Design Study of a Hybrid Power System for a Ferry Using Open Simulation Platform

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ABSTRACT

In a hybrid power system, an energy storage device unlocks the possibility of optimizing the design and operation. Only a properly tuned control strategy with correctly sized machinery under specific operation profiles will maximize the benefit. Therefore, a proper design should be chosen with consideration for the system behavior including the control strategy. This can be achieved using a dynamic system simulation. In this paper, a design study of a hybrid power system for a ferry is presented as a proof of concept for using Open Simulation Platform (OSP) for a design study at an early design stage. A complete system for a vessel and the power system is set up using the models contributed by different parties. A large number of sets of design parameters are created by the design of experiments. Results of simulations are presented, and the range of proper designs are selected based on the chosen criteria. A design tool was developed to integrate these processes for efficient use of the methodology. This study has successfully demonstrated the feasibility of the collaborative system design using co-simulation software from OSP.

KEY WORDS: Open Simulation Platform, System Simulation, System Design, Design Study, Hybrid Power System, Design of Experiments

INTRODUCTION

In a hybrid power system, battery banks or other types of energy storage system (ESS) unlocks possibility of optimizing the design or operation by easing the requirement for the power balance between the consumers and producers. Peak-shaving, load levelling, spinning reserve, zero-emission mode are such operations. A challenge is that these operations will not always save energy but maybe opposite. A proper control strategy with correctly sized machinery under specific operation profile will maximize the benefit of the novel technology. Here, the system performance is of the key interest rather than best performing components. In addition, dynamic property of the different power sources and control needs to be taken into account to evaluate the system performance. Therefore, it is often requirement to take a holistic approach to analyze a system and to consider dynamic response of the system. Using simulation models as a central tool for description of requirements, evaluation of designs and system integration and for assuring the transfer of knowledge through different stages of the design can guide the designers to make a good decision on their designs. Furthermore, system simulations enable the designer to efficiently explorer a large design space which is essential for designing a system with large flexibility in an optimal way.

Numerous studies on dynamic system modeling of marine hybrid power system can be found in literature. Ghimire *et al.* (2020) presented the simulation for shipboard DC hybrid power system which can run in real-time where hull and propulsion are modeled as a static load. Alwan *et al.* (2017) demonstrated a design study for a hybrid power and propulsion system using the system simulation that encompasses hull, propulsion in waves and a hybrid power system where all the modeling and simulation was done on one platform. Bø *et al.* (2015) also developed a modeling framework including the marine vessel, propulsion, power system and controllers such as DP controller and a power management system (PMS). The modeling framework is developed on MATLAB/Simulink. These simulation models or framework provide means to look into the system interaction, behavior and performance in a dynamic loading situation. However, the models are developed either on a single software tool or by an individual or a small group.

In practice, challenges for developing such a system dynamic model come with:

1) Lack of competence, information and resources in developing components from different domains
2) Lack of standards for integrating models that are developed in different domains and modeling tools

These challenges can be overcome by having a collaborative simulation platform in which multiple parties provide their own component models following an industrial standard to build a system model. The Open Simulation Platform (OSP) was initiated to solve these challenges. Using the OSP software, original equipment manufacturers (OEMs) can share their models without concern of losing their intellectual properties.

In this paper, we will present a design study for a hybrid power system for a passenger ferry using Open Simulation Platform (OSP). The design study described in the paper is performed as a proof of a concept that the OSP software can be used in an early design stage where the target system is not well-defined, and it is necessary to evaluate a large number of design cases. First, we will describe the OSP concept, and the joint industry project (JIP) related to. Then, the purpose, target system and methodology will be explained for the design study as a use case for the JIP followed by the modeling framework for the system and its components. Cases for the design study and the simulation result will be presented followed by the discussion and conclusion.

OPEN SIMULATION PLATFORM (OSP)

The OSP was initiated in 2017 by SINTEF, DNV GL, Kongsberg Maritime and NTNU. A Joint Industry Project (JIP) was later established and the OSP partners cover a wide range of stakeholders in the maritime industry. The OSP JIP was concluded in June 2020, and more information on project partners and background, as well as all project results are shared through a webpage. (*Open Simulation Platform*, 2021)

The vision of OSP is to 'enable collaborative digital twin simulations to solve challenges with designing, commissioning, operating and assuring complex, integrated systems.' Typically, such systems involve multiple suppliers that deliver components, sensors and software that shall work together, where simulation models are considered an important part of the continuously updated virtual documentation that shall follow a vessel from design phase and into operation (digital twin). OSP aims to make use of system simulation more accessible by allowing stakeholders to share and reuse models in an efficient way.

Today simulation is a core enabling technology when designing, optimizing and operating new assets. Specialized tools and methods for modelling and simulation are many, but they are typically not made available for collaboration and re-use. To best make use of these investments and assets, we need unifying approaches to enable digital collaboration across disciplines and sectors and throughout the lifecycle of an asset. One such approach is co-simulation. It allows to couple independent stand-alone simulation-models, including their numerical solvers, to establish full-system simulations and is well suited when the sub-simulators span a range of physical and engineering domains.

The OSP have adapted a well-known tool-independent standard *Functional Mock-Up Interface, or* FMI (Junghanns and Blochwitz, 2018) for short for making sub-models compatible with each other in a co-simulation context. FMI is completely open and free to use and is supported by a large and growing number of tools. From a simulation tool, you can then export the model as a Functional Mock-up Unit (FMU) that can be used with any tool that supports FMI for co-simulation. Using the existing FMI standard models developed by suppliers in their preferred tools, to create larger system simulations without revealing proprietary information. FMI standard has been widely adopted in the automotive and building industries in which a system simulation has an essential tool to verify the complex system before it production and deployment (Hirano *et al.*, 2018; Ko *et al.*, 2018; Aoun *et al.*, 2019).

FMI provides compatibility at low level but does not provide higher level information about what the simulation variables mean or how to set up the model interconnections. Coupling the models to create a co-simulation setup could therefore be a challenging task. Addressing this, the OSP Interface Specification was developed to configure such setups more efficiently.

OSP have also developed the SW that orchestrates the co-simulation, meaning that it handles time synchronization and communicate simulation values between the models. To drive standardization, ensure interoperability between stakeholders and tools, and enable common working processes, we strongly believe that a common, open-source software for co-simulation is key. The OSP software (libcosim), interface specification and a set of reference models are therefore openly shared and free to use for all (Kyllingstad *et al.*, 2021).

Furthermore, three use cases were set up to provide a working platform on which the software is tested as a proof of concept and, therefrom, user experience is fed back to the development to improve the quality of the software. Three use cases have been set up to demonstrate the use of OSP at different phases in a lifecycle of a ship:

- Design and proof concept for a hybrid ferry propulsion system
- Virtual commissioning of a coastal service vessel
- Operational planning for crane operation on R/V Gunnerus.

USE CASE FOR OSP JIP - DESIGN STUDY

The aim of the use case and design study

The first use case of the OSP project is the design and proof of concept case. In the use case, we aim to demonstrate the capability of OSP software as a simulation tool in the conceptual design phase where the uncertainty of the design is high, and one needs to explore as many options as possible to find the optimized design to start with. At this design stage, no specification of the power system and its components are determined, and the main purpose is to find optimal sizing of the main machinery components such as gensets, battery banks. The main question we try to answer through this design study is if co-simulation using OSP software is a useful tool for the system design in early stage. Therefore, the main goal of the design study is to explorer the design space of the hybrid power system together with control parameters of the system that gives minimum fuel consumption within allowed drop of SOC.

Target vessel and system

The target system in the project is a hybrid power system in a passenger ferry, which includes gensets and a battery bank to provide power to the propulsion motors. The main particular of the vessel is shown in Table 1 while Figure 1 shows the single line diagram of the power system as the topology of the system. We assumed that no further details of the system or component are given but to be determined at later stage. In Figure 1, all the gensets, the battery bank and the motors are connected to a single bus. Even though an actual vessel has two switchboards, we assumed that the bus tie breaker will be always closed. The power grid is AC and, therefore, the battery is connected by an inverter whereas the propulsion motors are connected by the corresponding frequency converter that consists of a rectifier, a DC link and an inverter. The battery is assumed to be of lithium-ion type.

Table 1 Main particulars of the target vessel

Length overall	80.8 m
Beam molded	17.0 m
Depth to main deck molded	5.7 m
Design draught	3.3 m
Gross Tonnage	2277 t
Capacity	300 passengers, 47 cars
Design speed	14 kts

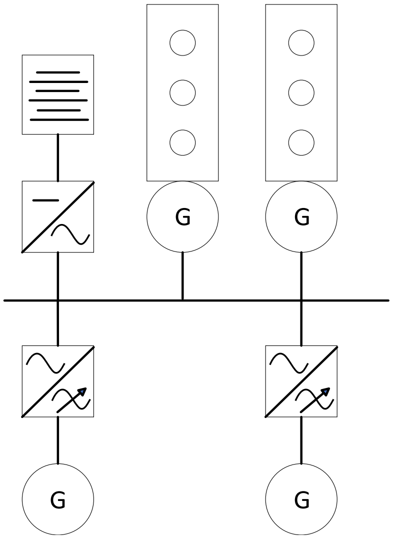


Figure 1 Single line diagram of the hybrid power system for the target vessel in the use case

Operation profile of the system

The ferry will transit from one terminal to another with a fixed speed reference at 12 knots. Figure 2 shows the reference speed of the vessel speed, simulated with a speed controller. A slight overshoot of the speed is observed at the end of acceleration phase. Figure 3 shows the power profile for the gensets and propulsion motors where a battery bank is inactive. There is a short period of burst in power for the acceleration. For such a power profile, a peak shaving strategy can be effective for downsizing the power sources and reducing fuel consumption.

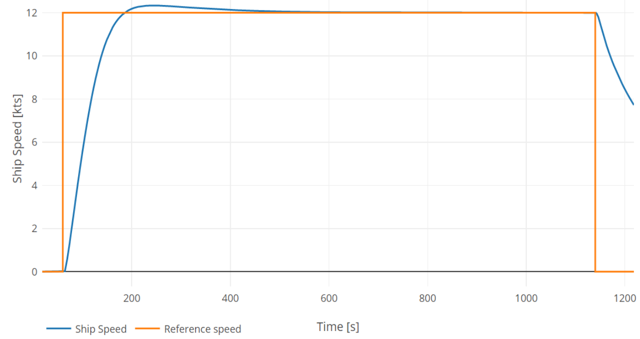


Figure 2 Speed profile of the vessel for a transit operation

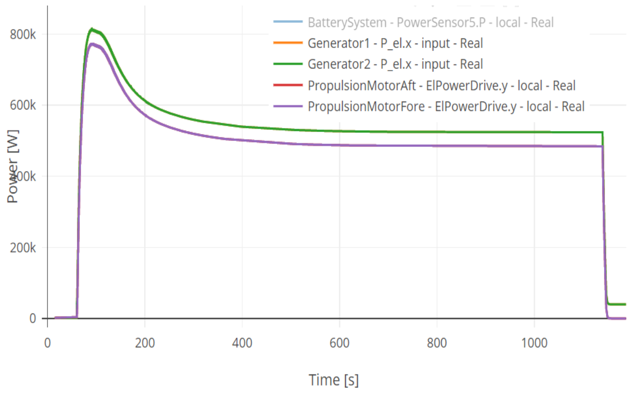


Figure 3 Power profile of the vessel for a transit operation.

SYSTEM MODELING

Scope of the system model

The simulation model should contain all the relevant components of the vessel system. For a physical part, it should have all related parts from propellers to engines as well as a hull. In addition, basic local and high-level controllers should be in place to run the system simulation in an intended scenario. In this design study, we identified the following components to be included to simulate the vessel operation.

- Physical components: hull, propeller, propulsion motor, switchboard, generator, battery bank, gas engine
- Control components: propulsion control, power / energy management system

Figure 4 show these components in the system structure.

Component Modeling and Controller Implementation

We distributed the responsibility of modeling for multiple parties in the project team. The hull and propulsion models were developed by Damen Shipyard. The electric motor model was developed by Vard Group. LNG engine and generator models are developed by DNVGL, and switchboard, battery bank and controller models are developed by SINTEF Ocean.

As the component models would be created by different partners in the use case, it was crucial to have common ground for the interfaces and the model fidelity for modeling. Considering that our main outputs of interest from the simulation are fuel consumption and SOC of the battery bank at the end of the journey, we identified the requirements for each component with which interfaces and modeling framework can be selected as shown in Table 5.

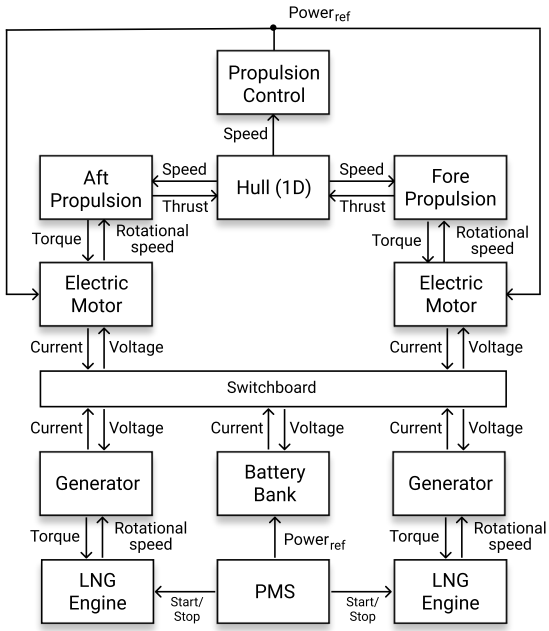
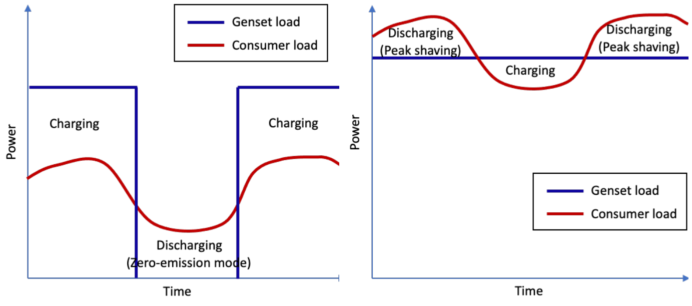


Figure 4 Physical and control components of the target vessel to be modeled for a system simulation

To run the system simulation with a minimum set of scenarios and parameters, two high-level controllers, a propulsion controller and power / energy management system (PMS) are implemented in addition to the physical components. The main functionality of each controller is summarized in Table 6. The propulsion controller is used to make sure the vessel travel at the reference speed given. This controller enables to define the operating scenario of the vessel for the given environment by a series of speed set points. We used a simple PID controllers that changes its output depending on the deviation and derivative in vessel speed. The controller gives a reference power for the propulsion motors to follow as an output.

The PMS is modeled to ensure that the power system can always meet the power demand and it operates at the best efficiency possible. We applied two strategies for the battery operation: peak shaving and zero-emission. In a zero-emission operation, the battery bank will provide all the power demand while the gensets are turned off when the overall power demand is low. This operation is schematically shown in Figure 5(a) in which the zero-emission operation is happening in the center area of the figure.



(a) (b)

Figure 5 Typical battery operation for a low-load profile

When the power demand is higher than what the gensets can provide in a short period time, the battery bank will provide the surplus power above the limit, so called peak shaving operation. With a peak shaving operation, rated power of gensets can be reduced, which will improve the loading of the gensets and lower the cost. This is schematically shown in Figure 5(b) where peak saving operation is happening in the begging and toward the end of the timeline.

To avoid depletion of the battery bank, the batteries will always be charged if the SOC is lower than the set limit. Furthermore, when zero-emission or peak-shaving is not happening, the battery will be charged until the SOC of the battery reaches the high limit typically set to above 0.7 to reserve energy for those operations. This is illustrated in both ends of the timeline in Figure 5(a) and in the middle of timeline in Figure 5(b). When the load is in the mid-range, gensets solely provide the power in demand.

To achieve the various operational mode of the power system depending on the magnitude of the consumer load, the SOC of the battery bank and the available power from the gensets, a state-machine based controller is applied to determine the mode of operation. A schematic of the state machine is shown in Figure 6.

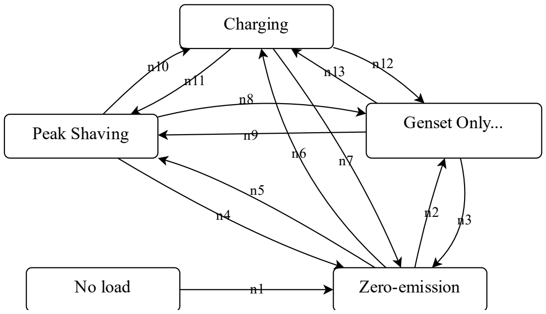


Figure 6 A state machine diagram of the PMS for the operation of the power system.

DESIGN CASES AND SIMULATION RESULTS

Design Variables

The main design variables that will affect the fuel consumption and SOC of the battery bank are selected as follows:

- Rated power for auxiliary engines: $P_{eng,rated}$
- Power limit for genset load, normalized: $\bar{P}_{\mathrm{eng},max}$
- Maximum genset load for zero-emission mode, normalized: $\bar{P}_{\mathrm{eng},min}$
- Battery energy capacity: C_{batt}

Sensible range of values for the variables are set for each variable and sampling types are chosen as shown in Table 2 Range of values and sampling type for the design variables.

Synthesis of Design Cases

The design cases are generated by a design of experiment method. To have efficient filling of the design spaces, a Sobol sequence is chosen for the sampling method (Satelli and Sobol, 1995). Implementation of the sampling method was taken from Chisari (2020). One hundred cases were generated for each battery capacity where a case is a set of the three variables: ($P_{eng,rated}$, $\bar{P}_{\mathrm{eng},max}$, $\bar{P}_{\mathrm{eng},min}$).

To reproduce the operational profile as in Figure 2, a scenario was set in which the operating parameters will change their values at given time as shown in Table 3. The scenario configuration and playing s one of the inherent functions of the OSP simulation.

Table 2 Range of values and sampling type for the design variables

Variables	Value range	Sampling type
$P_{eng,rated}$	400 – 800 kW	Continuous
$\bar{P}_{\mathrm{eng},max}$	0.7 – 0.95	Continuous
$\bar{P}_{\mathrm{eng},min}$	0.1 - 0.4	Continuous
C_{batt}	500, 750, 1000 kWh	Discrete

Table 3 Operational Scenario of the vessel and the power system

Time (s)	Parameter	Set value
60	Start hotel load	True
60	Vessel speed reference	12
1140	Vessel speed reference	0

System response from the simulation

First, a time series output of a typical case is observed to verify the behavior of the system as plotted in Figure 7. For this case, the design variables are set as follows:

- $P_{eng,rated}$: 725kW
- $\bar{P}_{\mathrm{eng},max}$: 0.872
- $\bar{P}_{\mathrm{eng},min}$: 0.231
- C_{batt} : 500 kWh

The power system starts being loaded with the hotel load at 60 seconds. At the same time, the propulsion motors will start spinning. First, all the power is drawn from batteries as the gensets are not started. PMS sends starting signal to the gensets. At t = 100s, the gensets are ready and get synchronized. They immediately start taking loads until it reaches its maximum value set for peak-shaving operation while batteries are topping off the remain power. As the propulsion load decreases as the vessel approaches its reference speed, battery will start being charged at t = 213.2s. The rate of charging increases as the power available from gensets are increasing as the propulsion goes further down. At t = 843s, the SOC of the battery reaches its maximum set point and charging stops. Now gensets are soles providing the power for propulsion and hotel load. At t = 1140s, the reference speed for vessel changes to 0 and the no propulsion power is required. As the power load is low, gensets are turned off and the vessel operates in a zero-emission mode.

Depending on values of the design variables, the system response will change. In Figure 8, the battery is continuously providing a part of the power for the consumers as the engines are underrated for the power demand. In this case, the SOC dropped by 24.1% per trip compared to almost none (0.5% per trip) in the case shown in Figure 7. For fuel consumption, it is 42.65kg / trip vs. 64.45kg / trip as the most of 1/3 of energy comes from the battery. If the charging facility allows such a drop in the smaller engine case, it will be a favorable choice but, if not, it becomes an unacceptable case.

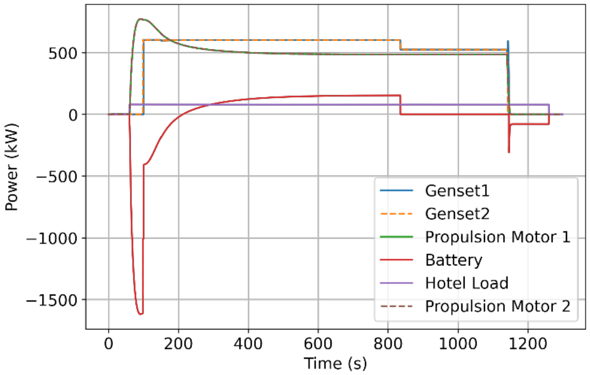


Figure 7 Time series of power in balance for gensets, a battery bank and consumer loads($P_{eng,rated}$ =725kW, $\bar{P}_{\mathrm{eng},max}$ =0.872, $\bar{P}_{\mathrm{eng},min}$ = 0.231, C_{batt} =500 kWh)

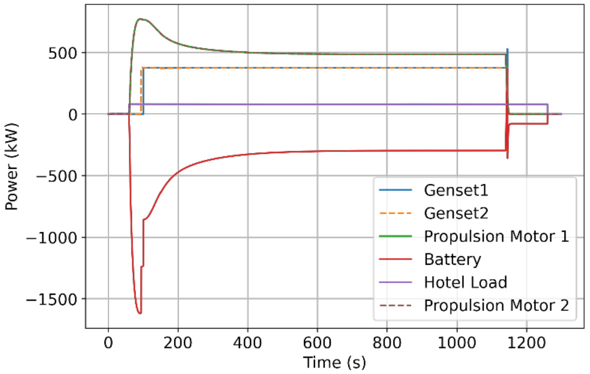


Figure 8 Time series of power in balance for gensets, a battery bank and consumer loads($P_{eng,rated}$ =559.4kW, $\bar{P}_{\mathrm{eng},max}$ =0.706, $\bar{P}_{\mathrm{eng},min}$ = 0.346, C_{batt} =500 kWh)

After verifying the dynamic responses of the system, the correlation between each design variable and the main outputs is studies to understand their relations. Figure 9, 10 and 11 are scatter matrix that show correlation among design variables and the simulation outputs for different battery capacities. Any scatter plot between two design variables shows well-distributed points over the plot area, which suggests that the design of experiment was effective. From the three figures, it is found that there are strong linear correlation between the rated power of gensets and both main outputs, whereas the correlation between the control parameters ($\bar{P}_{\mathrm{eng},max}$ and $\bar{P}_{\mathrm{eng},min}$) and the outputs are very weak. Initial conclusion from this result is that it is difficult to draw any solid simple rule of thumbs for selecting the correct control parameters that suits the given size of engines. It is also observed that the fuel consumption and SOC drop has a linear inverse correlation. However, a small but visible deviation in vertical direction is detected which suggests that there is certainly better design for the same amount of SOC drop.

This becomes more clear by observing the pareto front plot as shown in Figure 12. In this plot, each point represents a output from a design case. This presentation provides the insights into how the fuel consumption will change for the given battery pack and the given limitation of SOC drop per trip. The allowed drop in SOC will depend on the number of frequency of the trips, capacity of the charging facility at the port, and duration of port stay. When the requirements from the operation become more detailed, candidates for the best design can be easily picked from this result.

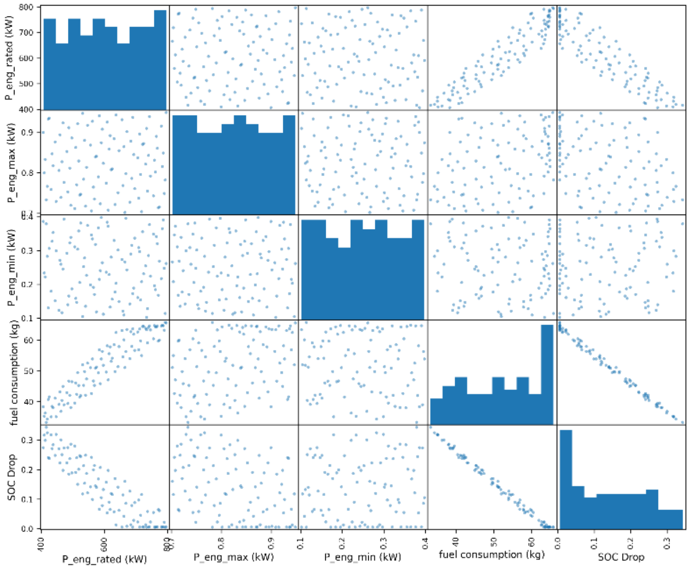


Figure 9 Scatter matrix of the design variables and simulation outputs (fuel consumption and SOC drop) for C_{batt} = 500 kWh

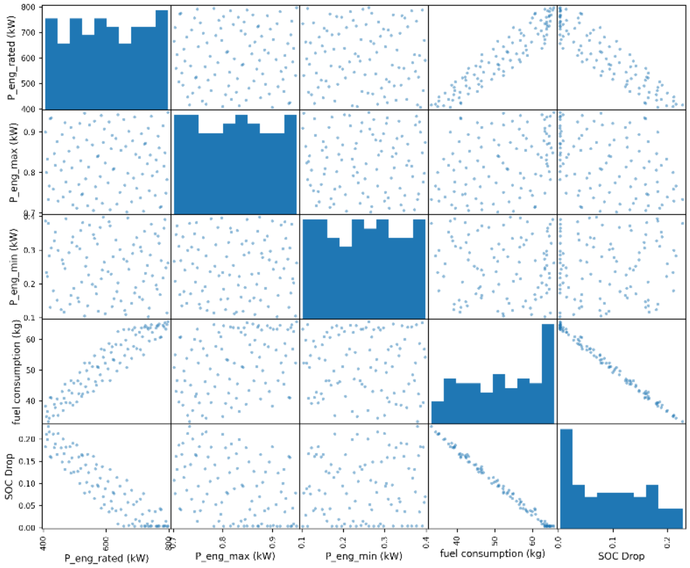


Figure 10 Scatter matrix of the design variables and simulation outputs (fuel consumption and SOC drop) for C_{batt} = 750 kWh

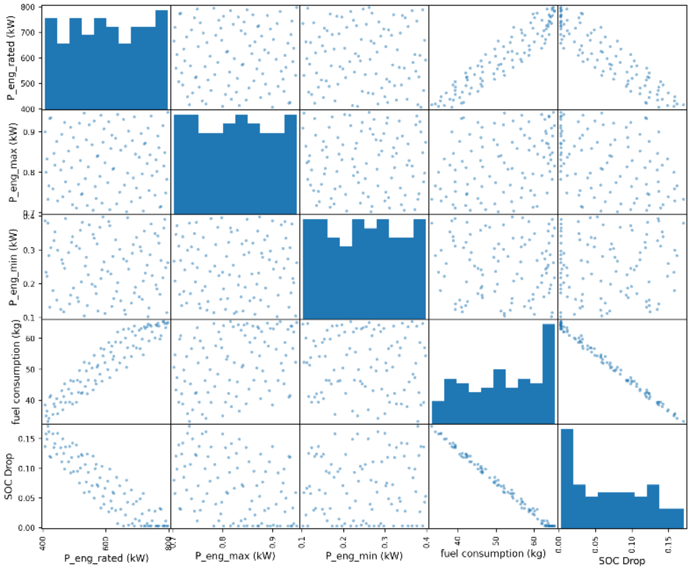


Figure 11 Scatter matrix of the design variables and simulation outputs (fuel consumption and SOC drop) for $C_{\text{batt}} = 750$ kWh

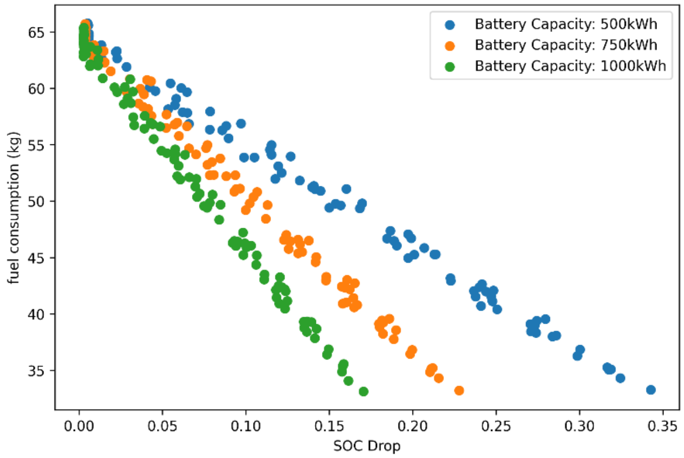


Figure 12 Pareto front plot for the two main outputs of the simulations: fuel consumption (kg) and SOC drop per trip.

We have selected the best design for the three different maximum allowed SOC drop cases: 5%, 10%, and 15% as shown in Table 4.

Table 4 Choices of the optimal design for different criteria of SOC drop per trip

C_{batt} (kWh)	$P_{eng,rated}$ (kW)	$\bar{P}_{\text{eng},max}$	$\bar{P}_{\text{eng},min}$	Fuel consumption (kg/trip)
SOC Drop 5%				
500	715.6	0.796	0.154	59.8
750	593.8	0.907	0.264	56.5
1000	562.5	0.927	0.334	54.5
SOC Drop 10%				
500	562.5	0.927	0.334	53.9
750	515.6	0.921	0.304	49.2
1000	468.8	0.923	0.245	45.2
SOC Drop 15%				
500	515.6	0.921	0.304	49.4
750	459.4	0.893	0.271	43.0
1000	412.5	0.833	0.222	36.4

CONCLUSIONS

Complexity in the problem of optimal design of a marine hybrid power system drives the need for a dynamic system simulation toward a conceptual design stage. An early collaboration with the key stakeholders and competent holders can overcome the challenges that rise from lack of common understanding, resources, competence and expertise. Open Simulation Platform can be such a platform on which partners can share their models without concern of loss of the intellectual property. The design study presented in this paper proves the feasibility of using the OSP software as a collaborative tool for the concept development of a complex system. However, the result has to be validated further before the actual design is fixed for the further development. This process is omitted in the current work but is crucial to provide the credibility of the simulation result.

ACKNOWLEDGEMENTS

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APPENDIX

Table 5 Requirements and modeling framework for the components of the system model

Component	Main requirements	Modeling Framework
Hull	Shall provide the vessel speed to the propeller, given the input of the thrust from the propeller.	First order response with inertia. Calm water resistance curve
Propeller	Shall provide rotational speed to the electric motor and thrust to the hull given the input of the motor torque and speed of the hull.	First order response with inertia, Open water propeller curve
Electric Motor	Shall provide torque on the propeller based on the given power set point.	First order response with look up for efficiency
Switchboards	Shall provide the power demand for each genset based on the load currents of consumers and the battery bank, generator status and bus-tie breaker status.	Constant voltage, Power balance
Generator	Shall provide the torque on the main engine based on the power demand from the switchboard.	First order response with look up for efficiency
LNG engines	Shall provide the fuel consumption rate based on its power load. Shall provide the speed response based on the load torque	First order response with inertia with loop up for efficiency

Table 6 Summary of the description for the controllers used in the system models

Controller	Control objective	Type	Output
Propulsion	Maintain the vessel speed to the given reference value	PID control with anti-wind up	Power reference for propulsion motors
Power / Energy management	Determine load sharing between the gensets and the battery Charge the battery when the SOC of the battery bank is lower than a set point Turn on / off the gensets in order to keep a minimum number of the gensets	State-machine-based control	Power reference for the battery bank Engine on/off command

This becomes more clear by observing the pareto front plot as shown in Figure 12. In this plot, each point represents a output from a design case. This presentation provides the insights into how the fuel consumption will change for the given battery pack and the given limitation of SOC drop per trip. The allowed drop in SOC will depend on the number of frequency of the trips, capacity of the charging facility at the port, and duration of port stay. When the requirements from the operation become more detailed, candidates for the best design can be easily picked from this result.