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SIMULATION OF HYBRID POWER SYSTEMS FOR VESSELS

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Abstract. *Climate concerns, regulations, and fuel costs are driving higher efficiency designs in the shipping industry. Research works suggest that hybrid power systems can be a viable option to reduce fuel consumption and emissions. However, more studies are required to analyze its net gains in different applications. In this work, numerical simulations of power systems are performed in a causal approach, including a non-hybrid or base case and a hybrid case, for a diesel-electric Platform Supply Vessel (PSV). Dynamical and static models are considered for the power sources, namely, diesel generator sets (gensets) and a lithium-ion battery pack connected through an AC electrical network. For the Energy Management System (EMS) of the base case, an optimization of gensets is performed, and for the hybrid case, a rule-based control combined with an optimization of the generators is considered. The analysis shows, for the case study, that the greatest potential for battery usage is achieved in near port operations. Cleaner operations were allowed in these regions due to the increase in energy efficiency and the disconnection of generators. A fuel consumption reduction of 6.35% and CO₂ emission reductions of 5.81% were achieved for the complete mission. Also, an increase of 1.73% in the overall energy efficiency was accomplished.*

Keywords: *hybrid power systems, marine vessels, energy efficiency, emission reductions, lithium-ion batteries*

1. INTRODUCTION

The shipping industry represents the carriage of 90% of the world trade, with projected growth in the following years (Kalikatzarakis *et al.*, 2018). However, the ship operation is responsible for 1.8% of the total 37.9 Gt of CO₂ emissions worldwide, comparable to the 8th nation on the ranking of top-emitting countries (Crippa *et al.*, 2019). Due to climate concerns, the International Maritime Organization (IMO) strategy is to reduce GHG emissions from vessels, requiring more efficient designs, and cutting CO₂ emissions by at least 40% by 2030, compared to 2008. Fuel costs are another driver for change in the shipping industry, accounting for as much as 50% to 60% of all operational costs (RAENG, 2020).

Hybrid technology can be a viable option to adapt vessels and for new designs. The automotive industry is already employing hybrid technologies successfully. For the shipping industry, it also looks promising. Research works suggest that reductions could achieve up to 10%–35% in fuel consumption and emissions (Geertsma *et al.*, 2017). In this context, Platform Supply Vessels (PSVs), a category of Offshore Support Vessels (OSVs) used in oil and gas platforms, are among the viable options to receive hybrid power supply due to their operational profile (Garcia *et al.*, 2019).

Some studies have been showing the potential for fuel savings, reduction of CO₂, GHG gases, and other components. Miyazaki *et al.* (2016) proposed a power system model to calculate the fuel savings and emission reduction potential of a ship hybrid powertrain with a battery module. A fuel consumption reduction of approximately 45% and a NO_x emission reduction of 85.6% were achieved. However, neither the load demand nor the CO₂ was described.

Peralta *et al.* (2019) analyzed the reduction of CO₂ emissions using a hybrid power system for a PSV and performed a sensitivity analysis. The energy dispatch was optimized, considering the cost of the energy sources. Reductions in CO₂ emissions of up to 8.7% were obtained with the addition of auxiliary diesel engines and batteries. For a combination of generators and a battery, a reduction in emissions of 7.4% was achieved. The optimization methodology and the models were not discussed in detail. Besides, the optimization is global, requiring the complete load profile, which is interesting for setting benchmarks. However, in a real situation, a causal approach is necessary.

Improving the energy management of a power system is very important to increase energy efficiency. Approaches for control strategies in energy management systems (EMS) include heuristic, based on rules or fuzzy logic, optimal and predictive (Geertsma *et al.*, 2017). In the works of Kalikatzarakis *et al.* (2018) and Chua *et al.* (2018), the formulations of EMS are described, and different options are compared for hybrid tugs. However, non-hybrid cases are not considered. In addition, the authors did not study the combination of rule-based strategies and the optimization of generators. Such a study can provide a more conservative perspective of the gains of hybrid solutions.

The hybridization of power systems allows the flexibility to combine different power modes; however, increasing power sources increases the number of systems and control complexity. The majority of works found in the literature define EMS to improve the power dispatch of Tugs and Ferries (Kalikatzarakis *et al.*, 2018; Chua *et al.*, 2018; Chua Wan Yuan *et al.*, 2017; Zhang *et al.*, 2020). In general, PSVs have more power sources and demand more power than Tugs and ferries, increasing the EMS design complexity for this class of vessels.

The objective of this work is to compare hybrid and non-hybrid power systems for a diesel-electric PSV. With this, we intend to contribute to the understanding of vessel hybridization, including the behavior of the powertrain and improvements in energy efficiency, which can lead to fuel economy and emission reduction. We will follow a causal approach for the numerical simulations, considering dynamical models and EMS that enable strategic power dispatch.

2. SYSTEM DESCRIPTION AND MODELING

In this study, we consider two power system topologies for a PSV: a base case, which is a non-hybrid design, and a hybrid power system, which considers the addition of a Li-ion battery to the base case. The base case power system comprises four equal diesel generator sets (gensets) with 1700 kW of electrical power each, resulting in 6800 kW. For the hybrid case, the same number of gensets was considered and we included a battery pack of Lithium Iron Phosphate (LiFePO₄/LFP) of nominal capacity and power of 1000 kWh and 1000 kW, respectively, resulting in 7800 kW.

The models presented here combine static and dynamic formulations, described by algebraic (AE) and ordinary differential equations (ODEs), respectively. The ODEs are solved using Runge-Kutta methods. The models and energy management strategies were implemented and simulated in MATLAB following the causal approach. The optimization of the generators was performed using Casadi, through the interior point method. The gensets and batteries are connected through a static electrical network, which accounts only for power balance, considering the conservation of energy. The battery converter model considers only a constant efficiency, whose symbol is η_c .

2.1 Mission profile

The mission profile in Fig. 1 is an adaptation of results found in the literature. To obtain this curve, the power demand in Peralta *et al.* (2019) was normalized by the nominal installed power of the four equal gensets (total of 7400 kW) and then multiplied by the nominal power installed of the four gensets studied in this work (total of 6800 kW). Then, white noise with small amplitude was added to represent fast oscillations of the load demand. Also, the mission time has been reduced by approximately 100 times, to enable faster simulations.

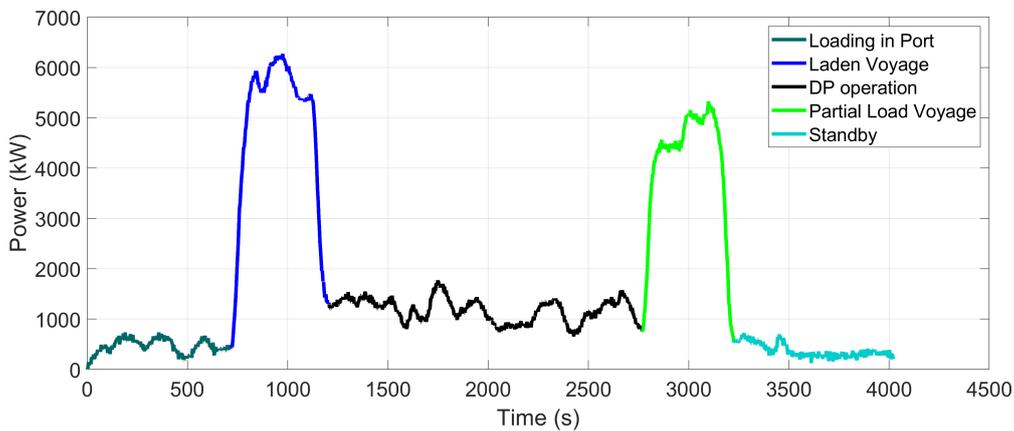


Figure 1: Power demand profile

The power demand in the mission is divided into five parts, starting with the loading in port, where the ship is loaded with goods. In the Laden Voyage, the ship travels fully loaded heading to the platform. When it stops, given appropriate conditions, the ship starts the Dynamical Positioning (DP), in which the forces acting on the vessel are counterbalanced by the thrusters to keep the ship at a defined position. After the DP, the ship travels back to the port with only part of the load, defining the partial load voyage. When the ship arrives near the port area, it can wait for a docking space to be available (standby).

2.2 Engine-generator set

A diesel engine-generator set model has been developed adapting the methodology presented in the work of Kalikatzarakis *et al.* (2018). A steady-state electrical model, based on a simplified per-phase circuit was considered for the

synchronous generator, omitting the Automatic Voltage Generator (AVR). The generator per-phase voltage u_g was defined as proportional to the engine speed ω_{dg} ,

$$u_g(t) = u_{g,nom} \frac{\omega_{dg}(t)}{\omega_{dg,nom}(t)}, \quad (1)$$

where its rate of change is determined by the nominal per-phase voltage $u_{g,nom}$ and engine speed $\omega_{dg,nom}$. The electrical frequency f is determined through the engine speed and the number of poles of the electrical motor P_p ,

$$f = \omega_{dg} \frac{P_p}{4\pi}. \quad (2)$$

The electrical power demand $P_{g,el}$ is translated in a current demand in the terminals of the generator i_g . The active power is defined as:

$$P_{g,el} = 3u_g(t)i_g(t) \cos(f_p) \quad (3)$$

in which $\cos(f_p)$ is the power factor. Considering only friction and copper losses, the generator losses can be written as

$$P_{g,loss}(t) = P_{g,nom}c_f + i_g(t)^2r_g, \quad (4)$$

where c_f is the friction rate and r_g is the resistance of the electrical motor per-phase. The mechanical load P_g due to the electrical demand can be defined as

$$P_g(t) = P_{g,el}(t) + P_{g,loss}(t), \quad (5)$$

while the torque load is determined through the power and rotational speed of the engine, as in

$$M_g(t) = \frac{P_g(t)}{\omega_{dg}(t)}. \quad (6)$$

A governor is required for the generator to regulate the fuel injection and control its angular speed. The rotation dynamics is described by

$$\frac{d\omega_{dg}}{dt} = \frac{M_{dg} - M_g}{J_{dg}}. \quad (7)$$

The variable M_{dg} is the engine torque obtained through the fuel combustion, and J_{dg} represents the generator moment of inertia. A polynomial fit was produced to represent the relation between the fuel consumption of the generator and the torque,

$$M_{dg} = a_0 + a_1\dot{m}_{f,dg} + a_2\dot{m}_{f,dg}^2 + a_3\dot{m}_{f,dg}^3 + a_4\dot{m}_{f,dg}^4, \quad (8)$$

in which the values a_i , with $i = 1, \dots, 4$, are polynomial coefficients. To control the engine speed an anti-windup PI control was implemented. The fuel to be injected was determined through

$$\dot{m}_{f,dg} = k_p(\omega_{dg,ref} - \omega_{dg}(t)) + k_i \int_0^t (\omega_{dg,ref} - \omega_{dg}(t))dt, \quad (9)$$

where the proportional and integral gains of the controller are k_p , and k_i , respectively, and $\omega_{dg,ref}$ is the velocity reference.

The genset model considers that the power demand can be supplied by the generator as fast as it is required and the EMS must determine the proper power references. The dynamics are handled by the engine speed. To account for the CO₂ emissions, a static model was developed through a polynomial fit,

$$\dot{m}_{CO_2} = c_0 + c_1P_{g,el}. \quad (10)$$

The model receives the electrical power output of the generator $P_{g,el}$ as input and gives as output the mass flow rate of carbon dioxide, \dot{m}_{CO_2} .

Since it is necessary to maintain the grid frequency in 60 Hz, the speed reference is set to be 1800 rpm and the engine speed will be regulated through the governor to seek this value. Therefore, a constant engine speed is a reasonable assumption.

2.3 Energy storage system – battery

The battery model considered in this work is based on a second-order Thevenin equivalent circuit for a lithium-iron-phosphate (LiFePO₄/LFP) cell. The structure of the model was mainly based on the work of Perez *et al.* (2017). Particularly, the LFP electrical and thermal performances have led to its use in maritime applications as mentioned in Kalikatzarakis *et al.* (2018).

2.3.1 Electrical Model

The circuit model comprises an open circuit voltage V_{OC} , function of the state of charge (SOC), a series ohmic resistor R_0 , and two RC pairs R_1, C_1, R_2, C_2 , which are functions of the SOC and the cell temperature. The cell temperature was considered constant and equal to 298.15 K. The variable $I(t)$ defines the current running through the battery (positive for discharging and negative for charging) and C_{bat} is the nominal capacity. The voltages across the two RC pairs are V_1 and V_2 . The set of differential equations below evaluates the voltage and SOC dynamics,

$$\frac{dSOC(t)}{dt} = -\frac{I(t)}{C_{bat}}, \quad (11)$$

$$\frac{dV_1(t)}{dt} = \frac{-V_1(t)}{R_1C_1} + \frac{I(t)}{C_1}, \quad (12)$$

$$\frac{dV_2(t)}{dt} = \frac{-V_2(t)}{R_2C_2} + \frac{I(t)}{C_2}, \quad (13)$$

while the voltage in the terminals of the cell is given by

$$V_t(t) = V_{oc}(SOC) - V_1(t) - V_2(t) - R_0I(t). \quad (14)$$

2.3.2 Battery Pack

The parametric data used to implement the model was taken from Perez *et al.* (2017). The battery pack model considers a combination of cells in series and in parallel with a uniform behavior. This means that the states are considered to be equal for all cells. With the mentioned hypothesis, the total capacity C_{pack} , resultant voltage V_{pack} , current I_{pack} and power in the terminals P_{pack} of the battery become:

$$C_{pack} = NP \times C_{bat}, \quad (15)$$

$$V_{pack} = NS \times V_t, \quad (16)$$

$$I_{pack} = NP \times I, \quad (17)$$

$$P_{pack} = V_{pack} \times I_{pack}. \quad (18)$$

The number of cells in parallel and in series are NP and NS , respectively. The values of NP and NS were determined considering the capacity and nominal power of the battery, 1000 kWh and 1000 kW. The nominal current of the battery is $2C$, following the values considered for an LFP battery pack with the same power and capacity in (Peralta *et al.*, 2019).

2.4 Genset optimization

As mentioned in Kalikatzarakis *et al.* (2018), quasi-static efficiency maps of the power modes suffice for fuel economy estimation in an optimization process. This allows fast computational optimization. The complete and transient model runs to provide global powertrain information, and an inner quasi-static loop runs with the reduced models for optimization. A quadratic relation between the fuel consumption $\dot{m}_{f,dg}$ and the electrical power output $P_{g,el}$ is established,

$$\dot{m}_{f,dg} = b_0 + b_1P_{g,el} + b_2P_{g,el}^2. \quad (19)$$

In this work, the generators will be optimized to reduce fuel consumption. Then, a cost function is assigned to the system considering the total fuel consumption for the four generators $\dot{m}_{f,opt}$,

$$\dot{m}_{f,opt}(t) = \sum_i^4 w_i \dot{m}_{f,dgi}(t). \quad (20)$$

The index i represents each of the four generators, and their instantaneous fuel consumption rate are $\dot{m}_{f,dgi}(t)$. The variable w_i is a weight, defined for each generator to customize the cost function with rules. Some constraints are

imposed to the optimization formulation, such as the power balance equality,

$$\sum_i^4 P_i = P_L. \quad (21)$$

In this constraint, the load assigned to the gensets P_L must be supplied, considering each power output of the generators, P_i . Moreover, the power balance limits must be satisfied as well,

$$0 \leq P_i \leq P_{nom}, \quad (22)$$

where P_{nom} is the nominal power of the generators (equal for all gensets). The resulting optimization problem consists of finding the power allocation vector \mathbf{u}^0 that minimizes the fuel consumption of the gensets and satisfies the mentioned constraints. That is,

$$\mathbf{u}^0(t) = \arg \min_{\mathbf{u}} \dot{m}_{f,opt}(P_i, P_L). \quad (23)$$

To force the system to work with fewer generators, a weight is assigned to the generators based on Tab. 1.

Table 1: Genset weights used for the simulations.

Power intervals	genset 1	genset 2	genset 3	genset 4
$0 \leq PL \leq P_{nom}$	1	5	5	5
$P_{nom} < PL \leq 2 P_{nom}$	1	1	5	5
$2 P_{nom} < PL \leq 3 P_{nom}$	1	1	1	5
$3 P_{nom} < PL \leq 4 P_{nom}$	1	1	1	1

2.5 Hybrid management strategy

In this work, the hybrid EMS is characterized by a combination of rule-based strategies that define the power split between the gensets and the battery, and an optimization process for power dispatch of the generators. The set of rules are based on the work of Chua *et al.* (2018), where a rule-based strategy was presented for two generators and a battery. Table 2 describes the heuristic control considered for managing the power modes. The SOC of the battery and the load demand P_{Load} are taken as inputs and, through the decision table, the power references for the set of generators and battery are determined. Then, the optimization occurs to assign the power dispatch of each generator.

Table 2: Rule-Based strategy for an all-electric hybrid power system with four gensets and a battery.

Power \ SOC	SOC		
	$SOC \leq SOC_{min}$	$SOC_{min} < SOC < SOC_{max}$	$SOC \geq SOC_{max}$
$P_{Load} \leq P_{G,on}$	$P_{GT} = P_{opt}$ $P_{bat} = P_{Load} - P_{GT}$ if($P_{bat} < P_{cmax}$) $P_{bat} = P_{cmax}$ $P_{GT} = P_{Load} - P_{bat}$ end	$P_{GT} = 0$ $P_{bat} = P_{Load}$ if($P_{bat} > P_{dmax}$) $P_{bat} = P_{dmax}$ $P_{GT} = P_{Load} - P_{bat}$ end	$P_{GT} = 0$ $P_{bat} = P_{Load}$ if($P_{bat} > P_{dmax}$) $P_{bat} = P_{dmax}$ $P_{GT} = P_{Load} - P_{bat}$ end
$P_{G,on} < P_{Load} \leq 4 P_{opt} \times f_{peak}$	$P_{GT} = n_g \times P_{opt}$ $P_{bat} = P_{Load} - P_{GT}$ if($P_{bat} < P_{cmax}$) $P_{bat} = P_{cmax}$ $P_{GT} = P_{Load} - P_{bat}$ end	$P_{GT} = n_g \times P_{opt}$ $P_{bat} = P_{Load} - P_{GT}$ if($P_{bat} < P_{cmax}$) $P_{bat} = P_{cmax}$ $P_{GT} = P_{Load} - P_{bat}$ end	$P_{GT} = P_{Load}$ $P_{bat} = 0$
$P_{Load} > 4 P_{opt} \times f_{peak}$	$P_{GT} = 4 P_{opt}$ $P_{bat} = 0$	$P_{GT} = 4 P_{opt} \times f_{peak}$ $P_{bat} = P_{Load} - P_{GT}$ if($P_{bat} > P_{dmax}$) $P_{bat} = P_{dmax}$ $P_{GT} = P_{Load} - P_{bat}$ $P_{GT} = \min(P_{GT}, 4 P_{nom})$ end	$P_{GT} = 4 P_{opt} \times f_{peak}$ $P_{bat} = P_{Load} - P_{GT}$ if($P_{bat} > P_{dmax}$) $P_{bat} = P_{dmax}$ $P_{GT} = P_{Load} - P_{bat}$ $P_{GT} = \min(P_{GT}, 4 P_{nom})$ end

Table 3: Parameters used for rule-based EMS.

Parameter	Symbol	Value	Unit
Lower genset power limit	$P_{G,on}$	700	kW
Fraction power to cut peaks	f_{peak}	0.9	-
Max discharging power	P_{dmax}	1000	kW
Max charging power	P_{cmax}	-1000	kW
Min state of charge	SOC_{min}	20%	-
Intermediate state of charge	SOC_m	40%	-
Max state of charge	SOC_{max}	80%	-

It is important to avoid the use of the generators in the less efficient regions, which are, in general, when the generators are working with low loads. The first line of Tab. 2 considers the low load demands of the mission. If the SOC is below the limit, one generator is switched on with the optimal power $P_{GT} = P_{opt}$. The excess of power is used to charge the battery, given the maximum charging power of the battery P_{cmax} . If necessary, the generator power reference can be readjusted in a way that only the demand is supplied. If the battery SOC is above the lower limit, the battery will supply the power, limited its maximum discharging power P_{dmax} , while the generator is kept off.

In the second line of Tab. 2, the load demand is above a lower limit to switch at least one generator on and below an upper bound. The value of f_{peak} , which is between 0 and 1, can be used to customize the mentioned upper power bound. In this regime, if the SOC is less than the maximum, the power set to the generators is optimal, given the range of power, and the least number of generators n_g that need to be switched on to balance the load. The excess of power assigned to the generators is used to charge the battery. If necessary, the power of the gensets can be readjusted to supply the required power. When the battery reaches the maximum SOC, the load is delivered to the set of generators, where an optimization takes place. If, after the optimization, loads less than or equal to $P_{G,on}$ are identified for at least one generator, the battery is allowed to supply power until an intermediate SOC_m limit, avoiding generator operation on low loads.

In the third line of Tab. 2, there is a condition to shave high load peaks using the battery. If necessary, the function min is applied to the power of the generators to limit the operation within the nominal bounds of operation. The load set to the generators is optimized.

2.6 The base and hybrid cases

In this work, there will be a comparison between two power systems. The non-hybrid power system or the base case will only use (four) gensets to supply the power demand. The power split between the generators will be determined through optimization. However, the power dispatch of the hybrid power system will be set through the ruled-based EMS and the optimization. The values of the parameters used for the EMS can be found below, in Tab. 3.

The parameters used for the simulations, shown in Tab. 4, were found in the literature, estimated based on the literature results, or were estimated using data obtained through communication with the naval industry (for the gensets).

2.7 Efficiency index for the power system

A global efficiency index η_{ps} is proposed in this work to study how the hybrid power system can increase the overall efficiency of the vessel. In addition, it can help in comparisons to avoid false interpretations of results. In some situations, mainly when the mission simulation time is small, a fuel consumption reduction can be achieved along with a decrease in the SOC. Looking only at the fuel savings, the energy spent by the battery is not considered.

To consider the power modes in the same base, the methodology is based on the total energy input and output. In the base case, the input energy is given by the energy stored in the fuel, $E_{in} = m_f Q_{lhv}$, where m_f considers all the mass of fuel consumed during the mission and Q_{lhv} is the low heat value of the diesel. Since a power balance is achieved, the output energy along the mission is determined as, $E_{out} = \int_0^{t_f} P_d dt$, where P_d is the power demand. For the base case, the efficiency is given by

$$\eta_{ps} = \frac{\int_0^{t_f} P_d dt}{m_f Q_{lhv}}. \quad (24)$$

For the hybrid case, the energy input of the gensets is defined as before. However, it is necessary to consider the energy flow associated with the battery SOC. In general, the final state of charge of the battery can be different than the initial. Therefore, we consider the amount of energy that would be required to restore the initial SOC, defined as $E_{bat} = \int_{t_f}^{t_b} V_{pack} I_{pack} dt$. The integration goes from the final time t_f until the time t_b , in which the battery restores its SOC_i . If the SOC_f is greater than the initial, the excess of energy could be used to supply some demand of the ship. Thus,

Table 4: Parameters used for the simulations

Parameter	Symbol	Value	Unit	Reference
Number of poles	P_p	4	-	D
Nominal frequency	f	60	hz	D
Power factor	$\cos(f_p)$	0.9	-	E
Nominal electrical power	P_{nom}	1700	kW	D
Friction rate	c_f	0.005	-	E
Generator internal resistance	r_g	0.0324	Ω	E
Moment of inertia	J_g	69.21	kgm^2	(GE, 2009)
	a_0	1.74×10^{-3}	kNm	E
Coefficients for engine torque fit	a_1	7.95×10	kNm/kg	E
	a_2	-5.16×10^2	$\text{kNms}^2/\text{kg}^2$	E
	a_3	1.64×10^4	$\text{kNms}^3/\text{kg}^3$	E
	a_4	-9.78×10^4	$\text{kNms}^4/\text{kg}^4$	E
Coefficients for fuel power relation	b_0	4×10^{-3}	kg/s	E
	b_1	6.4×10^{-5}	$\text{kg}/(\text{skW})$	E
	b_2	5.1×10^{-9}	$\text{kg}/(\text{skW}^2)$	E
Coefficients for CO2 power fit	c_0	0.022	kg/s	E
	c_1	0.00017	$\text{kg}/(\text{skW})$	E
Nominal grid voltage	$u_{g,nom}$	690	V	D
Diesel low heat value	Q_{lhv}	42780	kJ/kg	D
Number of cells in parallel	NP	1136	-	E
Number of cells in series	NS	63	-	E
Battery converter efficiency	η_c	97.5%	-	(Kalikatzarakis <i>et al.</i> , 2018)

E - estimated

D - directly obtained

the efficiency is:

$$\eta_{ps} = \frac{\int_0^{t_f} P_d dt + |\int_{t_f}^{t_b} V_{pack} I_{pack} dt|}{m_f Q_{lhv}} \quad (25)$$

When the SOC_f is smaller than SOC_i , it means that energy would be required for recharging the battery to its initial state. Then, an input of energy would be necessary. Therefore, in this case, the efficiency becomes:

$$\eta_{ps} = \frac{\int_0^{t_f} P_d dt}{m_f Q_{lhv} + |\int_{t_f}^{t_b} V_{pack} I_{pack} dt|} \quad (26)$$

3. RESULTS AND DISCUSSION

A strategy to increase the energy efficiency of a vessel's power system is to improve the power dispatch. For a better dispatch, options include optimizing the energy management system with the same power system topology or adding components such as a battery. Figure 2 shows the complete power demand and power dispatch of both the hybrid and non-hybrid power systems. The base case power dispatch, with gensets only, is represented in the first column of the results, in Fig. 2c, 2e, 2g and 2i with the load demand above, shown in Fig. 2a, for the visualization of the mission profile. The power dispatch of the hybrid case, including the battery and gensets, can be seen in the second column, Fig. 2b, 2d, 2f, 2h and 2j.

When the vessel is being loaded in port, part 1 of the mission, and when the vessel is in standby, part 5, it is possible to see that the load is smaller than the power capacity of one genset, which is 1700 kW. Therefore, the load is sustained by only one generator in the base case. However, in the hybrid case, the battery is heavily used in those parts of the mission, since the load is often smaller than 700 kW, which is the lower power limit for the genset to be switched on. Moreover, the gensets work in higher and more efficient power regions for the hybrid topology, in comparison with the base case. The hybrid system can also reduce the total genset operation time and reduce CO₂ emissions near the port.

In 2, the ship is on a laden voyage. Since the ship is fully loaded and traveling at the nominal speed, this part of the mission is characterized by high power demands. In the non-hybrid system, the first three gensets operate in the nominal condition almost all the time, with genset 4 balancing the higher load variations. Regarding the hybrid power system, a considerable difference appears in the use of genset 4, which operates in a steady-state and in a more efficient region, while the load variations are handled by the battery.

Evaluating the DP part, corresponding to range 3, genset 1 was set to deliver practically all demand, for the base case, with a small peak handled by genset 2. The hybrid system operated with only genset 1 switched on and the battery dealt mainly with lower and higher peaks, in short times. At the beginning of the DP, the battery was charged, allowing genset 1 to operate in nominal condition for some time, which did not happen in the base case in the same part of the mission. In both cases, no spinning reserve nor backup power were considered, and the generators were allowed to work at nominal power. As the power load is within the envelope of one genset, and above the lower power limit of 700 kW, almost all the time, the battery usage was limited in the DP part of the mission in this simulation.

Regarding the partial load voyage, part 4, gensets 1 and 2 operated at nominal power for the base case, while genset 3 handled the rest of the load with a small contribution of genset 4. Considering the hybrid case, the low load delivered by genset 4 was replaced by the battery power supply. This can improve the energy efficiency since genset 4 was operating below 500 kW in the base case for this part of the mission.

When analyzing the power dispatch of the hybrid and base cases, it can be noted that adding the battery allowed gensets to be disconnected in some conditions, mainly near the port. Also, a more efficient operation was observed, with the gensets running with higher loads. In Peralta *et al.* (2019), the hybrid power system simulation has shown the higher potential of CO₂ reductions for batteries near the port, in loading and standby operations, for a PSV, even allowing the disconnection of generators. Considering the relation between CO₂ emissions, fuel consumption, and the power system increase in efficiency, it can be said that the mentioned literature results are in accordance with the results obtained in this work. As it can be seen in Fig. (2), for laden and partial load voyage, the battery is quite used, something that does not happen in Peralta *et al.* (2019). The dispatch will depend on several factors such as load demand, the topology of the vessel's power system, and EMS. Therefore, differences are expected to occur.

Different aspects can be used to evaluate the gains of the hybridization of a vessel in its power supply system. For achieving a more cost-effective and cleaner operation, it is essential to analyze fuel consumption savings and CO₂ emissions. However, for a better perspective, it is also important to take into consideration the final state of charge SOC_f and evaluate the increase in vessel efficiency. Table 5 lists the masses of fuel consumed and CO₂ emissions, as well as mass reductions between the base case and the hybrid case. For the hybrid case, the initial and final states of charge are considered. Also, the global efficiency index is considered in the last column of the table for all cases. A fuel consumption reduction of 6.35% and CO₂ emission reductions of 5.81% were achieved. Although the SOC_f is smaller than the SOC_i, the power system efficiency increased by 1.73%. The addition of the battery allowed the reduction of fuel consumption, emissions, and an increase in the overall energy efficiency of the vessel's power system.

Table 5: Compilation of results for comparison between the base and hybrid cases

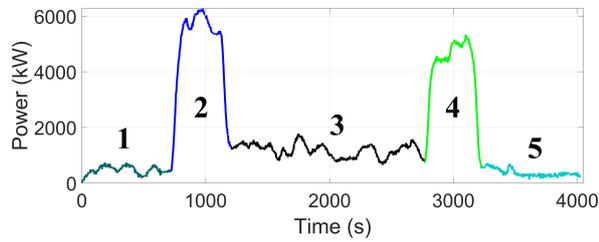
Case	Fuel		CO ₂ emissions		SOC		η_{ps}
	m_f	reduction	m_{CO_2}	reduction	SOC _i	SOC _f	
	[kg]	[%]	[kg]	[%]	[%]	[%]	
Base	414.59	-	1287.6	-	-	-	37.51
Hybrid	388.28	6.35	1212.8	5.81	80	62.39	39.24

The fuel consumption and CO₂ emission reductions vary in the literature for hybrid power systems using batteries, depending on the case of study. Fuel savings of up to 45% have been found in some works, for special cases (Miyazaki *et al.*, 2016). However, in a recent technical report from the European Maritime Safety Agency, the fuel savings potential for OSVs is expected to be between 5-20% (EMSA, 2020). The work of Peralta *et al.* (2019) was found to be the closer study to this work. The authors have reported a 7.4% reduction in CO₂ emissions, considering the addition of a 1000 kW/1000 kWh battery to a PSV power system, which comprised initially, four gensets with 1850 kW each unit. Based on the mentioned literature, the results obtained in this work are within an acceptable range of what has been expected for fuel savings and CO₂ emission reductions for a PSV.

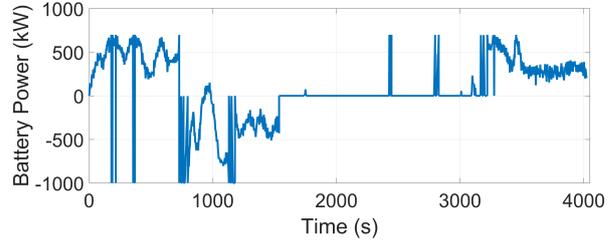
4. CONCLUSIONS

The methodology presented in this work has shown promising results. We used a causal because it enables the representation of real-time systems. Fuel savings, emission reductions, and an increase in energy efficiency were observed. The addition of the battery, with a consistent EMS control for power dispatch, allowed benefits for the PSV's power system. Understanding how hybrid solutions work, and their benefits, is essential for increasing the adoption of such technologies to achieve more cost-effective and cleaner vessel operations, as well as other improvements in performance. Based on the case study considered, the results suggest that:

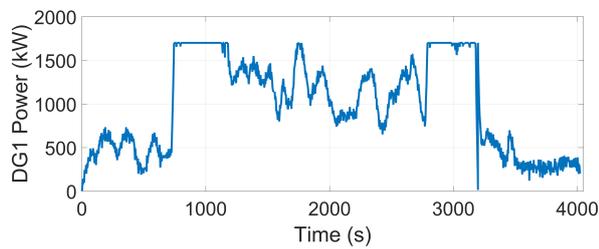
- The battery shows great usage potential when the ship is being loaded in port or on standby. In these parts of the mission, the generators operated in higher efficiency regions, and some were even disconnected. With this, the battery can enable cleaner operations near the port;



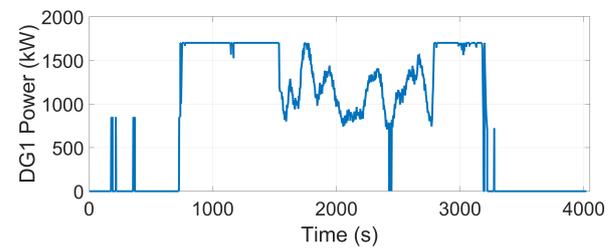
(a) Power demand profile



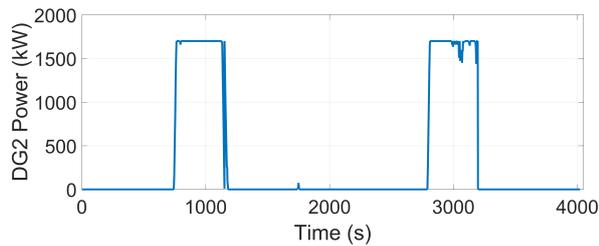
(b) Battery power dispatch



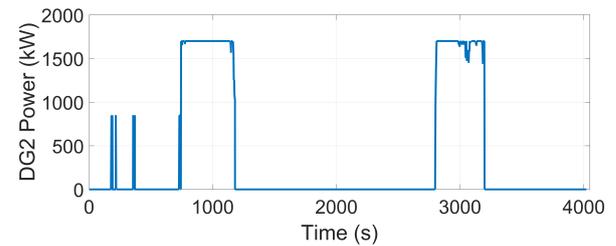
(c) Base case power dispatch - genset 1



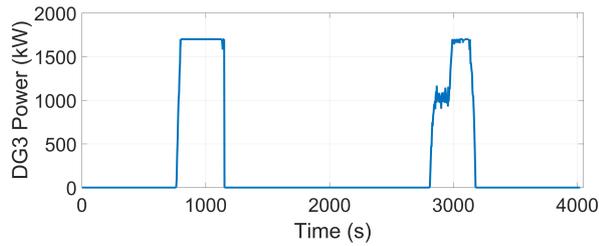
(d) Hybrid case power dispatch - genset 1



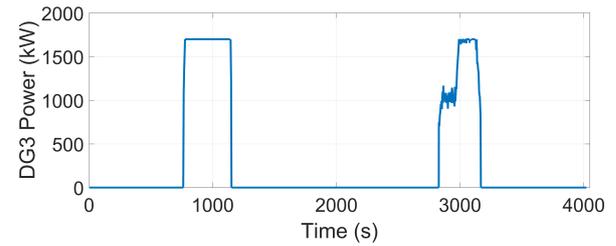
(e) Base case power dispatch - genset 2



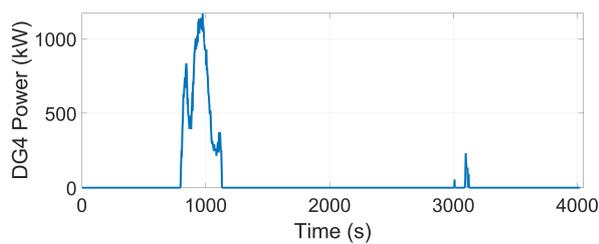
(f) Hybrid case power dispatch - genset 2



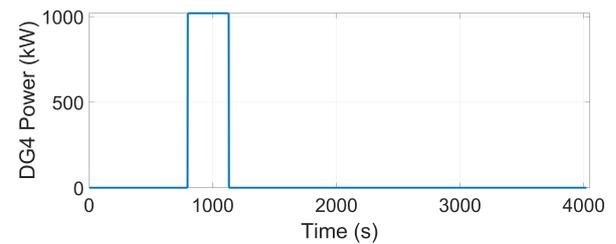
(g) Base case power dispatch - genset 3



(h) Hybrid case power dispatch - genset 3



(i) Base case power dispatch - genset 4



(j) Hybrid case power dispatch - genset 4

Figure 2: Power demand, and power dispatch of the base case (non-hybrid) and the hybrid power system

- For the laden and partial load voyages, the battery can also enable the generators to run at higher efficiencies;
- The battery was not much used in DP, probably due to the load profile, general assumptions, and EMS. In a real operation, due to the safety requirements and redundancy of gensets in DP, the battery could be used more effectively. Our group has been studying such conditions for further analysis and publications;
- The hybridization of the power system can enable an increase in energy efficiency and, therefore, reductions in fuel consumption and CO₂ emissions. An increase in the energy efficiency of 1.73%, fuel savings of 6.35%, and CO₂ emission reductions of 5.81% have been achieved by the hybrid solution.

Future work may look into designing specific energy management solutions for the DP part of the mission, and developing optimal strategies to improve the performance of the hybrid solutions, evaluating fuel consumption, emissions, as well as battery capacity fading. In addition, it would be interesting to test the power systems in different missions to analyze the robustness of the power dispatch strategies and the effects of the power profile on the behavior of the hybrid systems.

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