Data-Driven Efficiency Modeling and Analysis of All-Electric Ship Powertrain; A Comparison of Power System Architectures

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***Abstract*—In this paper, a data-driven dynamic efficiency model is developed for efficiency evaluation and comparison of ship electric powertrain with various system configurations and load-sharing methods. Based on the proposed method, the entire powertrain efficiency is assessed from the fuel consumption to the propulsion unit and the rest of the onboard load. The efficiency model is repeated for the conventional diesel-electric and the hybrid power system with batteries. In the latter case, the efficiency of the battery system is also included in the model. Then, the analysis is extended for different power system architectures such as AC- and DC onboard power systems. As a case study, system efficiency in a cruise ship is investigated using a real operational profile. A comprehensive analysis is performed to demonstrate the loss distribution in each subsystem of a hybrid AC- and DC power system. For a fair comparison between AC and DC, the battery charge level is equalized based on fuel compensation. The case study shows that hybridizing the ship power system increases system efficiency and enhances operational flexibility for the studied use case vessel. Further, the DC hybrid power system can improve the efficiency of the whole ship powertrain thanks to the variable speed operation of engines.**

***Index Terms*—Electric propulsion, ship hybrid power systems, power system efficiency, AC & DC power system.**

I. Introduction

WITH the ever-increasing onboard electrical power demand, the ship power systems evolve gradually to a complex system [1]. The complexity is even increased due to incorporating energy storage devices (ESDs), highly dynamic consumers, and various energy carriers, which do not operate in the same power system. Thus, the discussion of alternating current (AC) vs. direct current (DC) is once again being pertinent [2], since the time of Nikola Tesla and Thomas Edison at the end of the nineteenth-century [3]. The development of variable speed drives (VSDs) in the 1990s resulted in the paradigm shift from mechanical to an electrical propulsion system for most marine vessels [4]. The electrical propulsion system initiated the all-electric ship concept where the propulsion and auxiliary loads in the ship are supplied from a common electrical platform [5]. The common electrical platform is also incorporating ESDs in a hybrid power system.

Reduced emission and improved energy efficiency have been the key focus in the maritime industries and the regulatory bodies [6], [7]. Energy efficiency is a measure that quantifies how much percentage of energy input to a system is converted into applicable or intended output. In a hybrid ship power system, the input energy is usually the chemical energy in the fuel or electrical energy from the shore. The output energy is the actual mechanical energy output from the propulsion units and electrical power consumption as the hotel and auxiliary loads. For a hybrid power system with onboard battery charging, input energy is only the energy contained in the fuel consumed by the engines. Therefore, the lower the fuel consumption to produce intended output, the higher is the energy efficiency, and lower is the CO_2 emission.

To promote the energy-efficient components in the ship systems, the International Maritime Organization (IMO) implemented a mandatory regulation of Energy Efficiency Design Index (EEDI) in the new ship builds [8], which is expressed as the grams of CO_2 produced per ship's capacity-mile. Therefore, EEDI can be considered the measure for CO_2 emission, and the lower the EEDI, the better the efficiency. Based on EEDI and some adaptation for the existing vessels, Energy Efficiency Existing Ship Index (EEXI) is proposed. It is the measure of CO_2 emission per cargo ton and mile, which is applicable for the existing vessels above 400 Gross Tonnages (GT) from 2023 [9]. EEDI and EEXI are the measures of efficiency or emission based on the ship design in a new build and existing ships. Besides, it is also necessary to monitor and improve the operational efficiency of the ship systems, known as Ship Energy Efficiency Management Plan (SEEMP), and the tool for monitoring SEEMP as Energy Efficiency Operational Indicator (EEOI). SEEMP and EEOI represent the carbon intensity indicator (CII) which is the measure of actual emissions in operation given by grams of CO_2 emission per cargo capacity, and a nautical mile [10].

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Various measures are being implemented to improve energy efficiency and reduce the emission footprint. Some of the measures include selecting fuel types, waste heat recovery of exhaust gases, optimizing ship hull, adopting hybrid propulsion systems, and implementing hybrid electric power systems [8]. Hybridization of the power system is one of the key technologies to reduce emissions and increase energy efficiency, which applies to most vessel types. ESDs can be used in different operating modes such as peak shaving, dynamic ride through, spinning reserve, strategic loading, zero-emission operation, and power smoothing [6], [11] to harness its efficiency enhancement potential. The efficiency improvement is achieved by shifting the engine's operating point towards the optimal region, reducing the number of active generators in the bus, or reducing the start-stop of engine-generator sets. The proper operational mode selection for the ESDs helps increase energy efficiency and reduce emission, which is verified through the experimental results in a hybrid inland vessel [12]. Further, battery hybridization in a gas engine-driven power system considerably increases efficiency for the low loads and at low-speed; however, it may not increase efficiency in high loads and at high-speed [13].

The cruise ships are large vessels with relatively high propulsion, hotel, and auxiliary loads. These vessels are mostly sailing in tourist destinations with stricter emission regulations. To meet the regulations, hybridization of the power system is one of the promising solutions among other alternatives [14]. A typical hybrid power system configuration in a cruise ship is shown in Fig. 1.

Electricity is vital in the operation of marine vessels. Although there had been experiments on battery-powered electric propulsion in small boats since the late 1830s and the use of gun firing circuits and electric arc searchlights in the 1870s, the commercial shipboard electrical system can be traced back to the 1880s in the vessel *SS Columbia*, which had an onboard DC system [15]. Later, implementation of an onboard AC power system started with the development of the AC components such as induction motors, transformers, and generators. Once again, the DC power system's relevance is increasing to accommodate renewable energy sources, ESDs, and low or no-emission fuel cells. However, the AC power output from synchronous generators, driven by fossil-fueled engines, supplies a significant part of the total power demand. In addition, most of the hotel or auxiliary loads and the electric propulsion units operate in the AC system. Thus, hybridization of the power system through different energy carriers and storage involves both AC and DC systems and puts forward the need for power conversion to achieve one from the other.

The efficiency comparison for the low voltage DC and AC presented in [16] shows that the DC system is more efficient for home electrification. However, cost comparison may also be necessary to mention which of them is more viable. The DC distribution system offers an efficiency advantage compared to AC in modern residential areas. The DC microgrid in a land-based system is more efficient than AC; however, the costly components and immature safety systems are outlined as the setbacks [17]. An energy efficiency evaluation for shore-to-ship fast-charging in a hybrid power system of a vessel [18] shows that DC charging is more efficient for the onboard AC power system.

In the marine power systems, the AC grid with a fixed bus frequency has been dominating. However, different studies show that allowing the engine to run with speed irrespective of the bus frequency increases fuel-saving since the engine speed can be decreased when there are low load conditions. The variable frequency AC system can reduce approximately 5% fuel consumption compared to the fixed frequency AC system. Besides, uplifting it to a DC power system reduces the number of converters, dead weight, and space while increasing the efficiency [19]; however, its efficiency is calculated based on the variable speed operation of engines only. The variable-speed engine operation in a wind farm support vessel saves 4% - 6% fuel consumption at 65% - 90% load, whereas the fuel consumption may decrease by 20% - 25% for less than 65% load [20], [21] compared to the fixed speed engine operation. In contrast, thorough theoretical calculations for a naval electric ship in [22] shows that 60 Hz AC delivers less loss. Moreover, it reiterates the benefits of easy fault interruption, low maintenance requirements, low cost, and better component availability. These contradictory statements on power system efficiency highlight the research gap in the ship power system efficiency or loss calculations.

The power system component's efficiency depends on how much power is lost during its operation. The combination of losses in all parts results in the total loss of the system. Different methods, such as mechanistic or data-based modeling of losses, are discussed in the literature. The losses in various electrical components such as a generator, rectifier, DC-DC converter, and ESDs are mechanistically modeled and analyzed in [5] for a DC power system. The distribution of losses for electric motor and generator is investigated through their operational profile for a month in [23]. The modeling of losses in the electric machines through polynomial curve fitting using the data available in commercial data sheets are presented in [24]. The synchronous generator's efficiency estimation methods are established and verified with the shop trial and real ship operational data in [25]. The high power drives efficiency calculations are discussed in [26]. Besides, the energy efficiency of the hybrid power systems is hugely impacted by the control strategies implemented for optimal use of ESDs [27].

As the component efficiency varies with its loading or power output [28], the load profile or operational power profile analysis of a power system is essential while discussing the efficiency [20]. Therefore, it is essential to analyze the efficiency of a marine power system based on its typical operation power profile and power system configurations [29], [30]. The availability of a real operational power profile is also crucial to design the ESDs for a vessel power system [31], [32].

The mechanistic modeling of losses or efficiency also requires high fidelity modeling of the power system components. The measurement or calculation of the loss parameters and coefficients may also increase the computational effort of the efficiency evaluation process. Particularly, applying the load profiles in the scale of days and weeks significantly

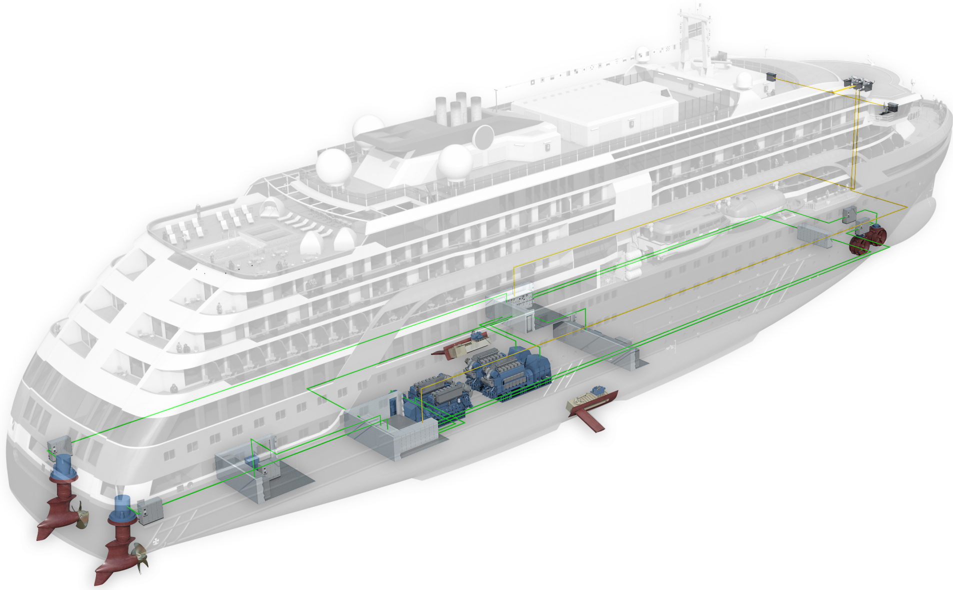

Fig. 1. Typical machinery, control and monitoring system for a hybrid power system in a cruise ship (Kongsberg Maritime©).

increases the computational time. Hence, the efficient models are to be developed with the required model fidelity and reasonable computational effort. It indicates the need for robust and flexible power-based efficiency models for the hybrid power system components, which can be integrated to configure the power system and eventually estimate overall efficiency. Moreover, using such models for comparing the energy efficiency between the AC and DC power systems for various marine vessels is not well represented in the literature. Furthermore, the applications of the system efficiency model in analyzing the effects of different factors such as environmental conditions or battery sizing in the system energy efficiency are not much discussed in the literature.

This work presents a generic and comprehensive efficiency analysis of the conventional and hybrid power system onboard a diesel-electric cruise ship. The efficiency analysis of the entire power system is performed based on each component's efficiency model, namely the data-driven efficiency model. The data extracted from the marine power system components' mechanistic efficiency models from the previous research are used to develop the dynamic polynomial-based efficiency models. Based on the components' efficiency dependencies, simple, rational, or surface polynomial models are established. These models are integrated to build the power system configuration in AC and DC systems using similar rated parameters for the components. The efficiency evaluation and analyses are carried out using the real ship's operational power profile data to reflect the realistic loading conditions. It is further extended to compare the system energy efficiency for AC and DC (fixed- and variable-speed) power systems, both for a conventional and hybrid power system. The charge levels in the energy storage devices are equalized to the initial level for fair energy efficiency comparison. Further, loss breakdown demonstrates the losses in different subsystems, while efficiency distribution presents the efficiency of each subsystem. Besides, the developed system efficiency model is used to investigate the effect of sea conditions and battery sizing on the energy efficiency of a hybrid power system. It is observed that the battery hybrid system performs better with fluctuating load conditions.

II. Electric Propulsion Topologies with AC and DC Power System Architecture

Electric propulsion is widely adopted in the ship propulsion system. In electric propulsion, the prime mover drives an electric generator to produce electric power. The electric power is then used to run the propulsion units, hotel, and auxiliary loads. Electric propulsion is often categorized into AC and DC systems based on the power system architecture in the main switchboard. The electric generator, producing AC power, is the most common onboard power source. Further, the power system can be hybridized using ESDs such as battery and supercapacitor, which operate in DC system. The recent development of highly efficient power converters has enabled the conversion of power back and forth. Therefore, the primary physical difference between the AC and DC power systems lies in the positioning of power converters.

The qualitative differences between AC and DC power system discussed in [5], [15], [19], [33]–[37] are summarized in Table I and sections II-1 and II-2. The typical marine AC and DC hybrid power systems are shown in Fig. 2, where power flow direction is indicated by the dashed lines with arrow.

1) AC Power System : The AC voltage energizes the main switchboard with a frequency of 50 Hz or 60 Hz in an AC hybrid power system. To interface ESD in the AC grid, it usually requires two bidirectional power converters, DC to DC and DC to AC. The variable-speed operation of the propulsion units is achieved by using AC to AC power converters. The hotel loads typically operate in system frequency; however, it may require voltage conversion using transformers. In an AC

TABLE I
GENERAL COMPARISON OF AC AND DC POWER SYSTEMS.

Characteristic	AC System	DC System
Reactive power	✔	✘
Voltage control	✔	✔
Frequency control	✔	✘
Synchronization	✔	✘
Harmonic distortion	✔	✘
Ripples	✘	✔
Variable speed engine	✘	✔
Bulky components	✔	✘
Easy voltage transformation	✔	✘
Easy ESD connections	✘	✔
Fuel saving potential	✘	✔
Well developed control systems	✔	✔
Well developed safety systems	✔	✘
Easy fault detection & isolation	✔	✘
Low maintenance	✔	✘
Better component availability	✔	✘
Proper standardization	✔	✘

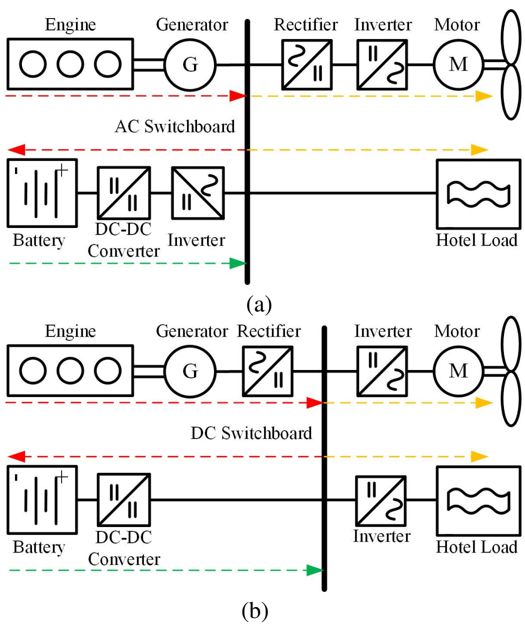

Fig. 2. Typical ship hybrid power system architectures. (a) AC system. (b) DC system.

system, both the frequency and voltage need to be controlled and monitored. The system frequency is eventually maintained by controlling the prime mover's speed, usually the conventional internal combustion engines. Therefore, nearly constant speed is necessary to maintain the system frequency even in low load conditions. Though the presence of reactive power complicates the system, it facilitates voltage regulation. In a multi-generator system, their voltage, frequency, and phase require synchronization.

Besides, the harmonic currents generated through the variable speed drives may create distortion and instability problems, usually removed using the harmonic filters to keep them under the allowable limits. The AC power system components such as transformers and filters are bulky and heavy, increasing the vessels' dead weight. On the one hand, the easy voltage transformation increases the flexibility of the system. On the other hand, power conversion necessity decreases the flexibility towards more renewable energy sources and ESDs. There are well-developed safety systems for AC, including failure detection and isolation. In general, the zero-crossing nature of the AC signals eases the system isolation in case of failure, thereby enhancing the safety systems. However, in a relatively complex AC power system with varying generator power ratings, the implementation of differential protection is increasing.

2) DC Power System: The DC voltage energizes the main switchboard in DC hybrid power system. To interface ESDs, a bidirectional DC to DC converter is required, whereas the AC output from the generators needs conversion to DC using a rectifier. The generator's rectifier can be either a diode rectifier or an IGBT-based active front end (AFE) rectifier. As the system voltage is already in DC, the rectifier part of the conventional VSDs is unnecessary. The voltage source inverters (VSIs) can produce variable frequency AC voltage to drive the propulsion units. Hotel loads are usually operating in the AC system; therefore, inverters are required. Depending on the voltage levels, voltage transformers may also be used after inverting. In a DC system, only the voltage needs to be regulated. The frequency and phases are of no interest, and their synchronization is not required. The system is free of frequency, so the prime-movers can be operated at a variable speed, allowing it to work in the more optimal and fuel-saving region.

There are no harmonic distortion issues in this power system. It also results in space-saving and less dead weight as the bulky AC equipment like a transformer and harmonic filters are in reduced numbers. However, the rectification of AC voltage can introduce ripples in the DC voltage, which can cause heating in the conductors. Based on the applications, ripples need filtering, where capacitive filtering is the most common one. Moreover, the absence of reactive power reduces its complexity. As the ESDs and emerging fuel cell systems operate in the DC system, their interconnection to the bus becomes relatively easier, increasing flexibility. However, the need for a power converter for the voltage transformation increases the complexity of the system. In addition, fault detection and isolation are relatively complex in this system due to the absence of zero-crossings.

III. EFFICIENCY MODELING OF HYBRID POWER SYSTEM

In general, a component efficiency (η) is given by the ratio of the output power (P_{out}) to the input power (P_{in}), which is a direct method of efficiency calculation. It can also be calculated using the power loss measurement (P_{loss}) and either of the power measurement, P_{out} or P_{in}.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} \tag{1}$$

During the discharging mode, the battery functions as a power source in a battery-based hybrid power system while as a power consumer during the charging mode. The power-based efficiency ($\eta_p(t)$) for a hybrid power system is expressed in (2), where P_{Load} is the power consumption such as a hotel

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load or the propulsion load and P_{Fuel} is the power associated with the engine actual fuel consumption.

$$\eta_p(t) = \frac{P_{out}(t)}{P_{in}(t)} = \frac{P_{Load}(t) + P_{Batt,ch}(t)}{P_{Fuel}(t) + P_{Batt,disch}(t)} \tag{2}$$

The energy efficiency ($\eta_e(t)$) is the ratio of output energy to the input energy, which can be expressed as (3) . It is the time average of the instantaneous or dynamic efficieny. The averaging can be calculated over the whole period of the load profile. Further, it facilitates the quantification for the efficiency comparison.

$$\eta_e(t) = \frac{\int P_{out}(t)dt}{\int P_{in}(t)dt} \tag{3}$$

A. Static Efficiency Modeling

Usually, the efficiency of a power system is calculated using the nominal or rated efficiency of the components at the rated output power, which can be defined as the overall static efficiency of the power system. The static efficiency does not include the information about the load and other operational inputs. In general, the rated efficiency of the fixed and variable speed diesel generators are similar. However, approximately 10% saving in fuel consumption can be achieved if the speed is decreased to 75% of the nominal speed when the actual load is around 55% [19]. For the mentioned fuel-saving in variable speed operation of an engine, efficiency increases by around 11%. The typical nominal efficiency for different power system components is included in Table II.

TABLE II
TYPICAL NOMINAL EFFICIENCY (η_R) OF THE POWER SYSTEM COMPONENTS.

Component	Efficiency η	Reference
Fixed speed diesel engine (η_{ef})	0.42	[31]
Variable speed diesel engine (η_{ev})	0.46	[19]
Synchronous generator (η_g)	0.967	[31]
Rectifier (η_r)	0.97	[38]
Battery bank (η_{bc}/η_{bd})	0.95	[39]
DC-DC converter (η_{cc}/η_{cd})	0.989	[40]
Inverter (η_i)	0.97	[41]
Propulsion motor (η_m)	0.965	[31]

As ESDs can act as a power source or a consumer, their operating modes need to be considered during the overall system efficiency calculation. P_b is the total power to or from the batteries, and P_h is the total power consumed by the hotel loads. Further, P_e and P_m are total output power from the engines and propulsion motor. The static efficiency of the AC, fixed speed DC (FSDC), and variable speed DC (VSDC) hybrid power system can be calculated as in 4 - 6, respectively, where $\gamma \in \{0,1\}$. γ is 0 for battery charging mode, whereas 1 for discharging mode. $j = 1, 2, ..s$ is number of batteries, whereas $k = 1, 2, ..t$ is number of engines. Similarly, $l = 1, 2, ..u$ is number of hotel loads and $n = 1, 2, ..v$ is number of propulsion motors.

$$\eta_{AC} = \left(\frac{\sum_j^s \gamma_j P_{b_j}\eta_{cd_j}\eta_{i_j} + \sum_k^t P_{e_k}\eta_{g_k}}{\sum_j^s \gamma_j \frac{P_{b_j}}{\eta_{bd_j}} + \sum_k^t \frac{P_{e_k}}{\eta_{ef_k}}}\right) \cdot \left(\frac{\sum_l^u P_{m_l} + \sum_n^v P_{h_n} + \sum_j^s (1-\gamma_j) P_{b_j}\eta_{bc_j}}{\sum_l^u \frac{P_{m.l}}{\eta_{r_l}\eta_{i_l}\eta_{m_l}} + \sum_n^v \frac{P_{h_n}}{\eta_{i_n}} + \sum_j^s (1-\gamma_j)\frac{P_{b_j}}{\eta_{cc_j}\eta_{i_j}}}\right) \tag{4}$$

$$\eta_{FSDC} = \left(\frac{\sum_j^s \gamma_j P_{b_j}\eta_{cd_j} + \sum_k^t P_{e_k}\eta_{g_k}\eta_{r_k}}{\sum_j^s \gamma_j \frac{P_{b_j}}{\eta_{bd_j}} + \sum_k^t \frac{P_{e_k}}{\eta_{ef_k}}}\right) \cdot \left(\frac{\sum_l^u P_{m_l} + \sum_n^v P_{h_n} + \sum_j^s (1-\gamma_j) P_{b_j}\eta_{bc_j}}{\sum_l^u \frac{P_{m_l}}{\eta_{i_l}\eta_{m_l}} + \sum_n^v \frac{P_{h_n}}{\eta_{i_n}} + \sum_j^s (1-\gamma_j)\frac{P_{b_j}}{\eta_{cc_j}}}\right) \tag{5}$$

$$\eta_{VSDC} = \left(\frac{\sum_j^s \gamma_j P_{b_j}\eta_{cd_j} + \sum_k^t P_{e_k}\eta_{g_k}\eta_{r_k}}{\sum_j^s \gamma_j \frac{P_{b_j}}{\eta_{bd_j}} + \sum_k^t \frac{P_{e_k}}{\eta_{ev_k}}}\right) \cdot \left(\frac{\sum_l^u P_{m_l} + \sum_n^v P_{h_n} + \sum_j^s (1-\gamma_j) P_{b_j}\eta_{bc_j}}{\sum_l^u \frac{P_{m_l}}{\eta_{i_l}\eta_{m_l}} + \sum_n^v \frac{P_{h_n}}{\eta_{i_n}} + \sum_j^s (1-\gamma_j)\frac{P_{b_j}}{\eta_{cc_j}}}\right) \tag{6}$$

B. Dynamic Efficiency Modelling

The power system efficiency analysis based on nominal power and efficiency does not always reflect a realistic efficiency calculation scenario. The efficiency for most of the components is considerably low at lower load conditions [23], [42]. Therefore, it is essential to evaluate the efficiency for any component and the system using operational or loading profiles.

The specific fuel oil consumption (SFOC) in the engine is a function of shaft speed (x) and output power (y), as shown in Fig. 3 (a) [21]. The shaft speed (x) and output power (y) are in percentage of their respective rated values. For the fixed speed operation, speed is nearly constant at the nominal value. While in the variable speed operation, the engine speed can be changed to minimize fuel consumption. However, certain engine speed needs to be maintained to attain engine operational parameters such as torque limit [24]. A typical variation of speed for the engine loading [43] is shown in Fig. 3 (b). The instantaneous fuel consumption ($\dot{m}_f$) can be calculated using specific fuel oil consumption ($SFOC(x, y)$) and the output power (P_e). The product of lower calorific heat value (h_n) and the fuel consumption ($\dot{m}_f$) gives the instantaneous input engine power from the consumed fuel (P_{fuel}). Further, engine efficiency can be expressed in terms of $SFOC$ in mg/J and lower calorific heat value (h_n) in MJ/kg [44], where $h_n = 42.6MJ/kg$ for diesel oil.

$$\dot{m}_f = SFOC \cdot P_e \tag{7}$$

$$P_{fuel} = \dot{m}_f \cdot h_n \tag{8}$$

$$\eta = \frac{P_e}{P_{fuel}} \cdot 100\% = \frac{1}{SFOC \cdot h_n} \cdot 100\% \tag{9}$$

As the cruise ship has relatively high load demands, the engine and generator capacities are also sized accordingly to supply high power loads. The SFOC for big engines is relatively lower than smaller ones. The SFOC data [45] for the required engine capacities are used to fit in a quadratic

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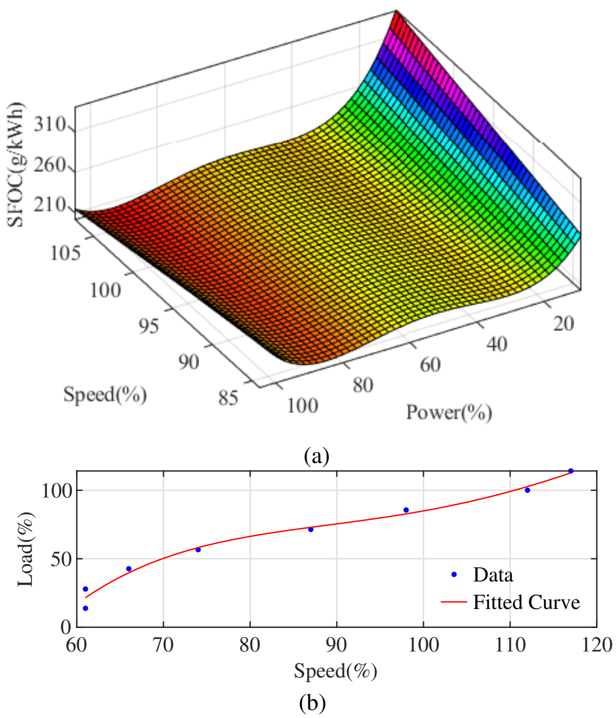

Fig. 3. Typical diesel engine properties. (a) Specific fuel oil consumption map. (b) Speed variation with loading for a variable speed diesel engine.

polynomial equation, which is plotted in Fig. 4. These SFOC data for the respective engines are further used to model the engine efficiency, using (7) - (9). Besides, from Fig. 4, it is obtained that for the fixed speed operation, the fuel consumption is minimum at 90% load power, whereas the fuel consumption is minimum at 73% load power for the variable speed operation. As SFOC data for the variable speed engine are estimated at the optimal engine speed, the variable speed information is already included in the SFOC curve. This load power resulting in minimum fuel consumption is referred to as optimal power. The efficiency curves for small and big engines are represented by a quadratic polynomial of engine load percentage.

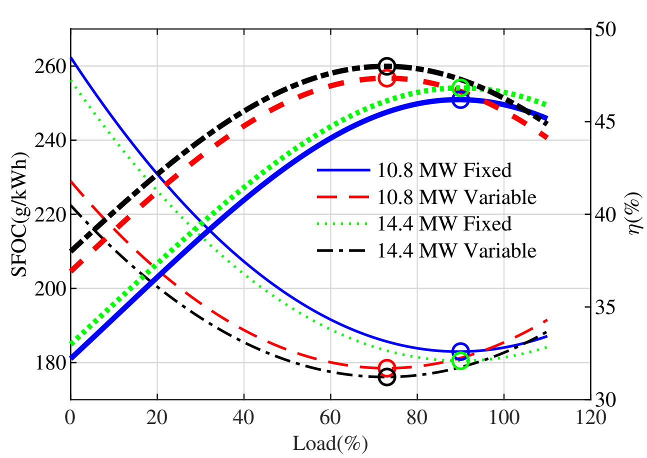

Fig. 4. SFOC and efficiency curves for the diesel engines in fixed and variable speed operations (Thick lines - efficiency, thin lines - SFOC).

The battery efficiency varies with the SoC and C-rate of the battery ($\eta = f(SoC, C - rate)$). Battery efficiency is usually given by the ratio of input and output power of the battery. In that case, the power is measured at the battery terminal ($P_{batt,terminal}$). However, while estimating the system efficiency, the battery may only be charged or discharged. Therefore, estimating actual power transferred into and out of the battery considering the ohmic and electrochemical losses is required. The actual power transferred is established as ($P_{batt,actual}$) as in (10) and (11) using the battery efficiencies during the charging and discharging modes, respectively.

$$P_{batt,actual} = \eta(x,y) \cdot P_{batt,terminal} \tag{10}$$

$$P_{batt,actual} = \frac{P_{batt,terminal}}{\eta(x,y)} \tag{11}$$

In this work, the dynamic modeling methodology and efficiency datasets for the hybrid power system components, established and tested in full-scale laboratory system in the previous work [46], are reused to develop simple, rational, and surface polynomial based component efficiency models. The developed models are more robust to be used for the entire load range (>0% to 100%) of the components and are included in Table VIII in the Appendix. For the battery efficiency model, the full-load efficiency during charging is considered when the SoC is at 40% and C-rate at 0.7, while it is considered when SoC is at 80% and C-rate is at 0.7 during discharging. Thus, the battery model is valid for the entire SoC range (>0% to 100%). However, C-rate can be 0.1 to 2.5 during charging, whereas 0.5 to 3.0 during discharging mode. For other components, efficiency models are a function of output power in the percentage of the rated power. These component efficiency models are further used to develop a system efficiency model for the cruise ship power system with AC, FSDC, and VSDC as main buses.

IV. Case Study - A Cruise Ship

The typical AC and DC power system configurations for a cruise ship are extended with battery systems as shown in Fig. 5 (a) and (b), respectively. Two azipods and two thrusters act as the power system load to each side of the bus. Hotel and auxiliary loads are divided equally into both sides of the main bus. Two unequally sized diesel generators on each side are supplying the power to the bus. Two battery banks [47], one on each side of the bus, are proposed to hybridize the power system. In this work, the battery bank on the right side of the bus serves as a spinning reserve and activates if any other power supply equipment fails. In contrast, the other battery bank shares load with generators, given that the battery SoC is inside the limits. The basic equipment ratings are presented in Table III. The subsystems are marked with alphanumeric notations.

A. Static System Efficiency

The static efficiencies are calculated for the battery with charging and discharging modes. Assuming that battery will be equally charged and discharged, the total system efficiency is calculated as the average of both battery modes. The cruise

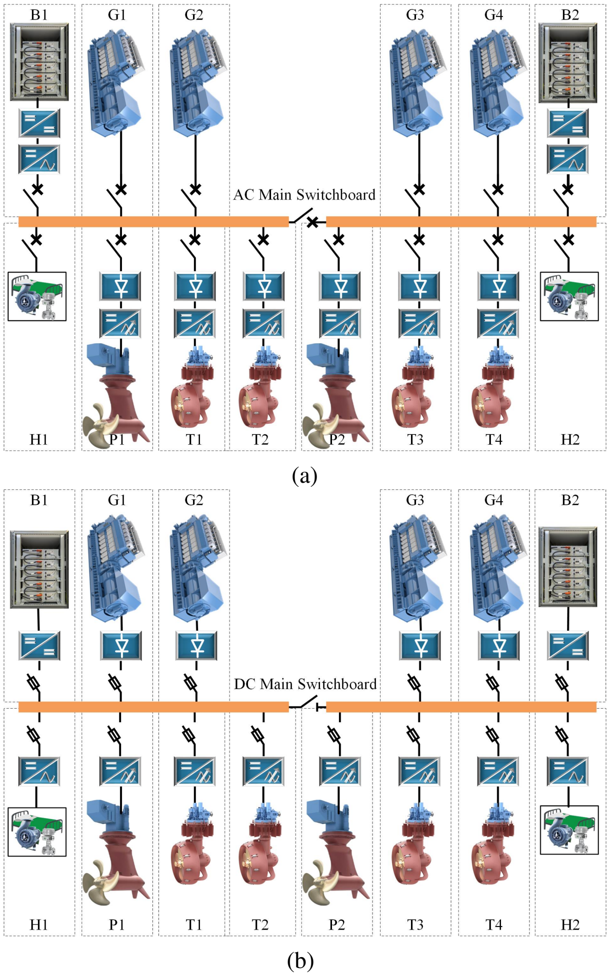

Fig. 5. Typical hybrid power system configurations for a cruise ship. (a) AC power system. (b) DC power system.

TABLE III
RATED COMPONENT PARAMETERS.

Components	Position	Capacity	Position	Capacity
Diesel engine	G1/G3	14.4 MW	G2/G4	10.8 MW
Generator	G1/G3	14.1 MW	G2/G4	9.38 MW
Rectifier	G1/G3	14.8 MW	G2/G4	9.85 MW
Battery	B1	13.4 kAh	B2	13.4 kAh
DC-DC Conv.	B1	13.4 MW	B2	13.4 MW
Inverter	B1	15.9 MW	B2	15.9 MW
Motor	P1	18.0 MW	P2	18.0 MW
Inverter	P1	18.9 MW	P2	18.9 MW
Rectifier	P1	19.8 MW	P2	19.8 MW
Motor	T1/T3	4.60 MW	T2/T4	4.60 MW
Inverter	T1T3	4.80 MW	T2/T4	4.80 MW
Rectifier	T1/T3	5.10 MW	T2/T4	5.10 MW
Hotel & Aux.	H1	7.5 MW	H2	7.5 MW
Inverter	H1	7.9 MW	H2	7.9 MW

ship configurations in Fig. 5 along with the component parameters from Table III are used. The nominal efficiency for the components is usually mentioned in the literature. However, the component provider usually provides the peak efficiency or the full-load efficiency. The static system efficiency is calculated using the efficiency mentioned in Table II and VIII separately for AC, FSDC, and VSDC systems, and presented in Table IV. The system efficiency varies widely with the different component efficiencies, which shows that the static efficiency does not necessarily represent the actual system efficiency. Further, it does not reflect the efficiency due to load changes, which is the dynamic factor in the ship power system. However, static efficiency remains the same no matter the system is operated in the efficient or inefficient region. Therefore, static efficiency can be a rough estimate but not reliable for dynamic or realistic load conditions.

TABLE IV
STATIC EFFICIENCY IN THE HYBRID DIESEL-ELECTRIC CRUISE SHIP.

Power System	Efficiency (%)		
	η_R	η_P	η_F
AC	42.73	46.19	43.70
FSDC	42.50	45.98	43.27
VSDC	46.26	46.95	43.02

B. Dynamic System Efficiency

The developed efficiency models for the hybrid power system components are used to develop system efficiency models with different power system architectures for a cruise ship. The conventional and hybrid power systems with AC, fixed speed DC, and variable speed DC are configured for efficiency evaluation and analysis. The real load profile is used to simulate the realistic operation of the cruise ship. The ESD configuration, rated parameters of the components, operational power profile, and energy management strategies (EMS) are kept uniform for both AC and DC power system architectures.

1) Load Analysis: A seven-day and four-hour-long load profile for an anonymous cruise ship is used in this study. The load power due to propulsion, hotel, and auxiliary loads are summed up to make a total load power profile, as shown in Fig. 6. The load demand for any vessel varies with its operating modes. The operation modes in a cruise ship can broadly be divided into berthing (at port), maneuvering, and cruising (at sea) [48].

During berthing mode, there are no or negligible propulsion loads. The primary load in this mode of operation will be the hotel and auxiliary load. The propulsion loads fluctuate in maneuvering state, whereas significant during cruising and vary with the ship's speed and weather conditions. From the load profile, it can be observed that the ship has been at port four different times, where the propulsion load is nearly zero. It suggests that the used profile consists of all three operating modes of a cruise ship. Further, it is observed that 60% of the load is due to the propulsion load, whereas hotel and auxiliary load account for the remaining 40% as shown in Fig. 7.

2) Efficiency Evaluation: The load-sharing among the generators in a cruise ship may vary with its operating modes. The proportional load-sharing leading to equal load percentage in the active generators is a usual load-sharing method. Traditionally, an additional generator is connected to the bus than the required number of generators to ensure safety. It lowers the load percentage in all active generators. However, in a

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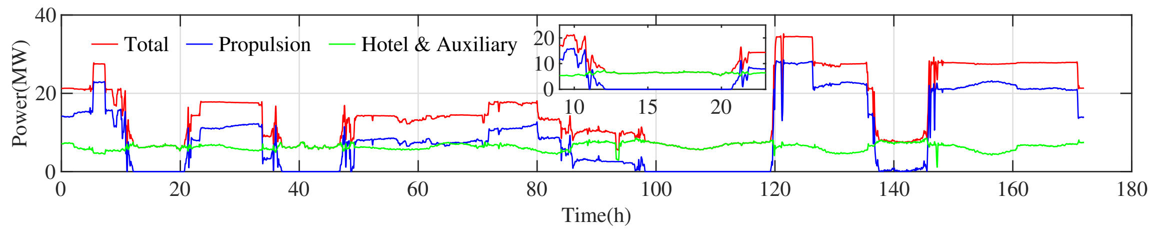

Fig. 6. A total power profile for a cruise ship during a seven days journey.

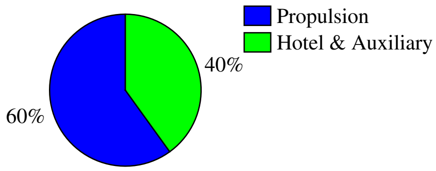

Fig. 7. Load profile division into propulsion, hotel, and auxiliary loads.

TABLE V
ENERGY EFFICIENCY AND FUEL CONSUMPTION IN THE CONVENTIONAL DIESEL-ELECTRIC CRUISE SHIP.

Power System	$\eta_e(\%)$	$m_f(tonn)$
AC	37.01	598.4
FSDC	36.42	608.1
VSDC	38.98	568.1

more optimal operation, the load-dependent start and stop of the generators are used, which allows a more optimal number of active generators. Also, in optimal generator numbers, the active generators proportionally share the load according to their capacity. The power-sharing among the generators in a conventional diesel-electric power system for the AC and VSDC architectures is shown in Fig. 8. Further, the simulation is also run for the FSDC architecture. The power-sharing among the generators for FSDC is similar to that of the AC system as both operate the diesel generator sets at nearly fixed speeds.

In the VSDC system, there is flexibility to vary the engine speed to reduce fuel consumption. The speed variation can be achieved using online optimization, which can increase the computational effort. However, the simplified, load-based approach can also be implemented to change engine speed [43]. As the nominal engine speed is 600 rpm, the engine can vary from 400 rpm to 600 rpm. The speed profile of the engines for the conventional diesel-electric cruise ship with variable speed DC system is shown in Fig. 9.

The power-based system efficiency response is compared between conventional AC and DC power systems in Fig. 10. As the optimal load in the variable speed engines is lower than that of the fixed speed engine, the VSDC power system is slightly more efficient than AC. The FSDC has the least efficiency mostly. The energy efficiency and total fuel consumption for a conventional power system with AC, FSDC, and VSDC are presented in Table V. The higher efficiency in the DC system is achieved due to variable speed operation. Using the fixed speed in DC does not help in efficiency increment as it works similarly to AC and with an additional power conversion for the generator power.

A battery pack ($B2$) is used as a spinning reserve in the diesel-electric hybrid power system case. It activates in case of failure in any other generator or battery. It helps to get rid of an extra backup generator. The other battery pack ($B1$) is actively used. It helps operate the active generators in the optimal region by sharing the load demand and handling the load variations while maintaining its SoC within the limit. The initial SoC in the batteries in all the simulation cases is kept equal to 60% to make the results comparable. A dedicated rule-based EMS designed to ensure battery charge level and load-sharing among the generators and battery. The main principle for the battery operation is based on using the battery to complement the engine-generator sets. If the battery SoC is lower than its lower limit (40%), battery charging is prioritized, while battery discharging is prioritized if the battery SoC is higher than its higher limit (80%). In between the limits, battery usage is load-dependent. The simulation is carried out for AC, FSDC, and VSDC systems. The power-sharing among the power carriers is presented in Fig. 11 for the fixed speed AC and variable speed DC. The results for the fixed speed DC are similar to that of AC. As the optimal power region for the variable speed engine is relatively lower than that of the fixed speed engine, an extra generator set is active for a longer duration in the VSDC than AC and FSDC power systems.

The discharging of the ESDs provides higher system efficiency, while charging of ESDs can also increase system efficiency by shifting the engine operating point towards the optimal region. The dynamic energy efficiency response for the given load profile is compared between AC, FSDC, and VSDC hybrid power systems in Fig. 12.

The energy efficiency, total fuel consumption, and final battery SoC for AC, FSDC, and VSDC hybrid power system configurations are presented in Table VI. It is observed that the VSDC is the most efficient, and FSDC is the least. However, it is observed that the final battery charge level is not equal in the simulated power system architectures, making the results incomparable.

Unequal use of battery energy complicates the energy efficiency comparisons in hybrid power systems. The final battery SoC should be equal in all hybrid power systems for a fair comparison. Besides, the battery should sustain the charge level to compare the energy efficiency between hybrid and conventional power systems. It means the final battery

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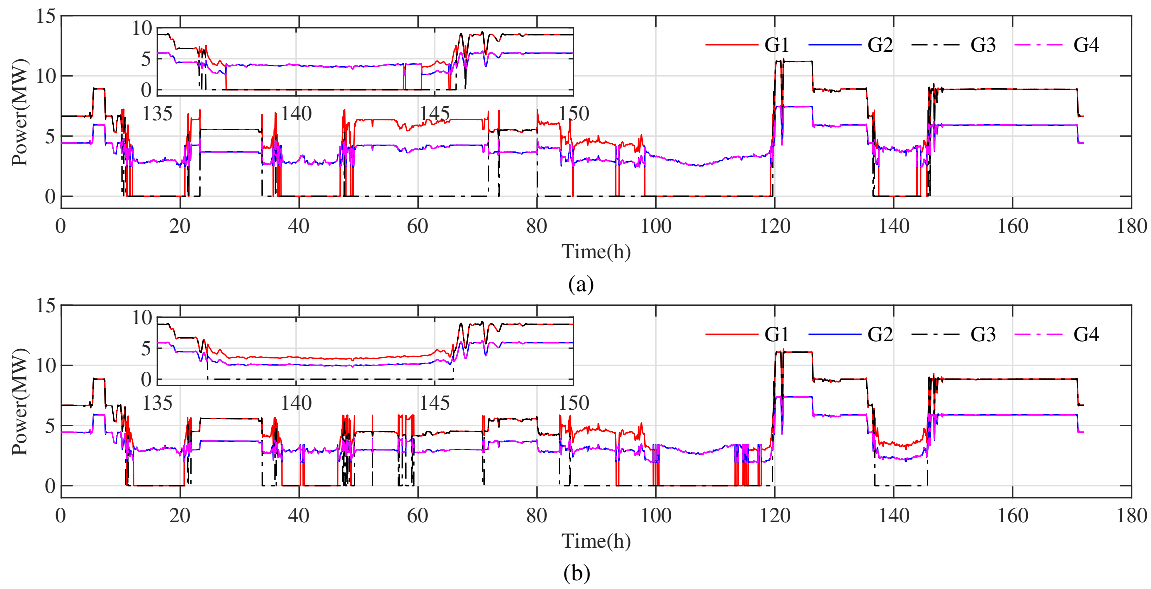

Fig. 8. Power-sharing among generators in a conventional diesel-electric cruise ship. (a) AC system. (b) VSDC system. (G1 - Generator 1, G2 - Generator 2, G3 - Generator 3, and G4 - Generator 4.)

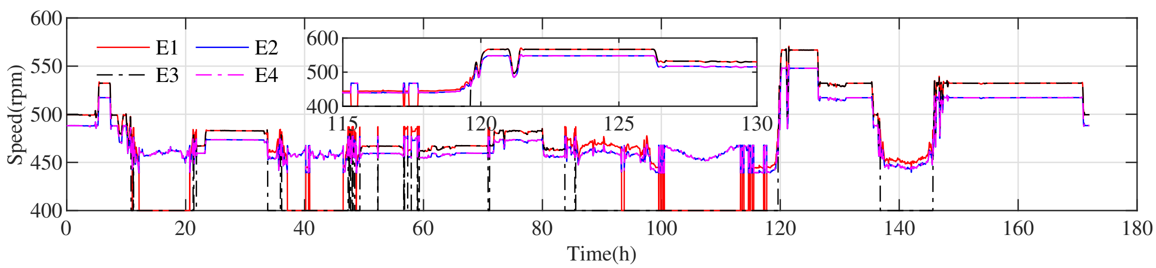

Fig. 9. Speed profile of diesel engines during variable speed operation in a DC system. (E1 - Engine 1, E2 - Engine 2, E3 - Engine 3, and E4 - Engine 4.)

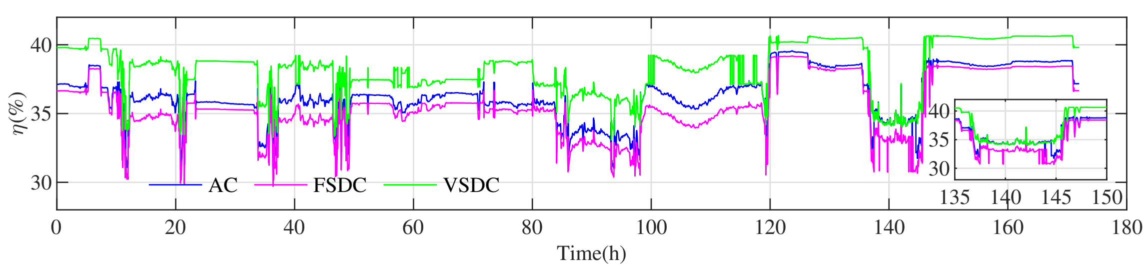

Fig. 10. Power-based (instantaneous) efficiency in the conventional diesel-electric cruise ship.

TABLE VI
ENERGY EFFICIENCY, FUEL CONSUMPTION, AND BATTERY SOC IN THE HYBRID DIESEL-ELECTRIC CRUISE SHIP.

Power System	$\eta_e(\%)$	$m_f(tonn)$	$SoC(\%)$
AC	42.37	558.9	66.54
FSDC	41.61	567.1	63.68
VSDC	42.94	550.1	44.69

SoC should be equal to the initial battery SoC, which makes the battery virtually unused. For sustaining the charge in the battery, different methods can be used.

As a first method, the extended load profile along with the customized EMS can be used to equalize the final and initial battery SoC [46]. Although this method enables a fair comparison of energy efficiency in the hybrid and conventional power system configurations, it does not reflect the realistic energy efficiency for the original load profile.

In the second method, the difference in initial and final battery SoC ($\Delta SoC(\%)$) is converted to equivalent fuel quantity ($m_{f,soc}$) using nominal battery capacity (C_{nom}), lower calorific heat value of the used fuel (h_n), and nominal system efficiency (η_{nom}) as in (12). The nominal system efficiency calculation requires static efficiency values for the components. The fuel quantity equivalent of SoC is further used to

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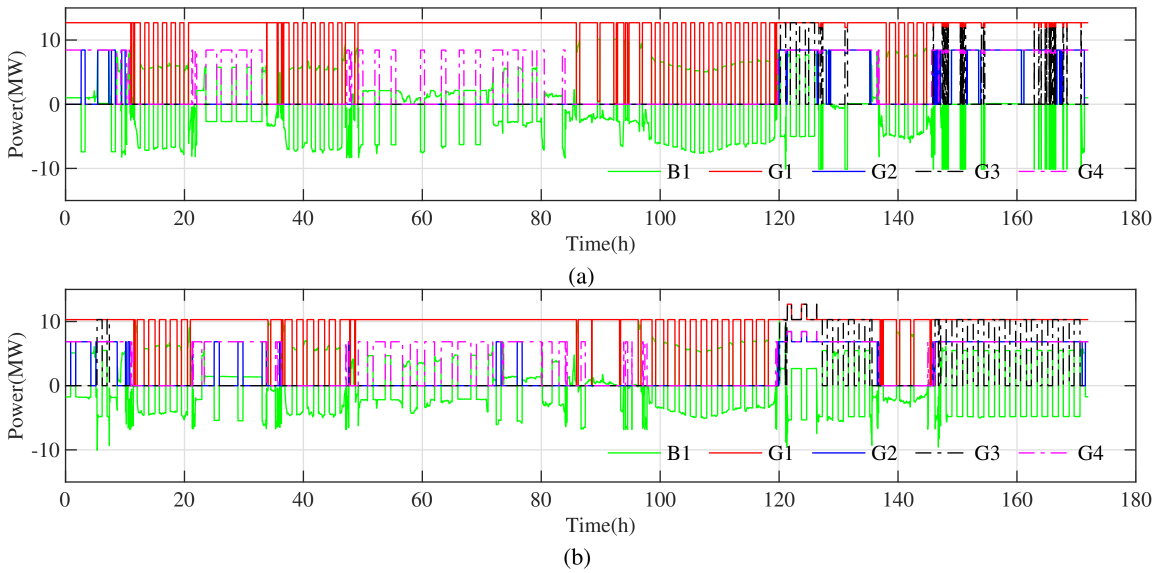

Fig. 11. Power-sharing among generators and battery in the hybrid diesel-electric cruise ship. (a) AC system. (b) VSDC system.

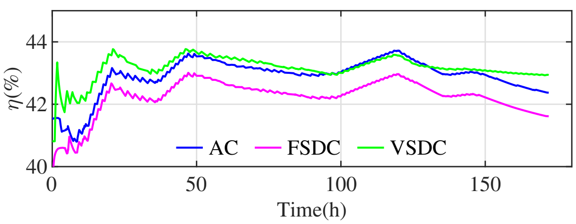

Fig. 12. Energy efficiency variation in the hybrid diesel-electric cruise ship.

TABLE VII
CORRECTED ENERGY EFFICIENCY IN THE HYBRID DIESEL-ELECTRIC CRUISE SHIP.

Power System	$\eta_{e,corr}(\%)$
AC	42.39
FSDC	41.62
VSDC	42.90

calculate corrected energy efficiency $\eta_{e,corr}$ using measured or simulated fuel mass m_f and energy efficiency η_e as in (13). This method is fairly simple to make the energy efficiency comparison of different power systems. However, this method results in a rough estimate as the components' static efficiency does not always represent the realistic efficiency for the actual operating condition.

$$m_{f,soc} = \frac{\Delta SoC \cdot C_{nom}}{\eta_{nom} \cdot h_n} \tag{12}$$

$$\eta_{e,corr} = \frac{\eta_e \cdot m_f}{(m_f + m_{f,soc})} \tag{13}$$

To avoid using static efficiency of the components, a simulation-based experiment method is designed using the existing simulation setups for AC and DC hybrid power system configurations in the third method. As the SFOC curve for small and big engines are different, the simulation experiments are performed using each engine, and the average fuel consumption is then used to correct the energy efficiency based on (13). No other loads are used during this experiment except battery charging load. The corrected energy efficiency ($\eta_{e,corr}$) while sustaining the battery charge level at 60% is shown in Table VII.

3) Efficiency and Loss Distribution: The efficiency and the loss complement each other. In addition to system efficiency, the efficiency in each subsystem is analyzed. The energy loss ($E_{Loss,i}$) and input energy ($E_{in,i}$) in each subsystem is used to evaluate the energy efficiency as in (14). Similarly, the percentage share of loss in each subsystem can be represented in terms of total loss ($\sum E_{Loss,i}$) in the system as in (15)

$$\eta_i = \big(1 - \frac{E_{Loss,i}}{E_{in,i}}\big) \cdot 100\% \tag{14}$$

$$Loss_{Normalized,i} = \frac{E_{Loss,i}}{\sum E_{Loss,i}} \cdot 100\% \tag{15}$$

where $i = 1, 2, ...10$ represent the subsystems as indicated in Fig. 5. The efficiency distribution and loss breakdown among subsystems in the conventional and hybrid power system with different architectures are presented in Fig. 13. It is observed that combustion engine-generator sets have the lowest energy efficiency. Compared to the AC power system, generation side efficiency in the VSDC are mostly higher due to the efficiency gained through the variable speed operation of the engines. It is also observed that the efficiency in the propulsion loads is relatively high; however, the losses in the propelling units such as propellers, thrusters, or azipods are not considered in this work. AC system has slightly lower energy efficiency in the propulsion systems. Besides, most of the losses in the system are in the diesel-generator sets, while load side subsystems have a considerably low loss. The loss breakdown is based on the total system loss and depends on the load profile and the load-sharing method. It means if a generator set is used for a

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longer time in one architecture, then it can have a higher loss and vice versa.

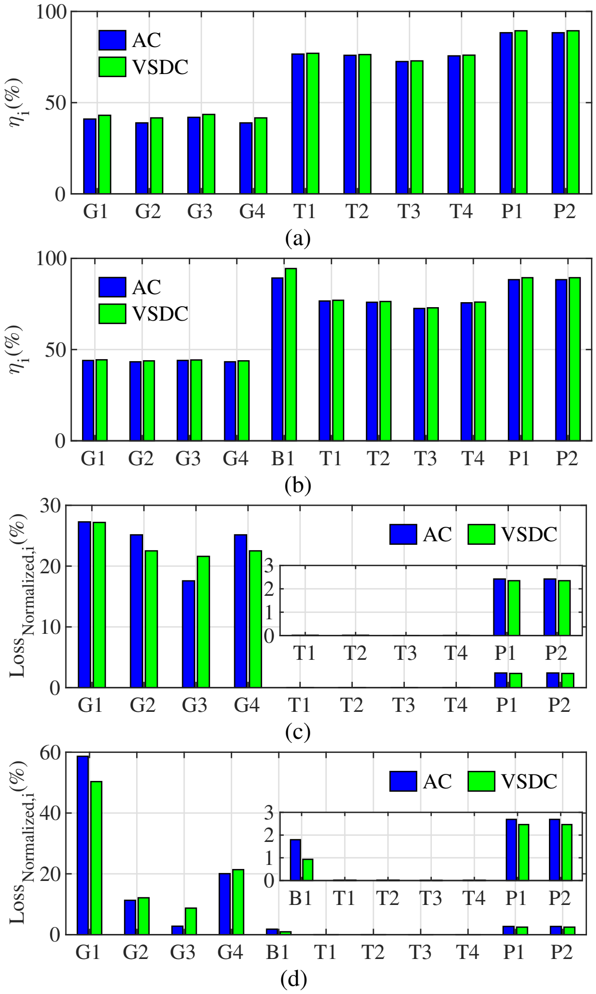

Fig. 13. Efficiency distribution and normalized loss breakdown in various subsystems in a cruise ship. (a) Efficiency in conventional diesel-electric. (b) Efficiency in hybrid diesel-electric. (c) Loss breakdown in conventional diesel-electric. (d) Loss breakdown in hybrid diesel-electric.

4) Effect of Sea Conditions on the Energy Efficiency: The weather and sea conditions affect the power system performance [31]. The propulsion units encounter varying wave resistance due to sea conditions, which will affect the entire power system. If the sea is moderate or rough, the fluctuating power demand from the propulsion units results in the varying load in the engines while maintaining the desired speed of the ship. In contrast, the large engines have a higher time constant, resulting in a slower response. However, as batteries have a faster response, the battery hybrid power system can effectively deal with the sea conditions.

The impact of actual weather is already represented in the load profile as it is an actual measured operational data from the real journey. However, it could be optimal to use the load profile data from different sea conditions to identify their effect in the studied power system architectures. However, actual load profiles for different sea conditions are not available. Therefore, the available real load profile is used to emulate load profiles in different sea conditions. The filtered load profile represents the calmer sea conditions than the real case, as shown in Fig. 14 (a). Similarly, moderate or rough sea conditions are represented by incorporating random signals with varying frequencies [29], as shown in Fig. 14 (b).

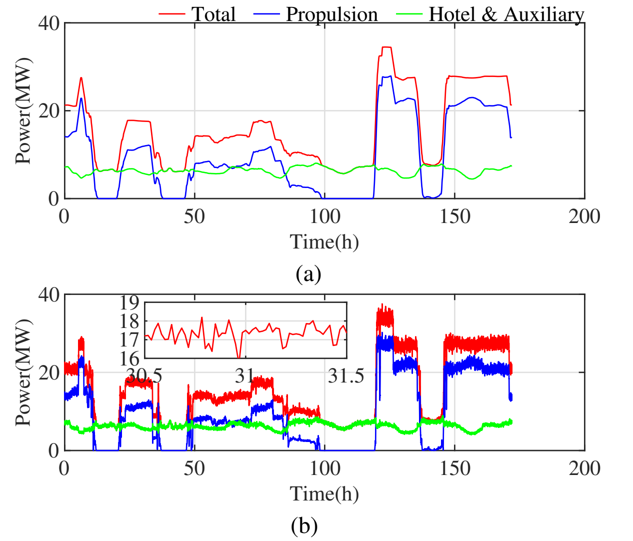

Fig. 14. Modified load profile representing sea conditions. (a) Calm sea. (b) Moderate or rough sea.

The simulation is repeated with the calm and rough sea conditions compared to the real case. The energy efficiency for all three sea conditions and power system architectures are presented in Fig. 15. The energy efficiency trend among the power system architectures is similar in all three weather conditions, which signifies that all power system architectures are similarly affected by the weather conditions. Therefore, the weather condition itself cannot be the deciding factor for selecting power system architecture. Further, it is observed that the energy efficiency for all three architectures in the calm sea condition is slightly less than in the real case. In contrast, it is slightly higher in the rough sea condition than in the real case. It signifies that the varying loads due to weather conditions are well handled by the battery such that diesel engines are less affected by the load fluctuations, which is one of the significant benefits of hybridizing the power system.

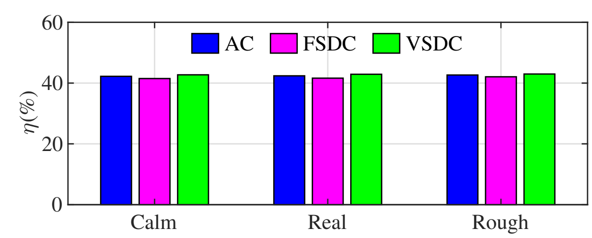

Fig. 15. The energy efficiency of the studied power system architectures in different sea conditions.

5) Effect of Battery Sizing on the Energy Efficiency: The energy efficiency of the hybrid power system can be affected by the battery sizing or capacity as it defines how long the battery can supply or consume the power requested by the EMS. Since the EMS sets battery power reference, the effect of battery size on energy efficiency varies with different EMS algorithms. However, it is aimed to investigate the effect of battery capacity on energy efficiency while keeping the same EMS algorithm.

For the investigation, the battery capacity (C) is set to n times the nominal capacity ($n.Cnom$), where $n = 0.5, 1, 2, 4, 8$. The simulation is run for each n in all three power system architectures. The obtained energy efficiency for each power system architecture is shown in Fig. 16. The efficiency is increasing in a similar slope for AC and FSDC, whereas a different slope for VSDC. It signifies that the total efficiency is also affected by the optimal operating point of the diesel engine. The system energy efficiency increment is higher from 0.5 to 1 than 1 to 2. From 2 to 4, efficiency increment is minor, which remains nearly constant for further increase in capacity. It shows that the energy efficiency increment saturates with the capacity increment for the given power system configuration and high-level control algorithm. It presents the necessity of different control algorithms and operation methodologies for batteries based on their capacity.

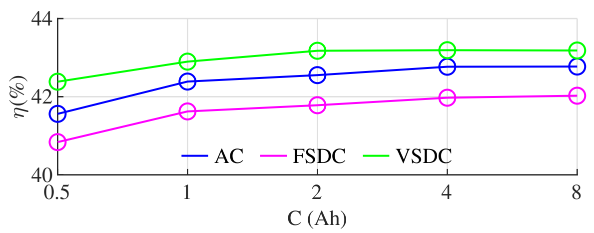

Fig. 16. The energy efficiency of the studied power system architectures with different battery sizing.

V. Conclusion

In this work, AC and DC power system architectures for a conventional and hybrid diesel-electric cruise ship are studied to evaluate and compare the energy efficiency. The polynomial-based efficiency models for the components are established and integrated to configure the studied power systems. The same initial battery SoC, load power profile, and power-sharing strategies are used to compare the power systems. In the case of a hybrid power system, it is realistic to use the battery so that the diesel engine operating point moves towards the optimal region, both in AC and DC systems. However, it resulted in unequal final battery SoCs, which are equalized for the comparison. Further loading, efficiency, and loss analysis are performed. For the studied load profile and the used control algorithm, the onboard battery hybridization of a cruise ship increased energy efficiency irrespective of the power system architectures. Besides, variable speed operation improves efficiency even in lower loads, due to which variable speed DC system offered better energy efficiency than AC and fixed speed DC. Moreover, the applications of the developed system efficiency model are extended on investigating the effect of weather and sea conditions and battery size on the energy efficiency of the hybrid power system. The hybrid power system has shown better performance under fluctuating load.

Since the shipboard power system is usually a tailor-made design, it is essential to evaluate the energy efficiency for different vessels with their realistic load profile to conclude which power system is more efficient for that particular vessel. This work provides a framework for a computationally efficient method to evaluate the efficiency of such complex systems. Furthermore, the evaluation should be continuously updated for new ship design solutions and emerging power system technologies. In general, the operation of energy storage is more efficient compared to the combustion engine-generator set. However, it is not feasible to replace all combustion engines with ESDs for all types of marine vessels with the existing technologies due to the size, weight, and degradation of ESDs. Therefore, harnessing an extra dimension provided by the hybridization with energy storage devices in a ship power system improves overall energy efficiency while reducing emissions.

Appendix

Table VIII shows the efficiency models of the components along with root mean squared error ($RMSE$) and the resulting peak- and full-load efficiencies (%). The power in the efficiency models is an input that is expressed in percentage (>0% - 100%) of the rated power. Similarly, SoC for the battery also expressed in percentage (>0% - 100%), whereas C-rate is a number between 0.5 (0.1) - 3 (2.5). The equipment with fixed losses can consume some power when idle or with no load. However, in this work, no idle mode is assumed for simplicity. So when there is no power output from the component, no loss- and power consumption is considered.

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TABLE VIII
EFFICIENCY MODELS OF THE COMPONENTS.

Component	Efficiency Model (%)	$RMSE(\%)$	$\eta_P(\%)$	$\eta_F(\%)$
Diesel Engine Small, Fixed speed	$\eta_{ef} = f(power) = f(x) = -0.0024x^2 + 0.4202x + 27.4382$	1.84	46.19	45.97
Diesel Engine Small,Variable speed	$\eta_{ev} = f(power) = f(x) = -0.0024x^2 + 0.3539x + 34.4187$	1.29	47.34	45.71
Diesel Engine Big, Fixed speed	$\eta_{ef} = f(power) = f(x) = -0.0023x^2 + 0.4080x + 28.4884$	1.66	46.82	46.63
Diesel Engine Big, Variable speed	$\eta_{ev} = f(power) = f(x) = -0.0023x^2 + 0.3353x + 35.7834$	1.10	47.97	46.39
Electric Generator	$\eta_g = f(power) = f(x) = \frac{-0.026024x^2 + 97.0165x + 5.3057}{x + 0.76677}$	0.03	94.34	93.74
Electric Motor	$\eta_m = f(power) = f(x) = \frac{-0.02949x^2 + 100.2849x + 11.7351}{x + 2.0215}$	0.04	95.65	95.52
Battery Charging	$\eta_{bc} = f(SoC, C-rate) = f(x,y) = 98.2006 - 0.0102x - 0.8608y + 0.0140xy - 1.3007y^2 - 0.0036xy^2 + 0.3373y^3$	0.22	98.20	96.99
Battery Discharging	$\eta_{bd} = f(SoC, C-rate) = f(x,y) = 96.3034 + 0.0486x - 0.2323y - 0.0309xy - 1.1432y^2 + 0.0070xy^2 + 0.2499y^3$	0.19	99.42	96.53
Buck Converter	$\eta_{cc} = f(power) = f(x) = \frac{-0.07178x^2 + 99.1532x + 14.1382}{x + 0.18274}$	0.25	98.10	91.94
Boost Converter	$\eta_{cd} = f(power) = f(x) = \frac{44.1724x^2 + 60965.5613x + 23646.058}{x^2 + 609.9782x + 271.85}$	0.09	98.58	92.07
Inverter	$\eta_i = f(power) = f(x) = \frac{49.1921x^2 + 76805.5233x + 23606.0005}{x^2 + 770.2964x + 647.8977}$	0.04	96.20	93.47
Diode Rectifier	$\eta_r = f(power) = f(x) = -0.018601x + 99.69976$	0.01	99.69	97.83

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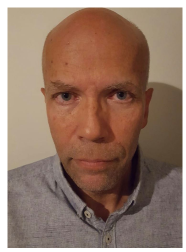

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