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Research Article

An Efficient and Cost-Effective Power Scheduling in Zero-Emission Ferry Ships

Armin Letafat,[1] Mehdi Rafiei,[2] Masoud Ardeshiri,[1] Morteza Sheikh,[2] Mohsen Banaei,[3] Jalil Boudjadar,[4] and Mohammad Hassan Khooban[4]

[1]*Department of Electronics and Electrical Engineering, Islamic Azad University, Kazerun Branch, Kazerun, Iran*
[2]*Department of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran*
[3]*Faculty of Engineering, Ferdowsi University of Mashhad, P.O. Box 91775-1111, Mashhad, Iran*
[4]*Department of Engineering, Aarhus University, Aarhus 8200, Denmark*

Correspondence should be addressed to Mohammad Hassan Khooban; mhkhoban@gmail.com

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Today's remarkable challenge of maritime transportation industry is the detrimental contamination generation from fossil fuels. To tackle such a challenge and reduce the contribution into air pollution, different power solutions have been considered; among others, hybrid energy-based solutions are powering many ferry boats. This paper introduces an energy management strategy (EMS) for a hybrid energy system (HES) of a ferry boat with the goal to optimize the performance and reduce the operation cost. HES considered for the ferry boat consists of different devices such as proton exchange membrane fuel cell (PEMFC), LI-ION battery bank, and cold ironing (CI). PEMFC systems are appropriate to employ as they are not polluting. The battery bank compensates for the abrupt variations of the load as the fuel cell has a slow dynamic against sudden changes of the load. Also, CI systems can improve the reduction of the expenses of energy management, during hours where the ferry boat is located at the harbor. To study the performance, cost and the pollution contribution (CO_2, NO_X, SO_X) of the proposed hybrid energy management strategy (HEMS), we compare it against three various types of HEM from the state-of-the-art and also available rule-based methods in the literature. The analysis results show a high applicability of the proposed HES. All results in this paper have been obtained in the MATLAB software environment.

1. Introduction

Renewable energy resources (RESs) have received growing attention in supplying the required energy of different systems during the last years. The marine industry has also been affected by this trend. Application of renewable and clean energies for supplying the required energy of the marine vessels like small ships and boats is growing and this has led to introducing the concept of Electric Ferry Boats (EFBs) in the marine industry. Different combinations of fossil fuel-based resources and RESs such as diesel generators (DGs), fuel cells (FCs), solar panels, storage batteries (SBs), and cold ironing (CI) [1–3] can be used in the EFBs for supplying the demand and providing the propulsion force of these boats. In this situation, optimal energy management of the EFB is an important subject from the viewpoint of both ship owners and reliability concerns that should be considered to reduce the operation cost while considering the operation constraints of the equipment.

Optimal energy management of the marine vessels has been studied before in the literature. The authors of [4] provided an energy management schedule in the electric ship according to the Model Predictive Control (MPC) to optimize the concordance between power generators and batteries' energy-saving under high-power ramp rate loads. The authors of [5] proposed manner-based energy management by means of Fuzzy Logic (FL) and Proportional-Integration (P-I) control in an all-electric ship with only electric storage devices. Abkenar et al. [6] apply a genetic algorithm to find the proper and safe operation of fuel cells in an electric ship with fuel cells and energy storage system. A subhourly energy management technique based on MPC has been employed for electric ships in an integrated power network having a variety of equipment such as FC, battery, photovoltaic cells, and two DGs [7]. Tang et al. [8] propose an optimal energy resources scheduling model for a large green ship supplied with diesel, battery, photovoltaic, and cold ironing. Different constraints of the model are involved in the objective function and hence, an unconstrained, large-scale, global optimization method is applied to solve the optimization problem. In [9], a nonlinear programming approach is used to find the optimal energy management of an all-electric ship supplied with a hybrid storage system. Optimal power resources scheduling of a ship with diesel generators and batteries alongside a combined cooling and heat power plant is formulated in [10]. The dynamic programming approach is used in [11] to solve the energy management problem of EFB with an energy storage system. Rule-based is applied in [12] to perform the energy management for a ship with a hybrid FC and battery energy system. Applying this method leads to a straightforward lookup table method which cannot necessarily lead to an optimal solution. Particle Swarm Optimization (PSO) algorithm is utilized in [13] for energy management of the shipboard loads. Hou et al. [14] solve the optimal energy management of a hybrid energy storage system for tracking the energy fluctuations of the shipboard loads. In [15], integrated perturbation analysis and sequential programming algorithms and MPC methods are used to solve the energy management problem of a boat with hybrid ultracapacitors and batteries. Optimal power allocation for a hybrid diesel engine and electric motor is performed for a ship without an energy storage system in [16].

There are also some studies in the literature that focus on each equipment of the EFBs such as CI possibility, pollution control, FCs characteristics, and application of solar panels and wind turbines in the EFBs. CI is one of the practical, beneficial energy generation sources to supply power during the ship berthing onshore or harbor where the energy requirements of the ship are provided through the port's connection of the ship to the Microgrids (MGs) or power networks located onshore. Nevertheless, CI has a low pollution rate [17, 18]. Over recent years, different studies have been conducted to optimize the utilization of CI. For instance, in [19], significant effects of the CI on the bus voltages and power quality of the Electrical and Distribution Network around Coast Zone have been investigated. The authors of [20] introduce a CI technology to assess the air pollution due to the presence of a ferry boat in port and a cost-benefit analysis to evaluate the profit quantity of the socioeconomic "Copenhagen-Denmark."

To minimize the perilous air pollutant, suspended particles (CO_2, NO_x, and SO_x), particularly the sulfur reduction rate, as well as component expenses of the system, a combined coast-side power source CI with liquefied natural gas (LNG) has been provided in [21]. Furthermore, in [21], an optimization algorithm based on a nonlinear model was implemented to find the best way for costs and emission terms.

FC is another energy generation source to satisfy the load demand of EMSs [22, 23]. Generally, the system operation of the FCs is based on a transform process, wherein the chemical energy is converted into electrical power [24]. Universally, FCs with various chemical fuels and distinguishing features have been deployed in maritime transportation and power electrical industry including low and high-temperature polymer membrane fuel cell (LT-HT-PEMFC), phosphoric acid fuel cell (PAFC), and solid oxide fuel cell (SOFC) [25]. Nonetheless, multiple disparate works have been carried out in previous studies on FCs. For instance, proton exchange membrane fuel cell (PEMFC) is a process, in which two elements such as oxygen and hydrogen are used for anode and cathode electrodes of the FC's cells to generate power. Zero emission, fast launch, high productivity and power density, low noise and operating temperature, and solid electrolyte are the several important features of the PEMFC.

In order to increase the ship power efficiency, a hybrid fuel cell system by considering several schedules is provided in [26] to decrease the rate of fuel or total energy consumption of the hybrid system. The authors of [27] studied the level of safety and hazardous operability of the molten carbonate fuel cell tanker in nautical systems. Moreover, FL approach has been applied for Failure Mode and Effect Analysis (FMEA) in the presence of FC with molten carbon fuel and gas turbine system for liquefied hydrogen tanker in the marine driven technology [28].

Considering the environmental protection as another important issue in the maritime transportation industry, many research efforts have been devoted to reduce the underlying pollution during recent years. The use of renewable energy sources, such as photovoltaic (PV) and wind turbine, is one of the alternatives that have been proposed. On the contrary, these sources, due to the weather dependency, cannot handle the total power of the ship during peak loads. Thus, to deal with this scenario, other renewable or fossil fuel resources must be used to provide energy. Batteries can also be used parallel to the PV and wind turbines to increase the efficiency of the systems with renewable energy resources [29]. This process will be accompanied by operation cost and environmental contamination.

Reviewing the abovementioned studies shows that there is a gap in the literature in the field of optimal daily energy management of EFBs with FCs as the main source of energy and batteries alongside with the CI. Most of the research studies that are performed in the field of marine vessels are focused on the ships with diesel generators such as [4, 7, 8] and [10], which are not categorized in the field of zero-emission boats. Some of the studies in the field of energy management for zero-emission EFBs consider only the energy storage systems as the main energy resource of the boats like [5, 9] and [11]. On the contrary, the design and application of zero-emission EFBs with the hybrid of FCs and batteries as the main energy resources have received growing attention during the last years. While there are some studies in the field of this type of ships such as [6, 12], these studies perform the energy management for short time intervals and their main goals are satisfying the dynamic constraints of the equipment.

In this paper, an optimal hybrid energy management strategy (HEMS) for an EFB with the FCs as the main energy resource, batteries, and possibility of CI at the harbors is proposed. The goal is obtaining an optimal power scheduling for the FCs, batteries, and CI that minimizes the total operation cost while considering the different operation constraints of the equipment. The characteristics of the proposed test system are adopted from practical research performed in [30, 31]. The capacities of FC systems are considered such that they can supply the total load power of the ship at any weather condition independently. The battery banks installed on the ship will compensate for the unexpected variations of the load because of the FC system slow dynamic. Moreover, the CI system can supply the ship's load power during the existence of the ship at the harbor, at hours where the price of CI system energy is lower than the price of FC system energy. In order to compare the simulation results of the proposed test system with other available hybrid energy systems for the boats, three different types of the energy systems that are based on the fossil fuel as the main energy resource are modeled and compared with the proposed model in this paper. Plus, the rule-based method introduced in [12] is also modeled and its results are compared with the proposed method.

The rest of this paper is organized as follows. Section 2 describes the topology of the electrical ferry boat. Section 3 expresses the hybrid energy management of the ship, including FC, battery, and CI. Finally, simulation results and conclusion are presented in Sections 4 and 5, respectively.

2. The Topology of the Electrical Ferry Boat Description

The topology of the proposed hybrid energy system for the considered ferry boat is illustrated in Figure 1 [30, 31]. This work considers a ferry boat equipped with two PEMFC systems with 200 kW and a PEMFC system with 100 kW capacity. In addition, 20 hydrogen reservoirs with 18.8 kg content from Luxer-GMT with 5,000 psi equivalent to 350 bar at high-pressure gas have been embedded on the ship which are adequate for one operational day without refueling. Also, the mentioned ferry boat has two electromotors with 250 kW rated power for each one. Furthermore, a room consisting of batteries is necessary to save and manage the power generation surplus of FC output after setting up the FC system on the ship. LI-ION batteries with 200 kWh charge capacity (two 100 kWh units) are utilized in the ferry boat to load power compensation. The FCs can continuously produce power along with the 24-hour duration because the FC installation on the ship is without any affiliation to the weather conditions. Therefore, no other renewable energy or fossil fuel sources are needed to supply the ship's loads. Since the total load demand of the ferry boat is met by FCs on an hourly basis, the battery bank installed on the ship requires low power for load supply. This has led to using a small size battery. Thus, employing the battery bank with a small size and not using the fossil fuel resource lead to a significant reduction in the exploitation cost of ship's hybrid energy system and air pollution as well. Ergo, the hybrid energy management strategy (HEMS), is carried out in the presence of FC and battery bank, while the ship is in sailing conditions. Nevertheless, the electric load requirement of the vessel is directly supplied through FC output and the excess of FC power is utilized to feed the battery room. FCs have slow dynamics; therefore, they cannot supply the unanticipated overload in hours with load abrupt variation. Hereupon, the batteries with a fast dynamic can be an appropriate choice to compensate for the power shortage caused by load variation. In this regard, the batteries can receive the energy through the surplus energy of FC and deliver the power to feed the vessel's load.

Table 1 represents the high-speed ferry boat technical specifications. However, all this information may not be necessary for performing the daily energy management of this boat. In order to model the different equipment in the energy management system, (1) the PEMFC systems are considered as a single FC system with a capacity equal to the sum of the generation capacities of all PEMFC systems, (2) all the batteries are considered as a single battery with the capacity of the sum of the capacities of available batteries in the boat, and (3) total load including electromotor load and shipboard loads are modeled as a single load.

3. Hybrid Energy Management Strategy of the Ship

As mentioned before, the goal of this paper is proposing an optimal energy management model for the understudy EFB that minimizes the operation cost and satisfies the operation constraints of the equipment. To this end, first, the objective function is presented, and then the operation constraints of FCs, batteries, and CI are modeled separately. Before starting the formulation, the power flow of the ship in the case that the boat is sailing and the case that the boat is at the harbor is described. Figure 2 indicates the power flow of the system when the boat is sailing. P_1 is the generated power by the FCs that is consumed by the boat loads. P_2 is the generated power of the FCs that is charged in the batteries. The sum of P_1 and P_2 represents the total generated power by the FCs. P_3 is the discharged power by the batteries to the boat loads.

When the ship is at the harbor, the CI can also be performed. Figure 3 represents this situation. P_4 is the consumed power the boat loads through the CI and P_5 represents the stored energy in the batteries through CI.

3.1. Objective Function.

3.1. Objective Function. Operation costs of the understudy zero-emission EFB are the cost of buying the required hydrogen for FCs plus the cost of the CI in the hours that the ship is at harbor. Moreover, a cost related to the degradation rate of the batteries is also considered in the models [8]. This cost is modeled by multiplying a predefined price (C_b) by the amount of discharged power of the batteries during the operation horizon. So, the total operation cost of the EFB is formulated as follows:

$$C_T = \sum_{t=1}^{24} \left(C_H \times M_H(t) + \rho(t) \times \left(P_4(t) + P_5(t)\right) + C_b \times P_3(t)\right). \tag{1}$$

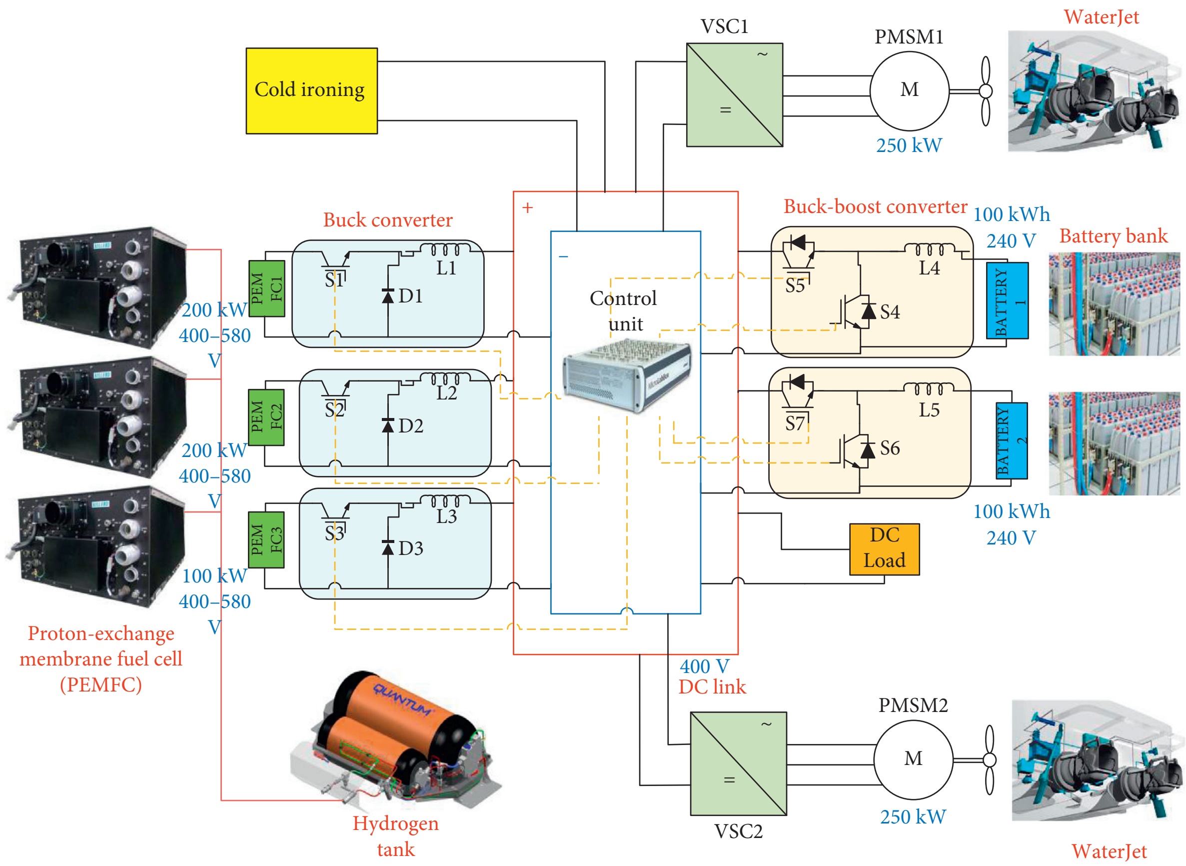

Figure 1: The proposed circuit of the hybrid energy system.

Table 1: Technical characteristics of the PEM fuel cell-battery hybrid system.

Type	High-speed passenger ferry
Overall length	24.5 m
Beam	8 m
Average speed	25.3 knots (47.2 km/h)
Maximum speed	32.5 knots (60.67 km/h)
Distance	8 nm
Total voyage time	9 hours
Fuel cell power	2 PEMFC of 200 kW each and a PEMFC of 100 kW
Hydrogen price	1.35 ($/kg)
Average shaft power	235.41 kW
Main engine power (MEP)	500 kW
Hydrogen fuel (kg)	376
Hydrogen per tank (kg)	18.8
Number of tanks	20
Battery capacity (kWh)	200
Battery charge efficiency	85%
Battery discharge efficiency	100%
Initial state of charge	85 kWh
Minimum allowable capacity (S_{min})	60 kWh (30% of the battery capacity)
Maximum allowable capacity (S_{max})	170 kWh (85% of the battery capacity)
Total investment cost of battery banks (F)	3562 $

First term of objective function is the cost of consuming $M_H(t)$ mass of hydrogen in the price of C_H. Second term is the cost of buying $(P_4(t) + P_5(t))$ kWh energy in the price of $\rho(t)$ through the CI and third term refers to the degradation rate of the batteries.

3.2. Fuel Cell Operation Cost and Constraints. The price of buying hydrogen is assumed to be known. The mass of consumed hydrogen in each hour of the day should be found. To this end, the relation between the generated power and output power of the FCs and the relation between the

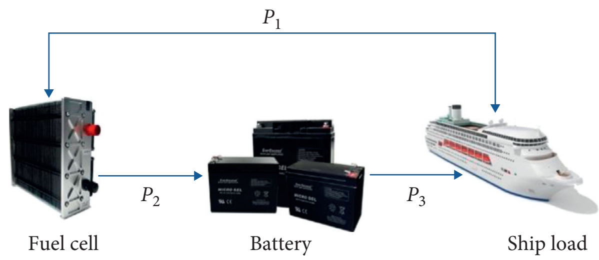

Figure 2: FC/battery/ship's load topology.

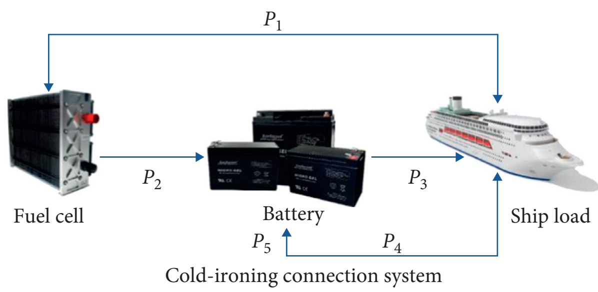

Figure 3: The topology of the fuel cell-battery-cold ironing.

generated power of the FCs and consumed mass of hydrogen are used. The efficiency formula is used to find the relation between the generated power and output power of the FCs. The efficiency curve of the FCs is presented in Figure 4. According to Figure 4, the efficiency of the FCs varies by changing the loading of the FCs. For the sake of simplicity, this curve is estimated by a fixed value for efficiency that according to references [32, 33] is 0.45. The relation between the generated power of the FCs and the consumed mass of hydrogen is written using the conversion coefficient that is equal to 0.03 (kg/kWh). So, the relation between the total output power of the FCs, i.e., $P_1 + P_2$, and the consumed mass of the hydrogen is written as follows:

$$M_H(t) = \frac{P1(t) + P2(t)}{0.45} \times 0.03. \tag{2}$$

The output power of the FCs is limited to the maximum nominal output power of all FCs. In addition, the output power of the FCs is positive. Below constraint is defined to consider these limitations:

$$0 \le P_1(t) + P_2(t) \le P_{\mathrm{FC}}^{\max}, \tag{3}$$

$$P_1(t) \ge 0, \tag{4}$$

$$P_2(t) \ge 0. \tag{5}$$

3.3. Cold-Ironing Cost and Constraints. CI is an electrical energy transmission system which is used to supply the required power of the ship equipment. The power is transmitted from the coast outlet to the ship and devices such as batteries. So, CI is considered in the aforesaid power flow dispatching, when the ferry ship or vessel is at the harbor.

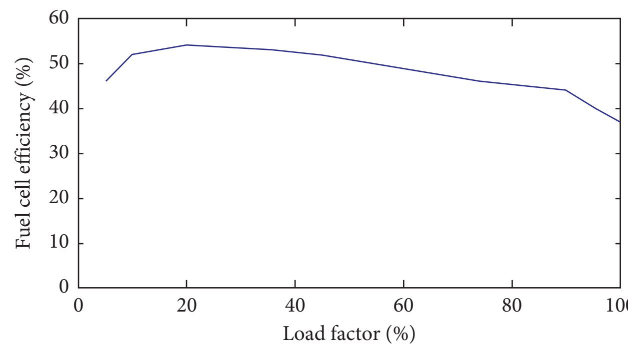

Figure 4: PEMFC efficiency curve.

In this work, the electricity price changes in the CI system are given over different hours of the day. The high, average, and low prices are considered for the peak, standard, and off-peak hours, respectively. In this regard, the workaday electricity price of CI is defined in equation (6) as follows:

$$\rho(t) = \begin{cases} \rho_p, & t \in [7.10) \cup [18.20), \\ \rho_s, & t \in [6.7) \cup [10.18) \cup [20.22), \\ \rho_o, & t \in [0.6) \cup [22.24), \end{cases} \tag{6}$$

where the CI system price at t^{th} hour is denoted by $\rho(t)$. The ρ_p, ρ_s, and ρ_o demonstrate the price for peak, standard, and off-peak hours and are presented in Table 2.

Since the CI is possible just in the case that the boat is at the harbor, the injected power by CI is considered equal to zero when the boat is sailing. So, the constraint below is considered in the model:

$$P_4(t) = 0 \text{ in hours that the boat is sailing}, \tag{7}$$

$$P_5(t) = 0 \text{ in hours that the boat is sailing}. \tag{8}$$

3.4. Batteries Degradation Cost and Operation Constraints. Charging and discharging power of the battery bank are determined through the FC power generated and load demand at given hour t. t is an integer demonstrating the t^{th} hour. One of the main challenges for modeling the batteries' operation is determining the value of the price that is considered for the batteries in (1), i.e., C_b. This cost refers to the degradation rate of the batteries and tries to reduce the aging rate of the batteries as much as possible. Studies show that this cost is mostly dependent on the discharged power of the batteries. Hence, only discharged power is considered in the objective function (1). In many studies in the literature, a constant value is assigned to this cost [18, 34]. This paper also considers a constant value for this price. The proposed method in [8] is used to determine the proper value for C_b. In [8], the concept of Depth of Discharge (DoD) and rainflow approach is used to calculate the C_b. In this method, first, for a dispatching plan, the SOC profile of the batteries is estimated. Then, the cycles of SOC profile is determined, and the DoD of each cycle (D_w) is calculated using the proposed

Table 2: HEMS assessed parameter.

Parameter	Value
Cold ironing price for peak period (ρ_p)	0.31538 \$/kWh
Cold ironing price for standard period (ρ_s)	0.15948 \$/kWh
Cold ironing price for low period (ρ_o)	0.06558 \$/kWh

method in [35]. Finally, the formulations below are used to calculate the C_b:

$$C_b = \sum_{w=1}^{l} \frac{F}{N_w}, \tag{9}$$

wherein F is the total investment cost of battery banks. N_w is calculated by equation (10) as follows:

$$N_w = -3278D_W^4 - 5D_W^3 + 12823D_W^2 - 14122D_W + 5112, \tag{10}$$

l is the number of charging and discharging cycles calculated through the rainflow approach, and D and N_W are the discharge depth and cycle lifetime, respectively [35]. C_b obtained in (9) is used in (1) as a constant to consider the operation cost related to the batteries.

The batteries state of charge (SOC) at any hour t, $S(t)$, depends on the SOC at the prior hour $S(t-1)$. The following situation must be considered for the energy flows from $t-i$ to t. The hourly battery SOC will be achieved via equations (11) and (12) [34].

Under sail,

$$S(t) = S(t-1) + \eta_c P_2(t) - \frac{1}{\eta_d} P_3(t). \tag{11}$$

At anchor,

$$S(t) = S(t-1) + \eta_c \left[P_2(t) + P_5(t)\right] - \frac{1}{\eta_d} P_3(t), \tag{12}$$

wherein both η_c and η_d represent the charging and discharging efficiency of the batteries, respectively. Considering equations (12) and (13), the current SOC can be expressed through the initial SOC $S(0)$ of a day in equations (13) and (14).

Under sail,

$$S(t) = S(0) + \eta_c \sum_{W=0}^{t-1} P_2(W) - \frac{1}{\eta_d} \sum_{W=0}^{t-1} P_3(W). \tag{13}$$

At anchor,

$$S(t) = S(0) + \eta_c \sum_{W=0}^{t-1} \left[P_2(W) + P_5(W)\right] - \frac{1}{\eta_d} \sum_{W=0}^{t-1} P_3(W). \tag{14}$$

The total energy storage of the battery bank should not be less than the minimum $S_{\min}$ and higher than the maximum $S_{\max}$ permissible capacity. This theorem is described in relation (15) as follows:

$$S_{\min} \le S(t) \le S_{\max}. \tag{15}$$

3.5. Power Generation and Consumption Balance Constraints. Equations (16) and (17) define the power flow when the ship is at anchorage and under sail.

Under sail,

$$P_1(t) + P_3(t) + P_5(t) = \mathrm{PL}(t), \quad (t = 1, 2, \ldots, N). \tag{16}$$

At anchor,

$$P_1(t) + P_3(t) = \mathrm{PL}(t), \quad (t = 1, 2, \ldots, N). \tag{17}$$

In equations (16) and (17), $\mathrm{PL}(t)$ is the electrical load demand of the vessel at t^{th} hour.

Proposed formulation (1)–(17) represents a linear model for the optimization problem of energy management in the zero-emission EFB. MATLAB software is used to solve this problem. By solving this problem, optimal hourly scheduling of FCs, batteries, and CI systems is obtained.

4. Simulation Results and Analysis

In this section, first, the proposed case study results are compared with the results of the four different case studies of hybrid energy systems of ferry boats. Then, the proposed optimization method is compared with the proposed rule-based method in reference [12] for hybrid FC/battery ferry boat.

4.1. Comparing the Energy Management Results for Different Case Studies. In this section, energy management, operation cost, and pollution rate results of the proposed hybrid FC/battery ferry boat are compared with three other hybrid energy system cases presented in [8]. The energy resources related to the first case study include diesel generator/cold ironing (CI). The energy systems used in the second case study are diesel generator/battery and CI. The third case study consists of hybrid energy systems such as the photovoltaic (PV)/battery/diesel generator/CI. These cases are modeled using the proposed method in [8]. In order to formulate the models in cases 1–3, optimization problems similar to the proposed formulation (1)–(17) in this paper are used considering the fact that FCs' variables, cost, and constraints are replaced by the variables, cost, and constraints of diesel generators and PV similar to the proposed method in [8]. The proposed model in this paper is also considered as the fourth case in the following simulations. It is well worth mentioning that the 24-hour profile of the ship's load power considered for four case studies is the same. Figure 5 shows the profile of the load power of the ship. The traveling scenario (including under-sail and at-anchor hours) is the same for all four cases. The ferry boat is located in the anchor at hours (1 to 8), (13 to 16), and (20 to 24), and for the rest of the hours the ship is patrolling on the sea.

In the first case study, since the ferry boat is just equipped with a diesel generator, CI will supply a portion of the load power of the ferry boat during the hours where the ship is at anchor and receive the energy from the diesel generator while the ship is patrolling on the sea. However, this scenario leads to cost and air pollution enhancement. The results of case 1 are depicted in Figure 6.

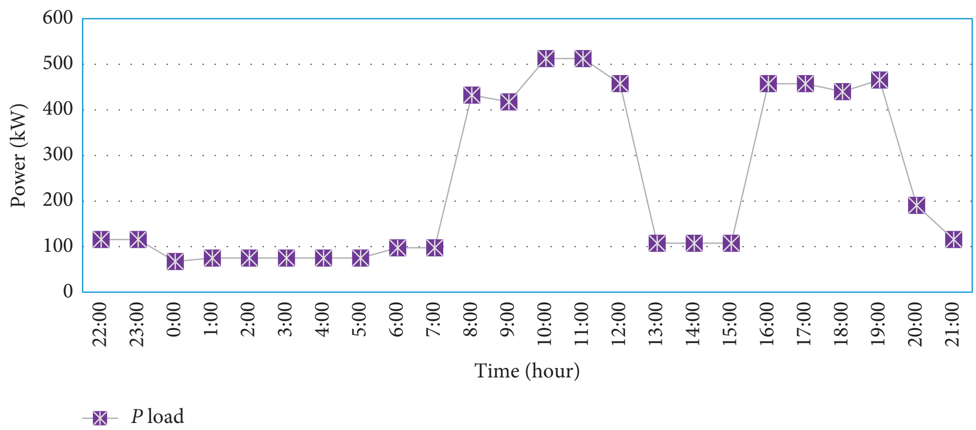

Figure 5: Ship's load power profile for 24 hours.

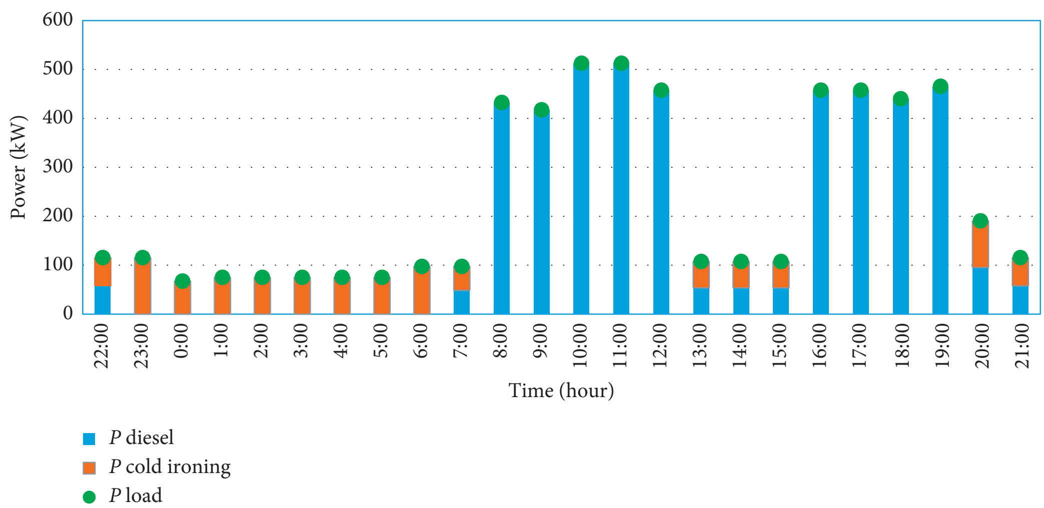

Figure 6: Hybrid energy management system case 1.

The battery bank considered for the second case study provides the part of the load power of the ship at some hours, wherein the pollution rate and cost have been reduced in comparison to the first case study, although the total operation cost due to the battery bank installation will increase. Figure 7 demonstrates the simulation results of case 2. As shown in Figure 7, in this case, the battery charges in hour 1:00 and discharges in hour 7:00.

The PV available in the third case study covers the part of the consumption power of the ship without using the fossil fuel which leads to decrease in the generated power rate through the diesel generator. Under such condition, the total cost of the energy supply and ecological contamination will decrease compared to the first and second cases, although the generated pollution rate due to the energy management used in the third case is high. The size of PV is considered equal to 7 kWh. Figure 8 shows the results related to case 3.

The management strategy applied for cases 1–3 is according to the process wherein the needed load of the ship is provided through the CI system at hours, and the energy price received from the CI system is cheaper than the diesel system, during the presence of the ship at anchor. On the other hand, if the energy price received from the diesel generator is cheaper than CI system, at least 50% of the load power is supplied via CI system because of the ecological contamination diesel generator function. Under such conditions, the rest of the load power is provided by the diesel generator.

HEMS of case 4 is investigated and related results are depicted in Figures 9–12. Figure 9 illustrates the generated power of all resources in the boat. Except for the hours when the ship is at anchor in port, the power generated by FC (P_1) provides all needed load power of the ship at per hours without the use of renewable energy resources or other fossil fuel to handle the ship's load power. In addition, a part of generated power by FC system is used for the charging of the battery banks (P_2). Since the FC systems have slow dynamics against the unexpected variations of the load power, ergo, the battery banks embedded on the ship, because of their fast dynamic, should compensate and cover the load abrupt changes. In this respect, the energy management strategy is considered somehow; at least 10 percent of the ship's load power is provided through the battery banks discharging power (P_3), during the hours that FC is supplying the needed

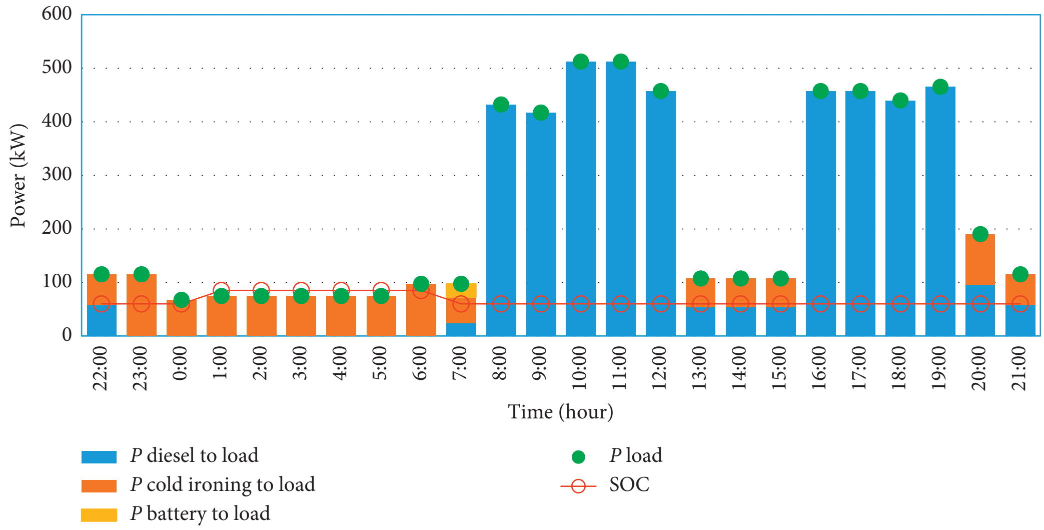

FIGURE 7: Hybrid energy management system case 2.

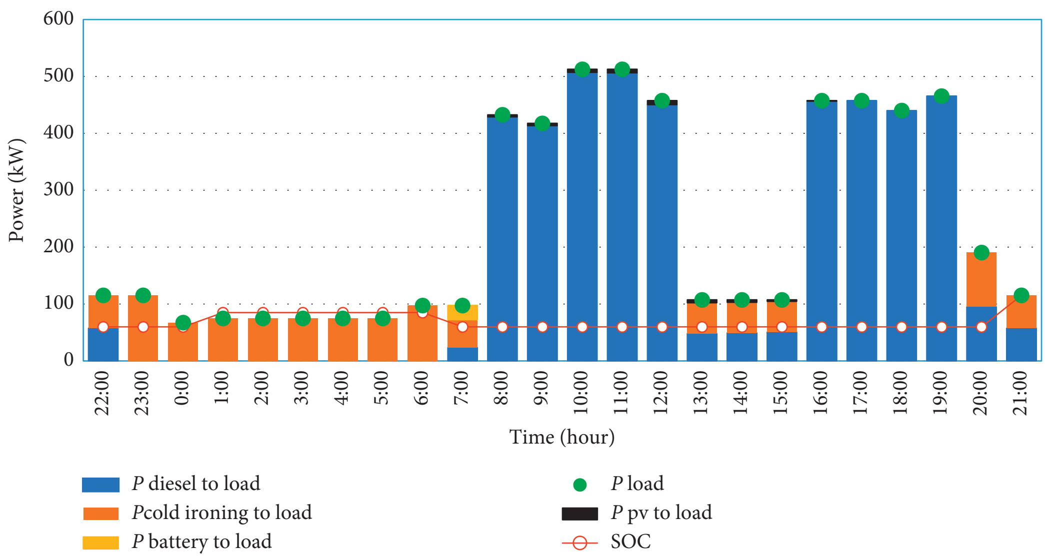

FIGURE 8: Hybrid energy management system case 3.

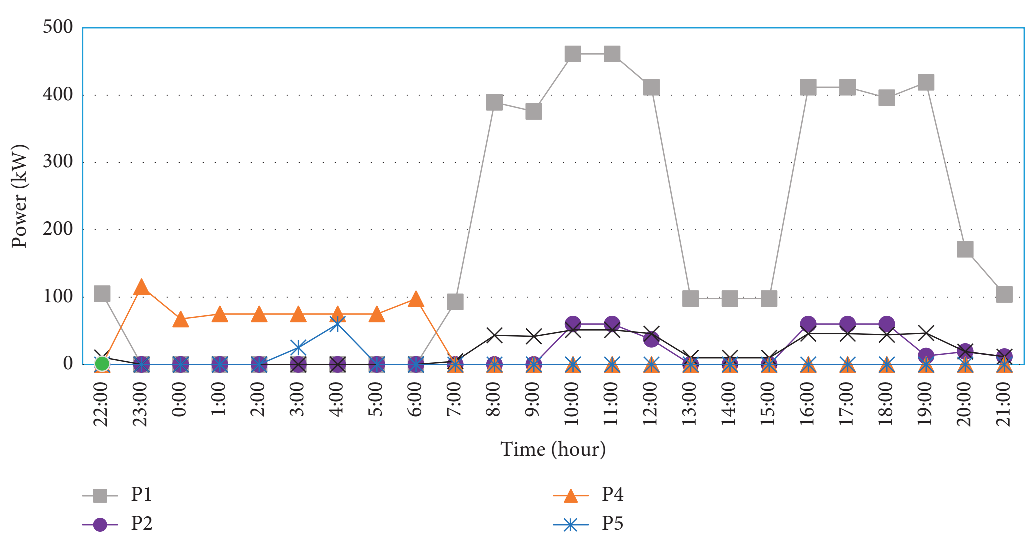

FIGURE 9: Hybrid energy management system in case 4. P_1 and P_4 illustrate the power flow from the fuel cell and cold ironing to feed the load and P_2 and P_5 demonstrate the power flow from the fuel cell and cold ironing to charge the battery bank and the P_3 is discharge power of the battery.

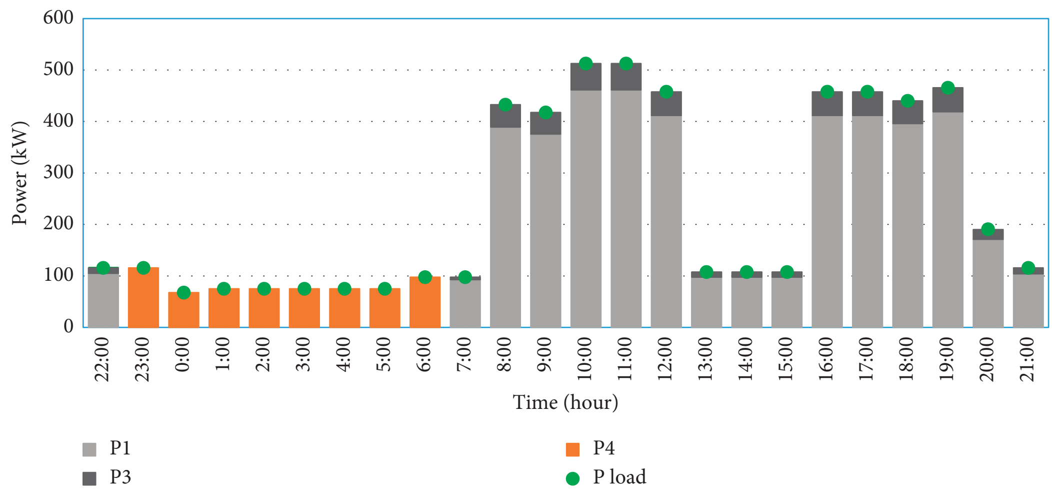

FIGURE 10: Injected power to the load by different resources in case 4.

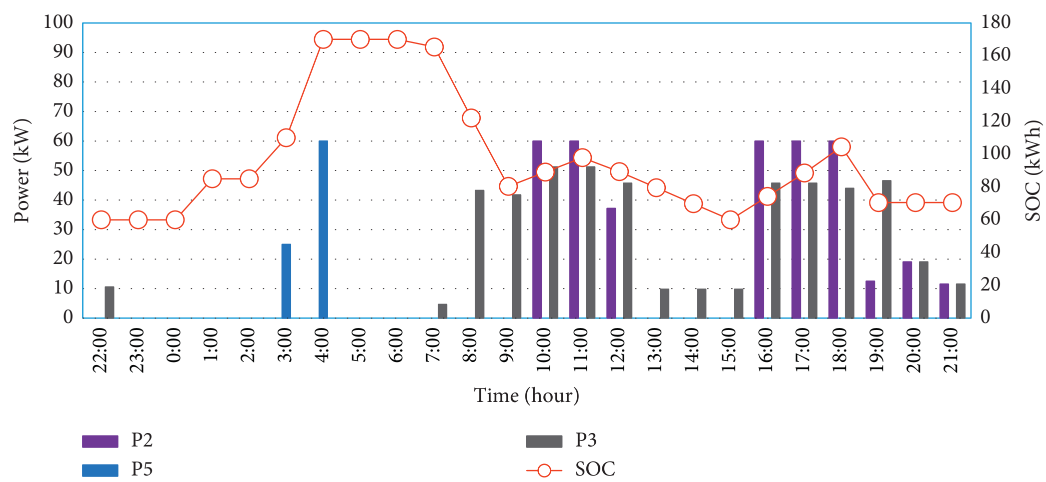

FIGURE 11: Batteries operation in case 4.

ship's load power as shown in Figure 10. Due to the lower energy price of CI system compared with the FC system at (1–6) and (23-24) hours, the ship will receive the required energy from the CI system (P_4) while being at anchor in port; also the battery bank can be charged from CI system (P_5) if needed. This fact is shown in both Figures 9 and 10. For the rest of the hours, while the ship is at the harbor, FC covers the load power of the ship due to the cheaper price of FC system compared with CI, although a small part of ship's load power is compensated by the battery banks because of FC system weak dynamic. The charging and discharging process of the batteries is depicted in Figure 11. Since the batteries should supply at least 10 percent of the load in hours that the FCs are active, batteries are frequently charged and discharged in different hours to have enough stored energy for covering 10 percent of the load in the next hours.

The hydrogen consumption process is presented in Figure 12. In hours that the FCs are not active, the mass of hydrogen consumption is zero. But in other hours, hydrogen is consumed and mass of remained hydrogen in the tank reduces.

All expenses value and pollution rate related to each of the four cases are listed in Table 3 separately. According to Table 3, the total costs and contamination rate (CO_2, NO_X, and SO_X) obtained from the energy management of case 1 are in high range. In case 2, the rate of total cost and ecological contamination is less than case 1 because of less fossil fuel usage. The use of PV in the energy management process of case 3 leads to reducing the total cost and pollution rate compared with case 1 and case 2, whereas the rate of costs and pollution is still high. Moreover, the installation of PV systems on the ship leads to the operation cost enhancement in this respect. As can be seen from Table 3 as the proposed case can satisfy the main objective of this paper which is to eliminate the emissions of CO_2, NO_X, and SO_X, the energy management considered for case 4 has a completely acceptable cost compared to the other three cases.

4.2. Comparing the Proposed Optimization Method with the Rule-Based Method in [12]. In order to compare the efficiency of the proposed method with available methods in the

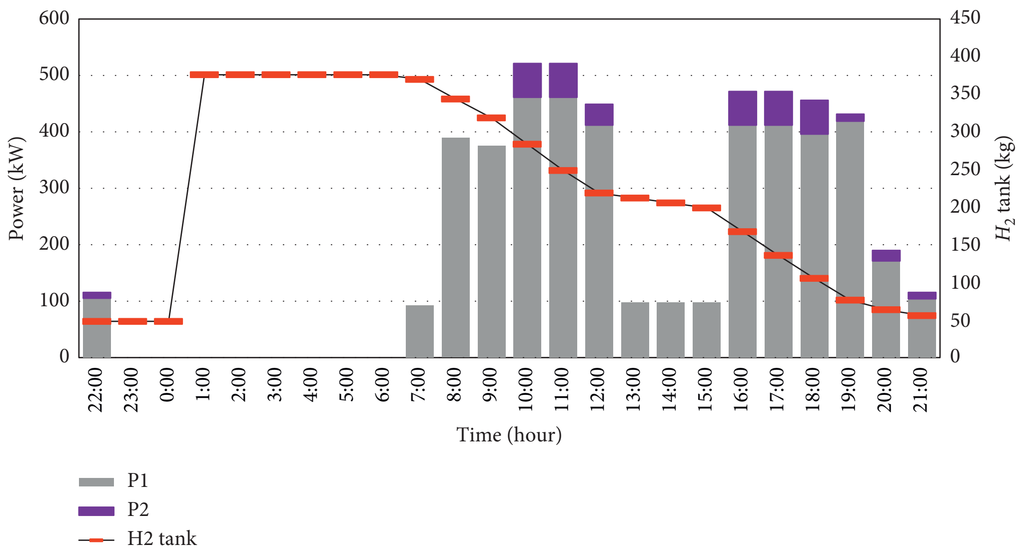

Figure 12: Output power of FCs and consumed hydrogen in case 4.

Table 3: Comparison of total costs and emission factors for different energy management strategy.

Case type	Under-sail cost ($)	At-anchor cost ($)	Total cost ($)	CO_2 (kg)	NO_x (kg)	SO_x (kg)
Case 1	395.497	117.672	477.179	3123.871	11.434	8.141
Case 2	357.532	117.682	475.214	3106.796	11.372	8.097
Case 3	354.682	117.682	472.081	3079.572	11.272	8.026
Case 4	426.486	69.530	496.016	0	0	0

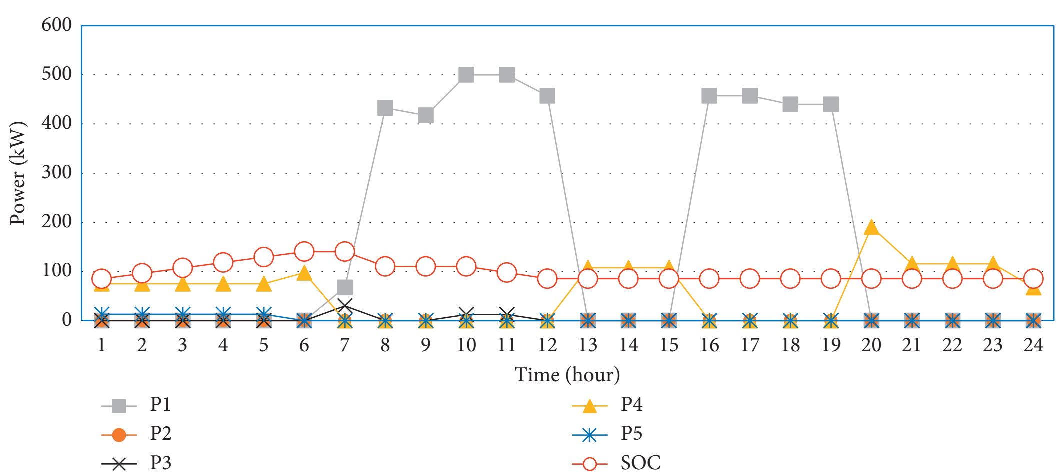

Figure 13: Hybrid energy management system rule-based method.

Table 4: Total costs and emission factors for rule-based method.

Case type	Under-sail cost ($)	At-anchor cost ($)	Total cost ($)	CO_2 (kg)	NO_x (kg)	SO_x (kg)
Proposed method	426.486	69.530	496.016	0	0	0
Rule-based	438.655	72.309	510.964	0	0	0

literature, the proposed rule-based method in [12] that is the available method for energy management of the hybrid FC/battery boat is modeled for the understudy case system. More information about the rules and assumptions of this rule-based method is presented in [12]. HEMS results are illustrated in Figure 13. The operation cost of the rule-based method is also presented in Table 4. Comparing the simulation results indicates that the operation cost of the rule-based method in both under-sail and at-anchor situations is more than the operation cost obtained in this paper by the proposed method. This results in 4% increase in total operation cost at the rule-based method compared to the proposed method in this paper.

5. Conclusion

Hybrid energy management system (HEMS) installation on the ships with optimal energy management can have a remarkable impact on the maritime industry to supply the power of the ship's load demand. The nautical industry targets, such as environmental protection, are not satisfied if the hybrid energy system applied for the ship is considered without optimal energy management. In this paper, four different case studies based on HEMS have been considered for the ferry boat, wherein each case study is along with optimal energy management. Also, all cases were analyzed and compared in terms of total costs and the generated rate of contamination. The total cost obtained from case 1 (diesel generator/cold ironing) is 477.179 $ and the rate of pollution $(CO_2, NO_X,$ and $SO_X)$ is 3123.871 kg, 11.434 kg, and 8.141 kg. The results of the total expenses and pollution rate $(CO_2, NO_X,$ and $SO_X)$, regarding the energy sources used in case 2 (diesel generator/cold ironing/battery) are 475.214 $ and 3106.796 kg, 11.372 kg, and 8.097 kg, respectively. The obtained results of costs and pollution rate $(CO_2, NO_X,$ and $SO_X)$, from the hybrid energy system utilized in case 3 (diesel generator/cold ironing/battery/PV), are 472.081 $ and 3079.572 kg, 11.272 kg, and 8.026 kg. Finally, case 4 is the major case study proposed in this literature. The hybrid energy system used for this case includes fuel cell/battery and cold ironing. Although the total cost obtained from case 4 is 496.016 $, the rate of generated contamination $(CO_2, NO_X,$ and $SO_X)$ is zero. Thus, by comparing the obtained results from case 4, although the HEMS proposed in this paper acceptably enhances the expenses compared with other cases, it drastically reduces the environmental contamination $(CO_2, NO_X,$ and $SO_X)$. The proposed method in this paper is also compared with the proposed rule-based method in the literature. Simulation results show that applying the proposed method in this paper reduces the total operation cost by about 4% compared to the rule-based method. Thereupon, the proposed test system and optimization method can be useful for the maritime transportation industry and improve the clean air as well.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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