, higher load factors are preferred when aiming to reduce overall fuel consumption. From the data, it is observed that at average load factors greater than 50%, the additional fuel saved for an extra kWh of energy, increases at the rate of the third decimal.

Upon combining the MTBO and SFOC curves together on Figure 2, it is evident that the ideal range of the average load factor should lie between 50% and 80%. Given that maintenance costs can be the in the order of thousands of euros and only a small fraction of fuel is saved as the load factor keeps increasing, the small savings at load factors greater than 80% do not translate to large monetary savings. Hence, preference is given to maintenance cost savings. This study will maintain the load factor between 60% and 80% to minimize fuel consumption and maintenance costs. This operation will ensure an average of 1.60 - 1.78 years of operational hours before overhaul and a much better fuel economy.

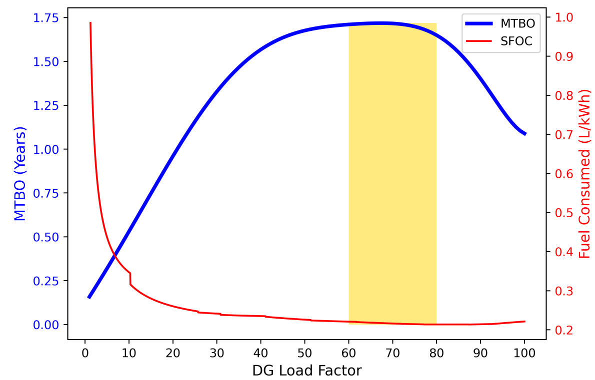

Fig. 2. The MTBO and SFOC Curve Comparison

C. Existing Vessel Operations Analysis

An analysis is conducted into the operations of this vessel. Two datasets were provided by the vessel operator. The first being in the Taiwan Strait and the second in the North Sea. The data from the Taiwan Strait was recorded in 5 minute intervals, whereas for the North Sea, it was recorded in 1 minute intervals. Analysis into the DP2 mode data showed that this vessel operates its DGs for most operations at an average load factor of less than 30%.

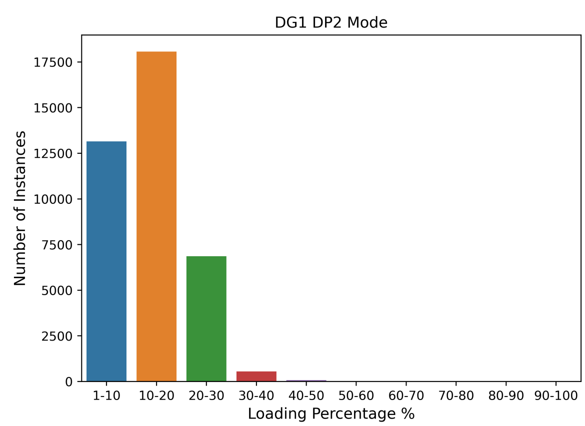

Fig. 3. DG1 Loading in the Taiwan Strait

In the Taiwan Strait, both DGs operated with an average load factor between 10% and 20% as seen on Figure 3 and Figure 4. Whereas in the North Sea, for a significant portion of time, DG1 operated at an average load factor between 20% and 30% as seen on Figure 5, while DG2 at average load factor between 10% and 20% as seen on Figure 6. At the same time, there have been instances in the North Sea, wherein the DGs have operated higher than 70% of their rated capacities. This

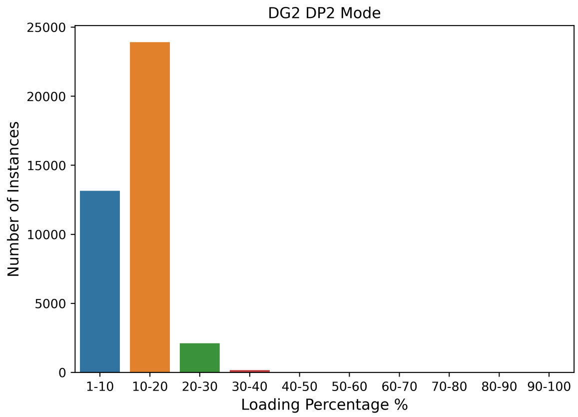

Fig. 4. DG2 Loading in the Taiwan Strait

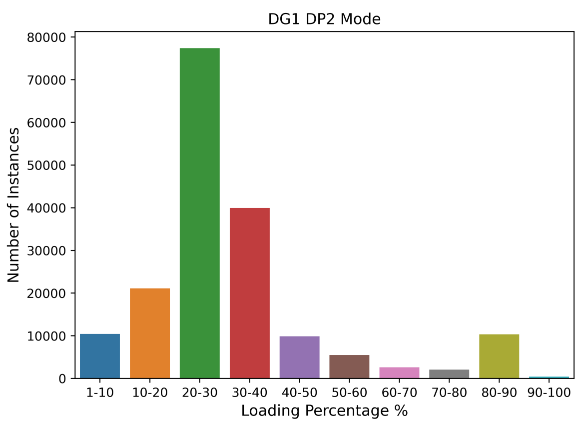

Fig. 5. DG1 Loading in the North Sea

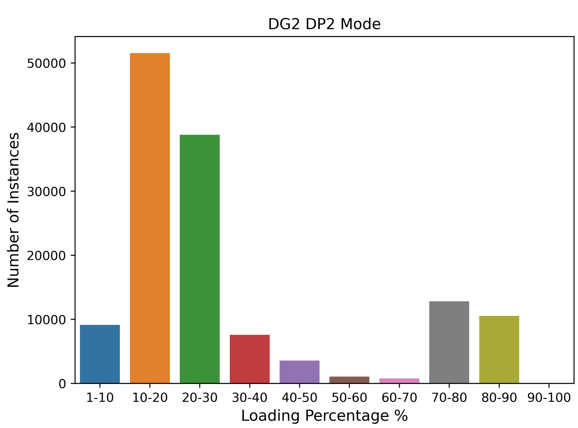

Fig. 6. DG2 Loading in the North Sea

data suggests that the vessel experiences calmer oceans in the Taiwan Strait, whilst the North Sea has more chaotic waters. The stronger the environmental disturbances, the more energy the DP2 system will need to reposition the vessel. Therefore, the load demand clearly is dependent on sea conditions and environmental forces at the time. The low average load factor makes the DGs susceptible to wet-stacking. This will have negative consequences for the maintenance of the DGs, GHG emissions and the overall fuel economy.

III. The Hybrid Solution

With the intention to decarbonize the vessel's operations and avoid the consequences of wet-stacking, modifying the vessel configuration to a hybrid was decided. Battery Energy Storage Systems (BESSs) of the Lithium Iron chemistry were selected. One BESS of 1 MWh capacity is placed on both the Port side (PS) and Starboard side (SB) of the vessel. Given that this vessel has an AC grid, bidirectional power converters are employed for AC to DC and DC to AC power conversion between the BESS and the grid. The single line diagram of the designed configuration is shown by Figure 7. The roles of the BESS and Energy Management System (EMS) will need to be defined, to make optimal use of the available Distributed Energy Resources (DERs) on the grid.

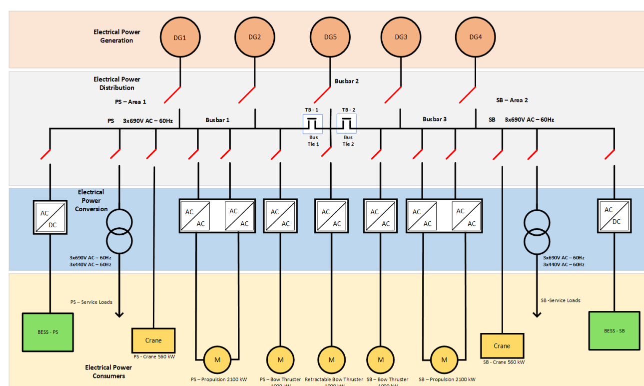

Fig. 7. Single Line Diagram of the Hybrid Cable Laying Vessel

A. *Roles of the Battery Energy Storage System*

With the understanding of the potential challenges with the use of DGs and the vessel operations data, the BESS for this vessel in the DP2 mode has the following roles. The main objective in this study is to operate the DG at high efficiency regions as discussed in section II-B.

- **Fully Electric Operation** : In this operation, the BESS takes over the entire load demand of the vessel. This is aimed at avoiding operation of the DGs at low load demands. Thereby, this operation can also reduce GHG emissions and excessive fuel consumption for the little energy delivered.
- **Spinning Reserve** : The BESS adds additional redundancy to the electrical grid. In the event of a fault

occurring at any one DG, the BESS can provide energy until the fault has been resolved.

- **Load Levelling** : In the event the load demand exceeds the optimal loading range of a certain generator, the BESS meets this additional load demand. This operation prevents the operation of the next DG at a non-optimal load range. It also prevents the operational DG from operating at loads greater than 80% of its rated capacity.
- **Peak Shaving** : In the event the load demand exceeds the capacity of a certain generator, the excess energy demand is met by the BESS to prevent the use of the next DG at a non-optimal load demand.

B. Objectives of the Energy Management System

The Energy Management System (EMS) now needs to additionally manage the BESS, alongside the existing DGs, thrusters, and cranes on the vessel. A breakdown of the requirements of the EMS is as follows.

- Optimize the use of DGs to keep the SFOC to a minimum for different load profiles.
- Make use of the most optimal DG for a certain load, in order to minimize maintenance expenses and GHG emissions.
- Ensure the integrity of the grid. The DP2 mode has a high redundancy requirement. The vessel must be able to continue operations even in the event of failure of one or more components on the grid.
- Use the BESS within the recommended C-rates to extend BESS lifetime.
- Operate the BESS at a Depth of Discharge (DoD), that can maximize BESS cycles and operational profits.
- Vessel load demands are considered as critical loads. These loads demands must be met by the grid at all times. Charging the BESS is considered non-critical during periods of high load demand.
- The BESS receives a maximum charge power of 1000 kW only if the most optimal DG at the time is able to supply.

IV. Real Time Simulation of the Hybrid Vessel Energy Management System

This section will first describe the model developed on the Typhoon HIL platform. Following this, the details into the simulation and their results are discussed.

A. Digital Twin of the Vessel in DP2 Mode

Figure 8 shows the modelled DP2 island grid of the now hybrid cable laying vessel. This island consists of one BESS rated at 1000 kWh, one DG rated at 2560 kW and one DG rated at 1912 kW as energy providers. As for the loads, there is one propulsion thruster rated at 2100 kW, one bow thruster rated at 1000 kW and the crane and hotel loads that can demand a maximum of 700 kW. Additionally, based on available data from the BESS manufacturer, it was decided to limit the C-rate of the BESS to 1C during both charge and discharge. The depth of discharge of the BESS is maintained

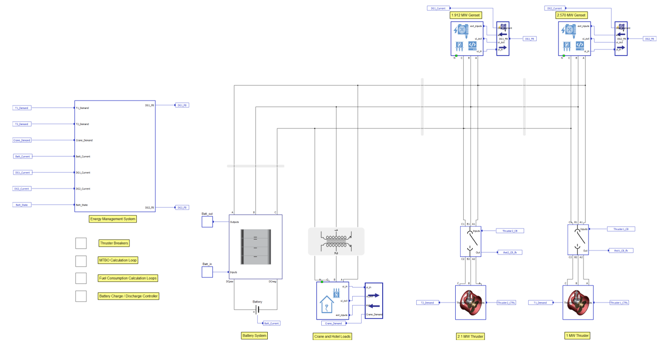

Fig. 8. Model of the Port Side created on Typhoon HIL

at 50%. Therefore, the BESS cycles between 30% and 80%. The sample time is modelled at 2μs, thereby enabling the EMS to continuously monitor and control the DERs on the grid mimicking real time dynamics. The designed model is simulated in real time on the SCADA interface of Typhoon HIL.

B. Simulation Findings

In order to determine the performance of the hybrid vessel in actual operating conditions, load profiles from the vessel's operations were utilized. Based on the data seen in section II-C, Figure 9 is assumed as the most probable operation profile throughout the year. The simulation started with an initial BESS State of Charge (SoC) of 30%. Once the grid has achieved synchronization, the EMS instructs DG1 to meet the vessel load demand and at the same time charge the BESS. The charge of the BESS is kept within 1C or 1000 kW. When the BESS is charged to a SoC of 80%, DG1 returns to standby if the load demand is less than 1000 kW. By this control approach, the whole operation is achieved using DG1 in combination with the BESS. DG2 remains on standby. This can be seen on Figure 10.

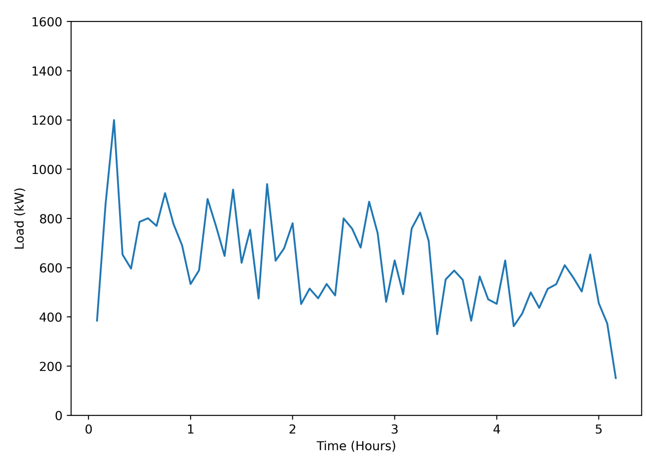

Fig. 9. The load profile from vessel operator

From Figure 10, it is noted that the vessel has operated under fully electric mode during the intervals when the load

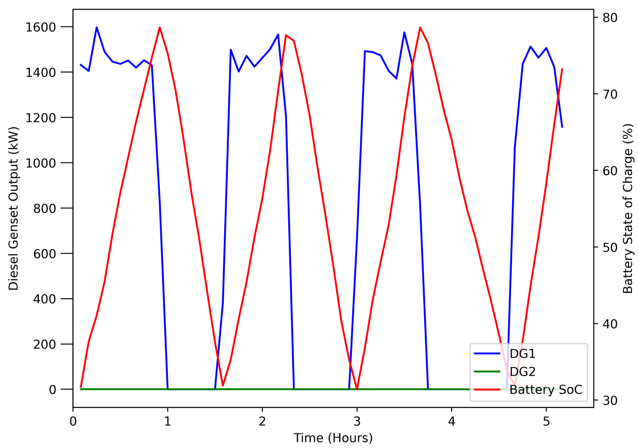

Fig. 10. Overview of DER operation in the hybrid vessel

demand was less than 1000 kW. The BESS met these demands, as these loads are not in the optimal operating region for DG1 or DG2. At the time when the BESS reached the 30% SoC threshold, DG1 entered into operation. It must be noted that the energy delivered by DG1 is limited by the region of ideal operation as discussed in section II-B. As a result, depending on the load demand at the time, the speed of charging the BESS will vary. For instance, the charging of the BESS was relatively slower for the first cycle when compared to the third cycle given the difference in load demands. Figure 11 shows that the operational DG maintained a consistently high load factor between 70% and 80% throughout its operation. Data logged during the simulation estimates an average load factor of 73.4%.

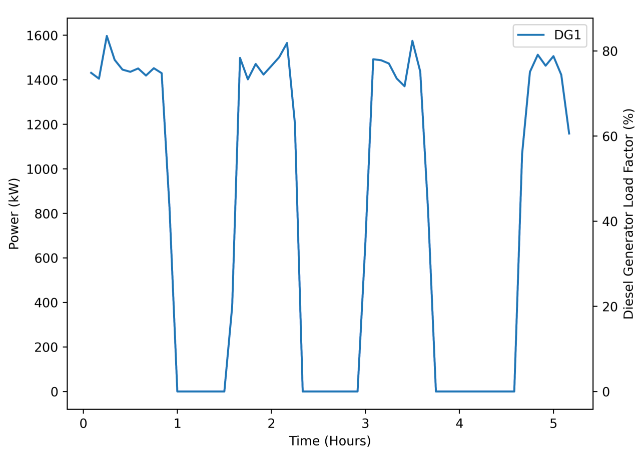

Fig. 11. Load Factor of operating diesel generators

However, there is now a key difference between the hybrid vessel and the non-hybrid vessel. The hybrid vessel now has a new load demand to be met, which is the BESS whenever it is undergoing charging. Figure 12 shows the new operational profile of the vessel. The excess energy produced by the DG which allows it to operate in a high efficiency region, is used to charge the BESS. The BESS meets all loads demands once charged, only if these demands are not in the region of ideal operation for the DG. The result of this operation is that whilst the DG operates in a high efficiency region, it is delivering more energy and in extension consuming some additional fuel for that energy it delivers. Additionally, given that the DP2 mode is a critical operating mode that requires instantaneous repositioning, the vessel can experience load demands greater than 2500 kW in a short time interval of one to two minutes. Therefore, during the operation of the BESS, the DGs will need to remain on standby, which consumes a certain amount of fuel. This standby fuel consumption reduces the total fuel that can be saved in the cycle, but has to be maintained given the criticality of the DP2 mode.

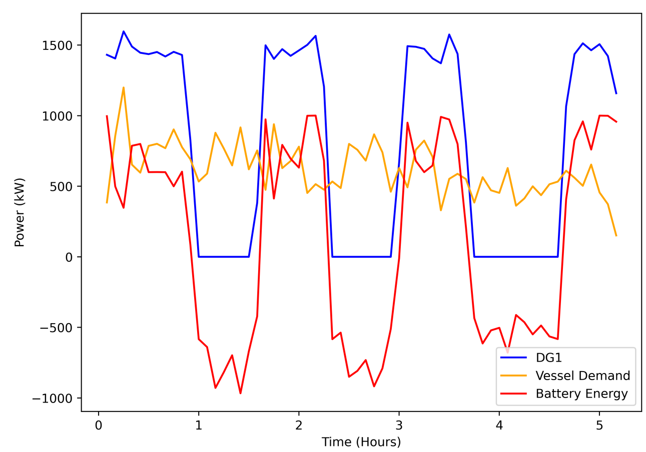

Fig. 12. The changed operational profile of the vessel

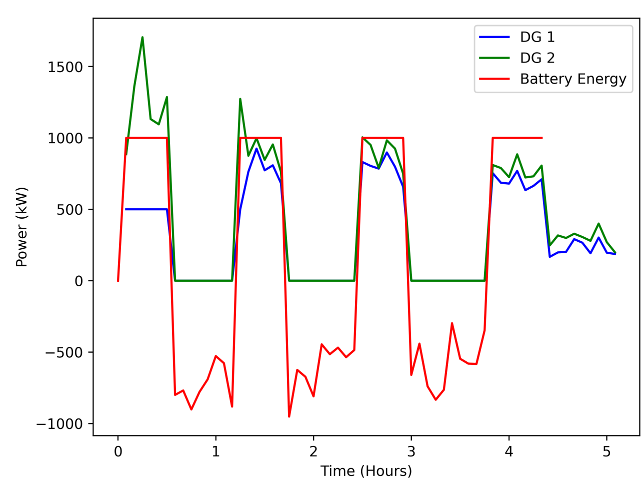

Fig. 13. Synchronous Control of DGs under new operation profile

Hence, in order to estimate fuel savings, the comparison will have to be made between the operation of the hybrid vessel with EMS control and without EMS control. The operation with EMS control, is the control that optimizes DG utilization. This control is aimed at minimizing specific fuel oil consumption, GHG emissions and delaying the minimum time before overhaul. The operation without EMS control is based on the synchronous control of the DGs. This control equally shares the load demands whenever the BESS undergoes a charge cycle or if the load demand exceeds the 1000 kW threshold. The synchronous control of DGs approach is shown by Figure 13. The 1000 kW of charge power for the BESS is shared equally between DG1 and DG2. The extra 500 kW are added to the DGs in addition to the energy originally delivered as per vessel operator data. This operation is made to replicate the EMS control analysis. As a result, the BESS is limited to three cycles.

V. Results and Discussion

A. Non - Hybrid Vessel Operation Results

Table III shows the result of operating the non-hybrid configuration of the vessel for the same load profile shown in Figure 9. This operation is conducted via synchronous control of the DGs. In this cycle, the vessel consumes 918.77 L of fuel and has low average load factors at 13.45% for DG1 and 16.95% for DG2. The total operational time for the DGs before overhaul comes up to about 0.7 years of continuous operation. It is also verified by literature that the low load factor results in costly DG maintenance procedures. As a result, the cost of maintenance each year assuming a 10 hour operation each day, comes to € 108,173 for each DG.

TABLE III
Estimates from Non-Hybrid Vessel Configuration

Parameter	Non - Hybrid Vessel
Net Fuel Consumption in Cycle	918.769 L
DG1 Average Load Factor	13.45 %
DG2 Average Load Factor	16.95 %
DG1 MTBO (years)	0.7
DG2 MTBO (years)	0.7
DG1 Maintenance Cost (per year)	€ 108,173
DG2 Maintenance Cost (per year)	€ 108,173

B. Hybrid Vessel Operation Results

Table IV shows the results of operating the vessel with EMS control and without EMS control. Clearly, the results indicate that the vessel operates better with EMS control. Under the EMS control approach, the optimal DG was used. As a result of which, the net fuel consumption of the whole cycle was 908.65 L. The EMS control ensured an average load factor of 73.4% for DG1. Assuming the same 10 hour operation a day, the MTBO of DG1 ranges between 1.71 to 1.78 years of continuous operation. The annual maintenance cost of DG1 is approximately € 50,904 due to fewer components needing replacement. It is assumed that DG2 will have a maintenance cost of approximately € 40,000 due to lower operational hours and operation at high load factors. At the same time, the operation without EMS uses the synchronous control approach for the DGs. This operation consumes more fuel and has the average load factor of both DGs under 30%. Whilst there is a delay to the MTBO and decreased annual maintenance savings, the most optimal solution is achieved with EMS control.

TABLE IV
Comparison between With EMS Control and without EMS Control

Parameter	With EMS	Without EMS
Net Fuel Consumption in Cycle	908.65 L	966.39 L
DG1 Average Load Factor	73.4%	29.51%
DG2 Average Load Factor	Standby Mode	30%
DG1 MTBO (years)	1.71	1.29
DG2 MTBO (years)	Standby Mode	1.29
DG1 Maintenance Cost (per year)	€ 50,904	€ 67,084
DG2 Maintenance Cost (per year)	€ 40,000	€ 67,084

C. Fuel and Maintenance Savings

Table V indicates the net savings that can be expected from the operation of the hybrid vessel each year. Assuming an average operation of 10 hours per day for 80% of the year, taking into account the PS and SB, a total of 67,448 L can be saved each year in the DP2 mode. This number equates to a 5.98% reduction in fuel consumption for the hybrid solution using the EMS against the hybrid solution without the EMS. The fuel density of Marine Gas Oil (MGO) is 860 kg/m^3 [12]. A total of 58 tons of MGO can be saved each year. As of 15th July 2024, the price of MGO in the market is $ 758.5 per ton of MGO [11]. On the same day, the United States Dollar to Euro conversion stands at 1 USD = 0.92 EUR [13]. DG1 saves an estimated € 57,268.10 and DG2 saves an estimated € 68,173.08 in maintenance costs annually. This is due to the hybrid solution enabling optimal DG operation against the non-hybrid vessel configuration. The saving of approximately € 50,000 per DG when operated at a high load factor was also suggested by the vessel owner. A total of € 291,579.88 can be saved from fuel and maintenance costs. It must also be noted that with delaying the MTBO, the DGs are available for longer operation. As a result, the vessel owner benefits from their continued commercial activities. At the time, the authors do not have access to information of the potential profit the vessel owner stands to gain.

TABLE V
Net Savings per year

Parameter	Value
Net Fuel Savings on PS and SB	67,448.496 L
Net MGO Saved on PS and SB	58,005.71 kg
Average MGO Fuel price	758.5 $/ton
Fuel Cost Savings	€ 40,697.53
DG1 Maintenance Cost Savings	€ 57,268.10
DG2 Maintenance Cost Savings	€ 68,173.08
Net Savings on PS and SB	€ 291,579.88

D. Emissions Reduction

With the European Union Emissions Trading System (EU ETS) getting involved in the maritime sector, vessel owners will aim to limit emissions. The emission factor of MGO is found to be 3.206 tons of CO_2 per ton of MGO [14]. The net emissions saved each year from reduced fuel consumption is valued at 185.96 tons of CO_2 each year. The reduced GHG emissions due to better combustion efficiency of the DGs is not considered, owing to the lack of reliable data. The European Commission (EC) is yet to set a price to the emission permits. The authors of [15], developed a model for estimating the cost of emissions. A breakdown of potential cost of emissions is given by Table VI. The authors of this work will consider the cost of € 67/ton CO_2 as the most likely price of one emission permit at the start of the EU ETS scheme for the maritime sector. The EC will continue to increase the price of emission permits in the following years to meet emission reduction goals.

TABLE VI
SAVED MONEY OF EMISSION REDUCTION

Emissions Cost per of ton CO_2	**€ 30**	**€ 67**	**€ 150**
Annual Savings (€)	5,578.80	12,459.32	27,894.00

VI. PROFITABILITY OF HYBRID SOLUTION

From the quotes received from two BESS manufacturers based in the Netherlands, the cost of two 1 MWh BESSs with their power converters and filters is valued at € 1,928,572. Taking into account the the savings from emissions, the Simple Payback Time (SPBT) based on different fuel price scenarios is shown by Table VII.

TABLE VII
SIMPLE PAYBACK TIME OF INVESTMENT

Fuel Price	**700 (€/ton)**	**800 (€/ton)**	**900 (€/ton)**
Annual Savings	€ 304,039	€ 309,746	€ 315,547
SPBT (Years)	6.34	6.22	6.11

Assuming a total lifespan of 10 years for the BESS and 7 years to make back the investment, the Return On Investment (ROI) is valued at € 912,117. From the commercial front, the project is profitable and with declining prices of the BESS technology in the coming years, it should be possible for the vessel owner to replace the old BESSs with the ROI. In order for the profitability to increase further, it is necessary for the price of MGO and emission permits to increase in the coming years.

VII. CONCLUSIONS

This paper investigated the feasibility of a hybrid power solution for a cable laying vessel. In order to make the most of the DERs available on the grid, the EMS of the vessel will need to be upgraded. With meticulous design, the EMS for the hybrid vessel can optimize overall performance by minimizing fuel oil consumption, GHG emissions and maintenance costs for the DGs. Now under the EMS control, the DGs operate at an average load factor that ranges between 70% and 80%. A net fuel consumption reduction of 5.98% is achieved and 185.96 tons of CO_2 has been offset annually. The maintenance costs of the DGs are reduced by approximately € 50,000 for each DG for each year. A return on investment of € 912,117 can be expected from this solution over the course of 10 years. Finally, the authors would like to acknowledge the lack of knowledge of future market MGO prices, inflation and interest rates which can influence the simple payback time, given that these are subject to geopolitical and financial decisions at the time.

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