Modeling and Simulation-based Design Evaluation of Hybrid Propulsion System for a Pilot Launch Boat

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Abstract – In this paper, a design-stage modeling, simulation, and power balance-based verification methodology for the hybrid electric pilot launch boat is reported. The developed model simulated using the real-world operation profile revealed that the proposed hybrid system can reduce the running hours of main- and generator-engines by 10.5 % and 56.8 % respectively with respect to the baseline diesel mechanic propulsion-based vessel. Although the full electric- and drift-modes of the hybrid system reduce the fuel consumption by 100 % and 52.3 % respectively, the additional fuel consumption due to the Power Take Out (PTO)-generators under the diesel mechanic- and hybrid-modes reduce the net fuel savings to 0.3% per year. The value of design space exploration study that could help to develop better design specification and operation parameters to improve the fuel savings of the hybrid electric system is discussed.

Keywords: Simulation; Propulsion; Hybridization; Verification; Design; Evaluation

INTRODUCTION

As a part of the Long-Term Low Emissions Development Strategy (LEDS), Singapore has set the target for net zero emission by 2050 [1]. From 2030 all new harbor crafts operating in Singapore waters must select one or more of the options such as full electric, be capable of using B100 or be compatible with net-zero fuels such as hydrogen.

Due to the push towards net-zero emission in Singapore, various harbor craft stake holders are exploring battery-based full-electric and hybrid-electric solutions. The PSA Marine (Pte) Ltd (PSAM) was planning to build two Full Electric Ready Plug In (FERPI) pilot launch boats that would be operated with internal combustion engines or Hybrid Electric Power System (HEPS) at the initial stage and in the future will be converted into Full Electric (FE). The Tank-to-Wake emissions for FE vessels are zero whereas for Hybrid Electric (HE) vessel the emission is dependent on various design parameters and operation variables. Some of them are battery capacity, operation profile of a vessel, number of times a battery can be charged, charging capacity, efficiency and capacity of propulsion motors / generators. The dependency on various design parameters and operation variables for HE designs needs proper evaluation at the design stage to identify the emission reduction efficacy. In line with the PSAM initiative, modeling and simulation were required for ship designers/system integrators to assess the proposed design. This involved using the reference operational profile from a 15 m pilot launch boat provided by PSAM.

One of the system integrators Brunvoll Mar-El (BME) AS had approached American Bureau of Shipping (ABS) for an independent third-party system energy efficiency evaluation using modeling and simulation. Conventionally, the design evaluation is carried out by simplified energy flow calculations in a spreadsheet with logical assumptions. In a hybrid propulsion system, the different modes of propulsion such as electric, hybrid and mechanic are selected based on the engine speed, which changes frequently based on the operation profile. The changes in engine speed influence the charging-rate of batteries under mechanical propulsion mode with shaft generators operating in Power Take Out (PTO) mode. Similarly, battery discharge-rate is influenced by electric propulsion mode with shaft generators operating in Power Take In (PTI) mode. Therefore, simplified static calculations cannot consider the dynamics of a HE propulsion system.

Based on the literature review [5]-[6], physics-based / white box and data-based / back box models have been used to study marine vessels. The physics-based models are typically used at the design stage of a vessel to study dynamic performance, stability, and fuel consumption whereas the data-based models are used at the operation stage of a vessel to estimate engine shaft power, fuel consumption, ship speed and conduct condition monitoring. The grey box models, which are the combination of both physics- and data-based models were reported to have better prediction accuracy than the white box models [6]. From the review, physics-based models are suited for the evaluation of a vessel at its design stage.

At the preliminary design stage of FERPI pilot launch boat, data such as operation profile from PSAM, specification and control strategy of battery powered HEPS from BME and Speed Power (SP) curve, General Arrangement (GA), Electrical Load Analysis (ELA), and engine technical data from the shipyard were available. The simulation model for the designs stage evaluation studies must be developed based on the available data. A physics-based modeling approach requires calibration of the developed models of different equipment for both steady state and transient conditions. However, data for transient conditions are not available at the design stage and calibration of the models with available data is inefficient as the available data can be directly used by different modeling approach. Therefore, a hybrid modeling approach that directly leverages the available data from owner, shipyard and system integrator is proposed and discussed in detail in this paper.

MODELING AND SIMULATION

To meet the design requirements of PSAM, BME has proposed a HEPS and shared the technical specifications of various equipment as shown in Table 1 and control strategy for HEPS as shown in Table 2 with ABS. Based on the data from BME and PSAM, the models were developed and simulated using the reference operation profile shared by PSAM. The simulation models for pilot launch boat with conventional Diesel Mechanic (DM) (baseline) and the proposed HEPS were developed to conduct a comparative study and thereby identify the relative fuel savings. The modeling process, methodology and operation profile analysis are discussed in this section.

A. Conceptual Model

The conceptual model provides an overview of various components and their interconnections of the proposed HEPS of BME as shown in Fig. 1. The Main Engines (MEs) coupled to the Fixed Pitch Propellers (FPPs) provide the required mechanical power for propulsion.

Table. 1. Equipment specifications for the HEPS

Equipment	Specification
Ship speed	24 knots
MEs	2 x 478 kW @ 1800 rpm
GEs	20.5 kW
PMM	2 x 200 kW @ 1800 rpm
Lithium-ion battery	187 kWh, 1.6C (discharge), 2.2C (charge)

Table. 2. Operation concept of the proposed HEPS of BME.

ME speed (rpm)	Operating modes	PMM 1	PMM 2	ME1	ME2	Hotel load	Battery
0	Port	OFF	OFF	OFF	OFF	ON	Charge*
≤ 650	Drift	OFF	OFF	OFF	OFF	ON	Discharge#
> 650 to ≤ 800	FE	PTI	PTI	OFF	OFF	ON	Charge* / Discharge#
>800 to ≤ 1500	HE	PTO	PTI	ON	OFF	ON	Charge* / Discharge#
> 1500	DM	PTO	PTO	ON	ON	ON	Charge* / Discharge#

***** *If the battery SOC fall below 13 %, DM mode was used from 650 rpm to max ME-speed to charge the battery to 93 % SOC*

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After the battery reached 93%, FE-, HE-, and DM-modes were selected based on the ME-speed until the SOC reached 13 %

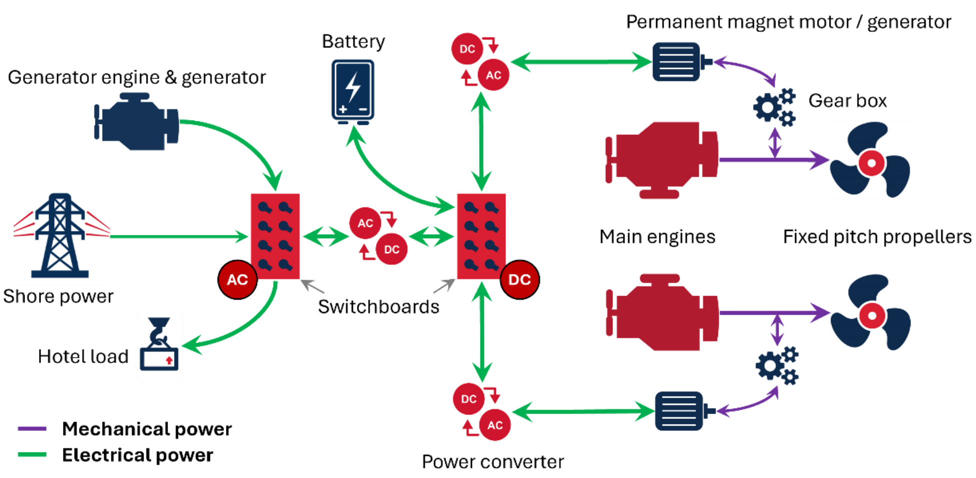


Fig. 1. Conceptual model of the proposed HEPS of BME

The Permanent Magnet Machines (PMMs) were mechanically coupled to the MEs via gear boxes and electrically coupled to the DC switchboard by means of AC-to-DC converter. Depending on the required speed of the MEs, the PMMs operate as motors or generators. The battery system connected to the DC switchboard could be charged by a shore charger or by the PMMs operating as generators. The electrical power to the hotel load can be supplied by the generator coupled to the Generator Engines (GEs) or the battery or the PTO-generators via DC-to-AC converter connected between the DC- and AC-switchboards.

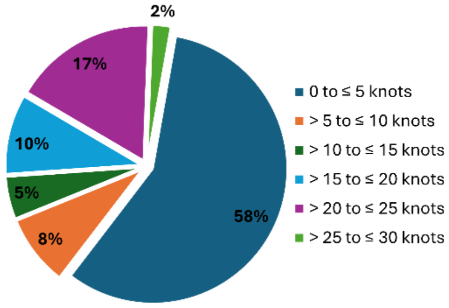
The conceptual model is the reference for building the simulation model and is developed to ensure that all the necessary components of a real-world system are considered in the modeling and simulation process.

B. Operation Concept

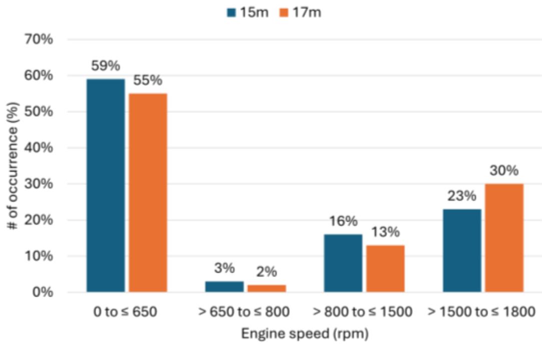
The operation concept of the proposed HEPS of BME is shown in Table 2. The ME speed and the available State of Charge (SOC) of the onboard battery were used to select the operating modes. The proposed operating window for the battery was between the SOC of 13 % to 93 % which means the battery was charged until it reached 93 % SOC and discharged up to 13 % SOC. The various modes as given in Table 2, were selected only when the battery was fully charged and ready for the discharge. The functionalities of various operating modes are as follows.

1. During the port mode, the boat was assumed to be moored at the jetty and the onboard battery can be charged using the available shore power if the battery SOC was less than 93 %.
2. In the drift mode, the MEs of the boat were switched off and the boat was away from the jetty. If the SOC of the battery was greater than 13 %, the battery provides power to the hotel load else the generator of GE was used.
3. In the FE mode, both the PMMs act as motors (PTI) to propel the boat and the battery provide power to both the PMMs and hotel load. If the available SOC was less than or equal to 13 %, the FE mode was changed to DM mode and the MEs were used for propulsion.
4. In the hybrid mode, one of the PMMs acts as a motor (PTI) and another one acts as a generator (PTO). The PMM that acts as a generator provides power to charge the battery, hotel load and other PMM (PTI) for propulsion. The ME which was coupled to the PTI-motor would be switched off so that the PTI-motor and other ME shares the propulsion load. If the SOC of the battery was less than or equal to 13 %, the hybrid mode was changed to DM mode and the batteries were charged by PMMs (PTO) until the SOC reached 93 %.
5. In the DM mode, the PMMs act as generators (PTO) and were used to charge the battery, if the SOC was less than or equal to 13 %.

Overall, the selection of FE- and hybrid-modes depend



(a) Ship speed of 15m boat



(b) Engine speed of 15m and 17m boats

Fig. 2. Reference speed profile and ME speed

on the ME speed and available SOC (≥ 13 %). If any one of the conditions was not satisfied, the DM-mode was selected such that the boat follow the reference operation profile.

C. Operation Profile

Fig. 2 presents the variables such as ship speed and rotational speed of the MEs of an operational 15 m pilot launch boat of PSAM which were measured using an onboard data logger for 245 hours at a regular interval of 1 minute. In Fig. 2(b), the ME speed for the proposed 17 m boat was calculated by mapping the operation profile (ship speed) of 15 m boat as shown in Fig. 2(a) with the SP-curve and engine performance curve (power vs speed) of 17 m boat. The engine speed for 17 m boat was estimated to identify the available time for different operating modes as shown in Table 2 so that appropriate size of battery and PMM can be selected for the HEPS. From the figure and Table 2, the following conclusions can be inferred for the proposed 17 m boat design.

1. There are variations in the distribution of ME speeds for 15 m operational boat and 17 m proposed new design. The is due to the upward shift in the SP- and engine performance-curves for 17 m boat when compared to the 15 m boat.
2. For 55 % of the operational time, the ME speeds were below 650 rpm during which the boat was expected to be away from the jetty with MEs switched off.
3. The estimated operation time for 17 m boat in DM mode was 7 % higher than the 15 m boat. On the other hand, the estimated times for other modes were lesser for 17 m boat.
4. The time for FE mode was less when compared to other modes.

Based on the ME speed distribution data as shown in Fig. 2(b), BME had developed the baseline specification and control strategy for the HEPS as shown in Table 1 and 2 respectively.

D. Simulation Model

The energy flow-based hybrid modelling approach was adopted by ABS to develop the simulation model of the HEPS proposed by BME. The developed simulation model was a combination of physics- and empirical-models that leverage the available design stage data shared by PSAM and BME. A brief overview of various components of the developed simulation model is discussed in this section.

MEs and GE: The empirical modeling method was used to develop the ME- and GE-components and verified with the engine curves in the technical data sheet provided by PSAM. The required mechanical shaft power is the input, and its corresponding fuel consumption is one of the outputs of the ME and GE-components. The running hours of the engines were also calculated based on the time interval of the operation profile data.

PMM: Both empirical- and physics-based modeling approaches were adopted for the PMM-models and verified with the performance data in the technical data sheet provided by BME. The PMM models can be used as both motor (PTI) and generator (PTO) based on the available SOC and operating modes as given in Table. 2. In the PTO-mode, the model calculates the available mechanical power of the ME based on the ME rotational speed and its corresponding crank shaft- and the delivered-power [8]. The calculated power was the additional mechanical power of the ME that can be utilized by the PMMs and was used to calculate the corresponding electrical power of PMMs by using the efficiency curves from the technical data sheet. Therefore, for each ME speed value the available PTO-power (electrical) was calculated for the PMMs which was then used to supply the power to the hotel loads and charge batteries.

In the PTI-mode, the required shaft power to drive the propeller was the input to the PMM model. Based on the input, the required electrical power was calculated using the same efficiency curve used in PTO mode. The required input electrical power to the PMMs was provided by the batteries.

Batteries, Converters and Hotel Loads: The physics-based modeling approach was adopted for the lithium-ion batteries. Battery model was calibrated using the specification data and verified using the voltage vs SOC curve provided by BME. Both physics and empirical methods were used to model the AC-to-DC and DC-to-AC power converters for charging the battery and to provide power to the hotel loads respectively. The hotel load was assumed to be the same throughout the simulation time and was represented by a single power consumer.

Hull Propeller: The hydrodynamic performance characteristics of the 17 m hull with the propeller was emulated using an empirical model based on the SP-data provided by PSAM.

POWER FLOW BASED MODEL VERIFICATION

The developed simulation model for the 17 m pilot launch boat with HEPS was simulated using the real-world operation profile of a 15 m boat sampled at an interval of 1 minute. As shown in Table 2, five different modes of operation were dynamically selected in the simulation model based on the ME rotational speed and battery SOC which were influenced by the operation profile. So, verification of the model under different operating modes must be carried out to ensure that the results are reliable. Fig. 3 presents the normalized values of model- input (ship speed) and other variables of hybrid mode that were computed during the simulation. From the Fig, the model input (ship speed) is characterized by fluctuations and intermittency which is also evident in the other model variables. Therefore, visual inspection-based verification of time domain simulation values is tedious and is not reliable. So, power balance-based approach was adopted by ABS to verify the simulation model

Table. 3. Power balance verification for different modes of the proposed 17m pilot launch boat.

Operating modes	Power balance equations
Port	1. Shore_power = Battery_charge_power 2. GE_output_power= Hotel_load
Drift	1. Battery_discharge_power + GE_output_power= Hotel_load
FE	1. PMM_1_PTI_power + PMM_2_PTI_power + Hotel_load = Battery_discharge_power 2. PMM_1_PTI_power + PMM_2_PTI_power – PMM_1_PTI_loss - PMM_2_PTI_loss = Delivered_power
Hybrid	1. PMM1_PTO_power + PMM1_PTO_loss + (Delivered_power/2) = ME1_shaft_power 2. PMM1_PTO_power = Battery_charge_power + PMM2_PTI_power + Hotel_load 3. PMM1_PTO_power + Battery_discharge_power = PMM2_PTI_power + Hotel_load 4. PMM_1_PTI_power – PMM_1_PTI_loss = (Delivered_power/2)
DM	1. PMM_x_PTO_power + PMM_x_PTO_loss + (Delivered_power/2) = ME_x_shaft_power 2. PMM_1_PTO_power + PMM_2_PTO_power = Battery_charge_power + Hotel_load

PMM_X_PTI_power	Input electrical power in PTI mode of PMM
PMM_X_PTO_power	Output electrical power in PTO mode of PMM (PMM_1 as a generator (PTO) and PMM_2 as a motor (PTI))
PMM_X_PTO_loss	Losses in the energy conversion from electrical to mechanical and vice versa
Delivered power	Total power delivered to the FPPs

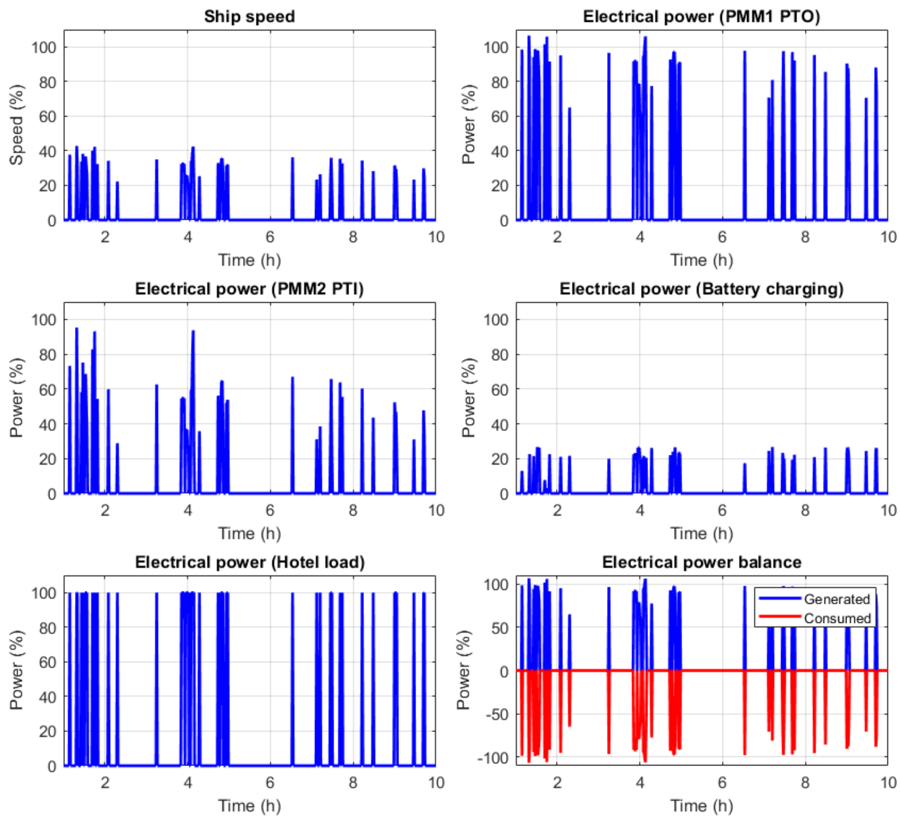


Fig. 3. Time dependent simulation model variables of hybrid mode of HEPS *(data of all other modes are made zero)*

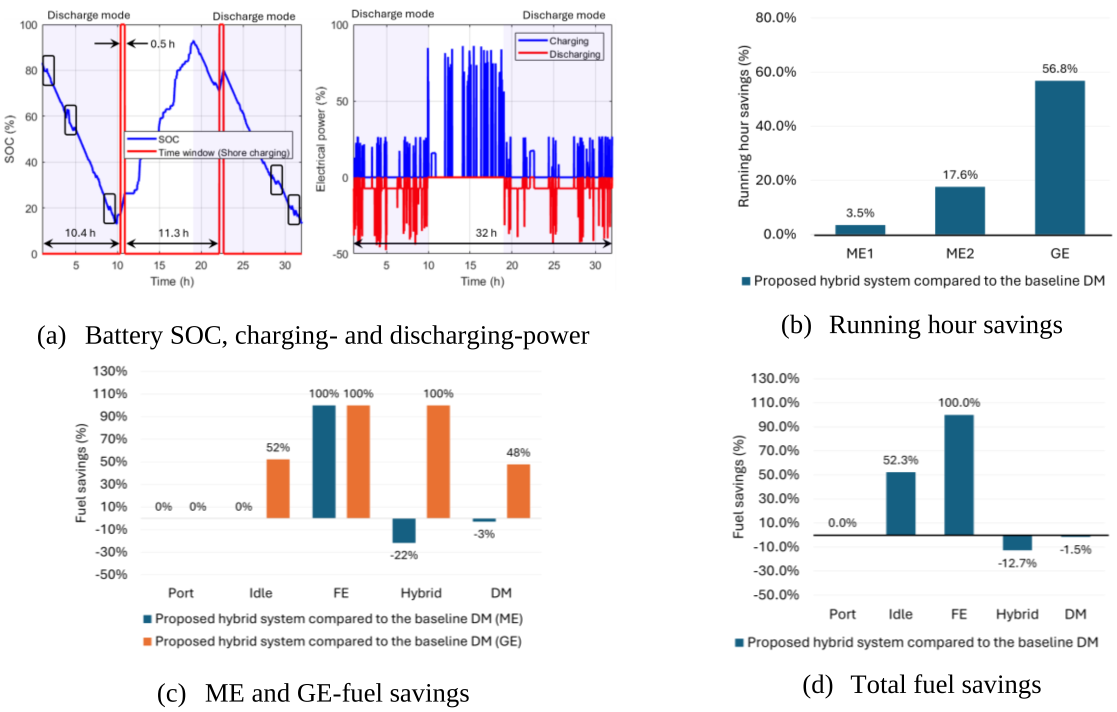
under different operating modes as shown in Table 3.

Fig. 3 presents the relevant simulation variables that were used to check the power balance equation (2) under hybrid mode. From the Fig, the electrical power generated by PMM_1 (PMM_1_PTO_power) under hybrid mode is consumed by battery (Battery_charge_power), PMM_2 (PMM_2_PTI_power) to drive one of the propellers and hotel load. So, the generated power should be equal to the consumption which is evident from the figure titled *Electrical power balance*. Similar verification approach was adopted for all the operating modes specified in Table 3.

SIMULATION RESULTS

The simulation results of the 17 m pilot launch boat with HEPS are shown in Fig. 4. For fuel savings and engine running hours, the simulation results of the proposed HEPS model were compared with the results of the model for conventional DM-propulsion based 17 m boat (baseline). From the figure, the following conclusions can be inferred.

1. In this simulation study, the battery was charged for thirty minutes with the shore power of 45 kW that corresponds to 9 % increase in the SOC. In the shown period of 32 hours, the battery was charged for two times. During the charging mode, as shown by the white area in Fig. 4 (a) the battery was not allowed to discharge until the SOC reached 93 % from 13 %. After the battery was fully charged (93 % SOC), it entered the discharge mode during which the generators (PTO) were used to charge under hybrid- and DM-modes which are marked by black boxes. This phenomenon can be clearly visualized from the normalized charging and discharging power which shows that during the discharge mode both charging- and discharging-powers were available, whereas for the charging mode only the charging power was available.
2. The proposed HEPS design can reduce the engine running hours when compared to the baseline DM based design. In the simulation model, the PMM1 attached to ME1 acted as a generator during the hybrid mode. On the other hand, PMM2 was used to provide the propulsion power instead of ME2 (ME2



(a) Battery SOC, charging- and discharging-power

(b) Running hour savings

(c) ME and GE-fuel savings

(d) Total fuel savings

Fig. 4. Simulation results for the proposed 17m hybrid electric pilot launch boat

was switched off). Therefore, the running hour savings for ME2 was higher when compared to ME1. The total running hour savings for MEs (ME1+ME2) of hybrid design when compared to the baseline DM is 10.5 %. From Fig. 2(b), the drift mode occurs for 55 % of the total time of the considered operation profile. As the batteries were used to provide the required power to the hotel loads and GE was switched off, the running hours savings for the GEs were significant.

3. The ME- and GE-fuel savings of the proposed HEPS when compared to the baseline DM based design is shown in Fig. 4 (c). In the port mode, the battery of the hybrid design was charged using the shore power and the hybrid design consumes the same amount of fuel as that of the baseline design for the hotel load. So, there are no fuel savings. In the drift mode, hybrid design used batteries to provide the power to the hotel load when compared to the baseline design in which GE was used. So, for the considered operation profile about 52 % of fuel savings was estimated for the hybrid design. In the FE mode, the battery provided power to the PMMs and the hotel load. Therefore, hybrid design can provide 100 % fuel savings when compared to the baseline DM design. In the hybrid mode, the ME of the hybrid design consumes more fuel (22 %) when compared to the baseline design. This was due to the PTO mode of the PMM, which added mechanical load to the ME and thereby increase the fuel consumption. On the other hand, the GE was switched off in the hybrid design and the power to the hotel load was provided by the PTO-generators and batteries. Therefore 100% savings in the GE-fuel consumptions was estimated. In the DM mode, the ME of the hybrid design consumed 3 % additional fuel due to the PTO-generators and GE was less utilized for the hotel load due to the availability of the power from the PTO-generators. Therefore, 48 % of fuel savings were estimated for the GE of hybrid design when compared to the baseline DM design.

4. Fig. 4(d) shows the estimated total fuel savings under different modes of the proposed hybrid design when compared to the baseline DM design. For port-, drift- and FE-modes the total (ME+GE) fuel savings are the same as that of the individual fuel savings due to the MEs and GE. For hybrid and DM-modes, the total savings are negative as the fuel consumed by MEs are much higher than the fuel savings obtained by GE.

SIMULATION STUDY INFERENCE

The fuel consumption under different modes of the proposed HEPS concept was added together and compared with the total fuel consumption of the baseline conventional DM vessel to estimate the fuel savings. The estimated savings for the duration of the reference operation profile (245 hours) was then extrapolated for a year which showed that the proposed HEPS concept can provide savings of 0.3 % per year. The fuel saving performance of the proposed hybrid design is significantly influenced by the operational profile requirements, which are essential for meeting job orders and maintaining the 1:1 replacement ratio when transitioning from conventional to hybrid vessels. However, the fuel savings can be improved by changing the PMM-, battery-size, charging time, charging interval, shore power capacity and speed range for different modes. Based on this case study, the following items were recommended for the evaluation of HEPS.

1. A dynamic simulation model along with its control philosophy and the reference operation profile.
2. Power flow-based verification approach due to multiple operating modes and control strategy.
3. Baseline specifications of PMM and battery can be selected as the starting point of evaluation. But to find out the best combination of various operating margins, equipment capacities, and operation principle that can provide better fuel savings than the baseline specifications, a Design Space Exploration (DSE) study is recommended.

CONCLUSIONS

The developed simulation model of the pilot launch boat was based on the data available at the design stage of the vessel and considered the dynamics due to the control strategy of the proposed HEPS and reference operation profile of BME and PSAM respectively. The study based on the developed model revealed that the power balance-based verification approach is recommended for the HEPS and DSE study could be used to select appropriate combination of specifications and operating principles that can provide better fuel savings than the baseline case.

ACKNOWLEDGMENTS

We would like to thank the members of BME and PSAM for their valuable input and support throughout the modeling and simulation study.

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