Energy Management of a Zero-Emission Ferry Boat With a Fuel-Cell-Based Hybrid Energy System: Feasibility Assessment

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***Abstract*—Due to the increasing impacts of ships pollutants on the environment and the preventive laws that are tightening every day, the utilization of all-electric ships is a recent emerging technology. Being a promising technology, the usage of fuel cells as the main energy resource of marine vessels is an interesting choice. In this article, an all-electric hybrid energy system with zero emission based on fuel cell, battery, and cold-ironing is proposed and analyzed. To this end, actual data of a ferry boat, including load profiles and paths, are considered to assess the feasibility of the proposed energy system. The configuration of the boat and energy resources as well as the problem constraints are modeled and analyzed. Finally, the boat's energy management in hourly form for a one-day period is implemented. The improved sine cosine algorithm is used for the power dispatch optimization, and all models are implemented in MATLAB software. Based on the analysis results, the proposed hybrid system and the energy management method have high performance as an applicable method for the marine vessels. In addition, to be a zero-emission ship, the proposed system has an acceptable energy cost.**

***Index Terms*—Energy management, fuel cell, hybrid energy system, improved sine cosine algorithm, zero-emission ships.**

I. Introduction

POLLUTANTS, such as CO_2 or NO_x, in the shipping industry have high environmental impacts, such as air pollution and greenhouse gases. It has been said that this industry is responsible for about 3%–5% of global CO_2 emissions. Without any preventive program in the marine industry, its emissions would increase drastically [1]. Fortunately, some rules have been imposed to reduce pollution, especially in onshore environments. The cold-ironing is an example, which is defined as the connection of ships to the onshore power network. In some parts of the world, it is obligatory to connect the ships to this network to supply a part of the required energy.

One of the efficient solutions for reducing pollutions, which is assessed in divers transfer industries, such as air and road transfer, is all-electric vehicles. Nevertheless, this concept is rarely implemented on ships. The implementation of such systems on ships requires special considerations. Subsequently, the research in this subject is an interesting topic, and new power generation, control, and optimization methods are developed every day. The utilization of fuel cells is an applicable choice to obtain a zero-emission ship [2]. Fuel cells are highly efficient power resources without any pollution in the place of utilization. In order to improve the energy system performance, the fuel cells can be used in a hybrid system with other clean energy resources, such as photovoltaics (PVs), energy storage devices, and cold-ironing.

Generally, in order to reduce the ship's pollution with changes in the power generation system, three different approaches are implemented in the state of the art.

A. Utilization of Energy Storage Systems With Diesel Generators

These storage systems make it possible to store the power in low peak time and use it in high peak time, which leads to improving the energy efficiency and reduce the emission [3]–[6].

Lhomme and Trovão [4] studied a hybrid energy storage system based on batteries and supercapacitors for the casting-off and docking maneuvers of a ship. The results show a reduction of 1.39 kg CO_2 during the maneuvers and the total emission and consumption by 20%.

B. Utilization of Green Power Sources With Diesel Generators

The zero-emission power resources, such as PVs, as an auxiliary resource can highly improve the fuel consumption rate and emissions [7]–[12].

In [10], the equivalent consumption minimization strategy (ECMS) is applied to a hybrid propulsion plant with a hybrid power supply in order to modify the fuel consumption. As a result, the ECMS method can save 6% additional fuel consumption.

A hybrid energy system based on photovoltaics, batteries, diesel generator, and cold-ironing is assessed in [12]. A

Manuscript received August 4, 2019; revised December 10, 2019, February 10, 2020, and March 26, 2020; accepted April 21, 2020. Date of publication May 7, 2020; date of current version October 30, 2020. This work was supported by the Energy Technology Development and Demonstration Program (EUDP) under Grant 64018-0721, HFC: Hydrogen Fuel Cell and Battery Hybrid Technology for Marine Applications.
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Digital Object Identifier 10.1109/TIE.2020.2992005

large-scale global optimization method is used to implement energy management. The proposed method made a robust control performance and great cost saving.

C. All-Electric Ships

This technology generally requires higher power costs [13]–[17]. Nonetheless, as a zero-emission marine vessel system, it is not yet concerned by the strict environmental laws and penalties; therefore, these ships have a high potential to be the next generation of ships.

A battery/flywheel hybrid energy storage system is used in an all-electric ship in [16], where to facilitate real-time implementation, a model predictive control (MPC) algorithm is developed. The results show the effectiveness of the proposed system.

In [17], a large-scale PV is proposed for an ocean-going green ship, where the MPPT of the all-electric system is modeled as a large-scale global optimization. The research work carried out leads to a safe and efficient PV operation under diverse environmental conditions. An important challenge of these ships is their power management and control strategy [18]–[22].

A two-step multiobjective method for hybrid energy storage system management is presented in [19]. The first step is responsible for regulating the system energy with the diesel generators. The second step's responsibility is to divide the active power of the energy system into individual storage systems for minimizing battery damages.

The proposed electrical energy system in this article is in the form of a zero-emission hybrid system based on fuel cells, batteries, and cold-ironing. Considering the high efficiency and other applicable features of fuel cells, it is selected as the main power resource. Nevertheless, due to fuel cell limitations, it is not possible to use it as the only main energy source. The slow dynamic is an important limitation of fuel cells, and, therefore, they cannot follow the fast changes in loads. Therefore, in the proposed energy system, the batteries are considered too. Based on the fast dynamic of batteries, their utilization with fuel cells leads to having a highly efficient power resource with the ability to follow the fast dynamic of load variations.

The analysis and feasibility assessment of the proposed hybrid energy system is implemented using real information on a ferry boat. In some stop points of the boat, there is a possibility to connect the boat to the onshore power network. Therefore, the cold-ironing energy resource is considered in the hybrid energy system. One of the most important limitations in ships' energy system design is the limitation of mass and volume [1]. The utilization of cold-ironing makes the opportunity to reduce the required capacity of H_2 tanks and batteries. As a result, the combination of three mentioned energy resources leads to an efficient hybrid energy system with a high ability to follow the load changes and acceptable mass and volume.

An important problem in the energy management of ships is their complicated constraints. The reason for the complexity is the time and location-based limitations of refueling, the location-based differences in power generation profile, etc. In previous research works, two approaches are used to implement these constraints. In the first approach [14], the power of each energy resource is determined based on a defined decision-making process. In these kinds of methods, the generated power is selected manually based on the load and generation conditions and the value of the stored energy. The constraints are satisfied by this method, but based on the manual selection, there is no guarantee that the selected plan is the best possible one. In the second approach of constraints implementation [12], all constraints are modeled in the optimization cost function as penalty functions. By considering the high number of constraints, adding all of them to the cost function in the form of penalty functions reduces the search and update ability of the optimization algorithm.

In this article, a novel structure of zero-emission ferry ships is proposed. In the proposed emission-free ferry model, the fuel cells are considered as a main power supply of the ship power system, as well as batteries are utilized as an auxiliary power source to enhance the resiliency and compactness of the system. This kind of a modern ship power grid can be assumed as a special mobile microgrid, in which power scheduling plays a significant role in increasing operational time and reduction in energy storage systems. Hence, the main focus of this article is to introduce a high-performance and cost-effective energy management for the proposed model. To this end, the constraints are modeled in the form of mathematical equations to determine and update the optimization parameters. Among all constraints, only the H_2 tanks constraint is modeled as a penalty function. In addition, to find the optimal plan instead of a manual selection, the proposed procedure increases the search and update the method ability. Consequently, after studying the boat and path specifications and the assessment of the limitation and considerations of the energy resources, the energy management system is optimized. As the boat path is completed in a one-day period, the energy management problem is implemented in the form of hourly averages for 24 hours. The hourly transferred powers among all energy resources and loads are assumed as the optimization parameters. Also, the daily cost of the generated power is defined as the cost function. Hence, the implemented optimization is a one-objective minimization problem. To find the optimal solution, the improved sine cosine algorithm (ISCA) is used in this study for the first time, to the best of our knowledge. In this algorithm, the improvisation approach established in the harmony search (HS) is used with a sine–cosine algorithm (SCA), which leads to avoiding the convergence to a local optimum point and makes a higher exploration ability. To sum up, the present contributions of this article can be expressed as follows.

1) Proposing a new full-electric ferry ship power grid for a daily journey.
2) Assessment of a hybrid zero-emission energy system based on the fuel cell, battery, and cold-ironing.
3) Utilization of real information of a ferry boat, including boat, path, and load profile data.
4) Modeling the constraints of energy management system in the form of mathematical equations on the search zone of the optimization parameters.
5) Suggesting a high-performance and cost-effective optimal energy management algorithm for the proposed emission-free ferry ship.

TABLE I
BOAT'S SPECIFICATIONS

Parameter	Value
Type	Passenger
Overall length (m)	47
Beam (m)	10
Main engines power (kW)	600
Maximum speed (knots)	13
Average speed (knots)	11

6) Utilization of the improved sine cosine optimization algorithm for solving the ferry's power scheduling problem.

The remainder of this study is organized as follows. In Section II, the information related to the boat, paths, and loads profile is presented. The specifications and required considerations in modeling the energy resources and their energy costs are studied in Section III. Section IV includes the explanations of the energy management implementation, which consists of the optimization method, constraints, and cost function. The numerical results are presented in Section V. Finally, Section VI concludes this article.

II. Problem Description

As it has been said, the aim of this article is to design the energy management of a zero-emission ferry boat. The proposed hybrid energy system in this article contains fuel cell, battery, and cold-ironing. These energy sources supply the boat's required power, including engine power and other power consumption, such as lighting and radars. In this section, the specifications of the boat, paths, and energy profile are presented.

A. Boat Specifications

The considered boat is a bay tour ferry, which is used to transfer travelers for a one-day tour journey. This boat is currently operating with a diesel engine, and in this article, the feasibility of a zero-emission alternative energy system is assessed. The boat specification boat is presented in Table I.

In power management, two states are considered for the boat: "on sail" and "at anchor." In "at anchor" state, it is possible to connect the boat to the onshore power network, which is known as cold-ironing. In order to reduce the pollution, it is mandatory for boats with emission to connect to the onshore network even if it costs more than the power generated at the boat. As the studied boat is a zero-emission one, based on the energy requirements and costs, the connection to the onshore power network is optional.

Therefore, the schematic views of the boat consist in energy sources and consumptions for "on sail" and "at anchor" states are presented in Fig. 1(a) and (b), respectively.

According to Fig. 1, the generated power by the fuel cells and entranced power of the cold-ironing are used to supply the loads and charge the batteries. Also, the power outage of batteries is only used to supply the loads. Thus, power transfer paths are defined as follows.:

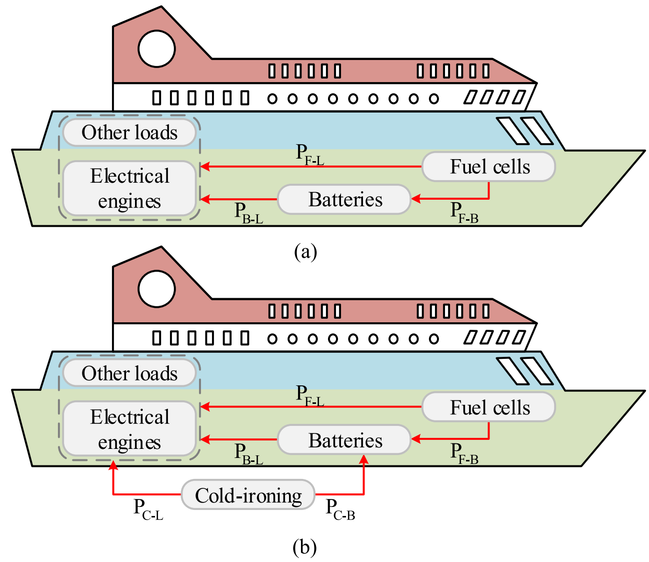

Fig. 1. Schematic of power paths. (a) On sail. (b) At anchor.

P_{F-L} transferred power from fuel cells to supply the loads;
P_{F-B} transferred power from fuel cells to charge the batteries;
P_{B-L} transferred power from batteries to supply the loads;
P_{C-L} transferred power from cold-ironing to supply the loads;
P_{C-B} transferred power from cold-ironing to charge the batteries.

B. Path Specifications

There are three stops in the paths of the boat. The entire travel lasts 1 day (24 hours), which includes on the sail and at anchor time. A chemotic view of the boat's paths and approximate time is illustrated in Fig. 2.

The travel starts at 6 A.M. from point "A." After four hours on sail, the boat arrives on point "B" at 10 A.M. Afterward, the boat stays for three hours at point "B" and then departures for point "C" at 1 P.M. This part of travel lasts five hours. Therefore, the boat arrives on point "C" at 6 P.M. After a two-hour stop, the boat leaves the point "C" at 8 P.M. to return to point "A" and then spends five hours to start the next travel.

It is shown in Fig. 2 that in the first and second journeys, the boat uses only one engine, but on the third journey, it uses its both engines. Also, the cold-ironing is only available on points "A" and "B." On the other hand, the H_2 tanks can get charged only on points "A" and "C."

C. Power Profile

Based on the boat's path, the studied time period is equal to 24 hours. The supply loads include the engine load and usual consumption loads. Fig. 3 shows the load diagram of the boat for a 24-hour journey. The diagram illustrates the engines, usual consumption, and total required loads.

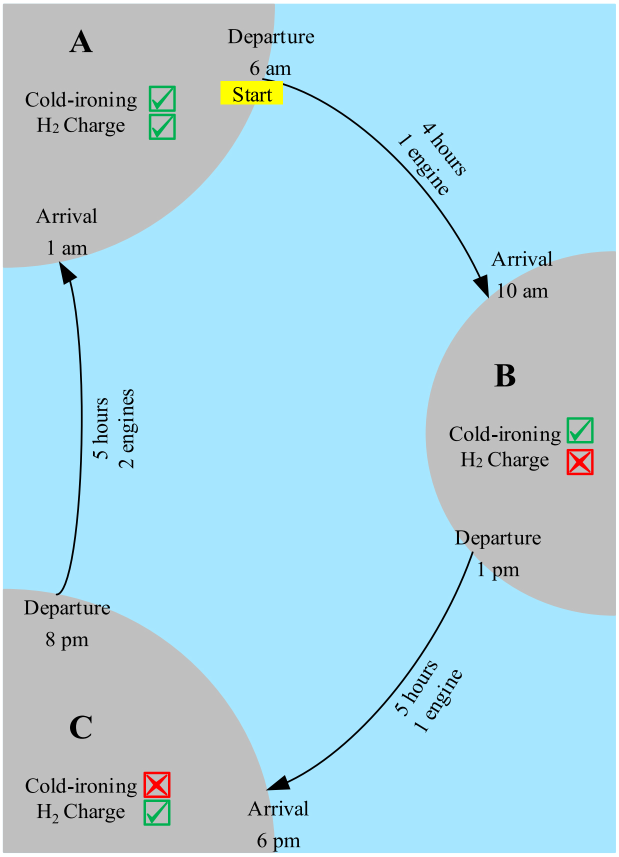

Fig. 2. Path specifications.

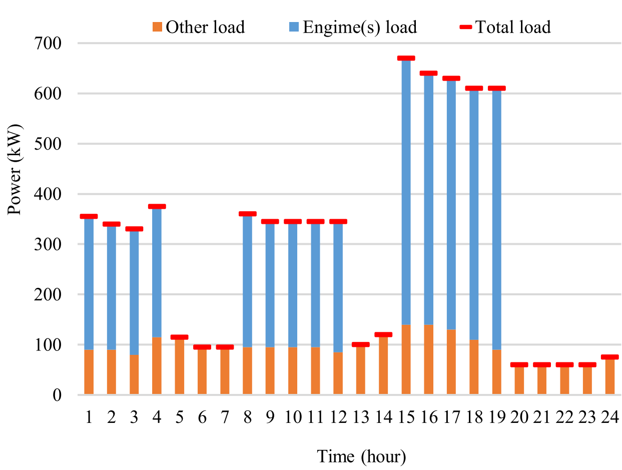

Fig. 3. Load profile for 24 hours.

It can be seen from Fig. 3 that the boat's required power profile is presented in the form of hourly averages for a 24-hour period. The consumption power by two engines at anchors is equal to zero. Moreover, the hourly average of engine power in journeys with the utilization of one and two engines is equal to 250 and 500 kWh, respectively. Also, as the required engine power in starts and stops is higher than usual sailing, because of boat's casting-off and docking maneuvers, the average required power of engines in first and last hour of each journey is higher than other hours of the journey. Also, the usual consumption loads include lighting and necessary loads. The lightning loads have different values based on the time of a day, but the necessary loads (such as radars) are constantly in use.

III. Consideration of the Energy System

According to the Section II, the proposed energy system consists of the fuel cell, battery, and cold-ironing. A general view of the proposed circuit is illustrated in Fig. 4. It can be seen that all energy sources and loads are connected to a 400 V dc bus. In total, there are three fuel cells, including two fuel cells with 300 kW and one fuel cell with 100 kW power. All these fuel cells are designed and manufactured using the HD7-100 module. Also, the cold-ironing and two sets of 200-kW batteries are connected to the dc bus. According to Fig. 4, loads consist of two 400-kW waterjets as engines, as well as dc loads (e.g., radars, sonar and etc.) are also connected to the dc bus. The electronic converters are used to connect the components to the dc link, and a control system is used to operate them. Here, the specifications and considerations of each power source are presented.

A. Fuel Cell

The efficiency to output power diagram of an HD7-100 fuel cell is presented in Fig. 5. Based on this figure and the specifications of the utilized fuel cells in the proposed system (see Fig. 4), the maximum fuel cell power, generated by all of them, is equal to 700 kW. However, by considering that it is possible to use only one fuel cell, the minimum power generated by fuel cells (both 300 kW fuel cells are OFF and the 100-kW fuel cell operates in its minimum power) is equal to 10 kW.

It has been said that fuel cells have a slow dynamic and cannot follow the rapid changes in loads [23]. Therefore, in order to satisfy the fast dynamic of load variations, the batteries are used to amortize the load and compensate fuel cell.

Given that in this article, the power management of a boat is studied in form of hourly averages, it is not possible to see the fast dynamic of the loads. Nevertheless, in order to consider the loads fast dynamic, the coefficient β is defined as the factor of high dynamic part of the loads. Therefore, it is supposed that $\beta * 100\%$ of loads in each hour (equal to fast dynamic changes) must be supplied by batteries or cold-ironing. This assumption is modeled in constraints.

Based on the small changes in the fuel cell's efficiency in different power outputs, it is acceptable that for all possible power outage, the H_2 consumption for each kWh of energy is constant [24]. As a result, the operation cost of fuel cells in hour i, which is equal to consumed H_2, is modeled in form of a constant coefficient in fuel cell's power output

$$\mathrm{OC}_{\text{fuel cell}}^{i} = c_f * E_f^i \tag{1}$$

where E_f^i is equal to the transferred power from fuel cells to the load and batteries in hour i.

In addition to the operation cost, the investment costs must be taken into account to effectively evaluate the applicability

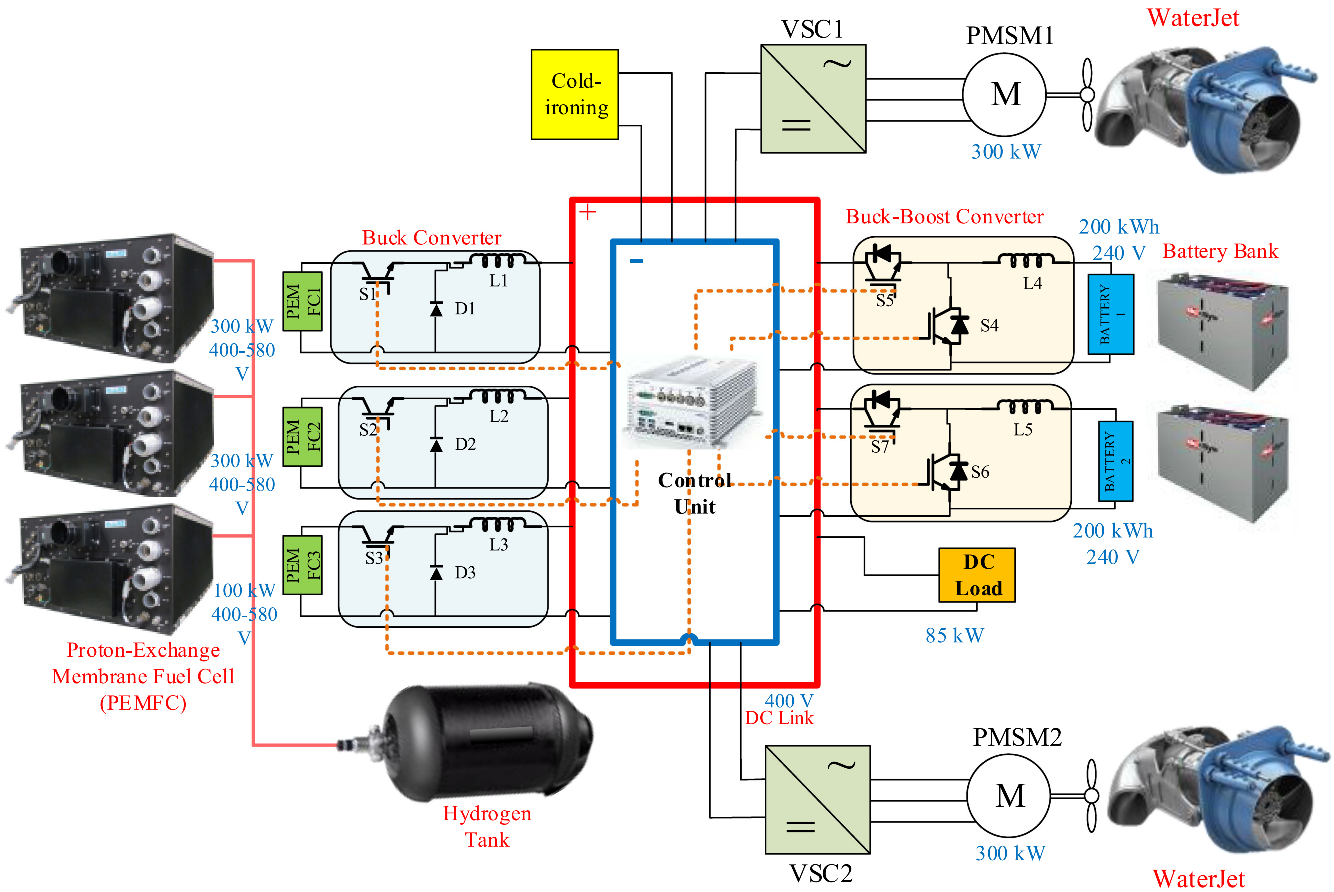

Fig. 4. Proposed circuit of the energy system.

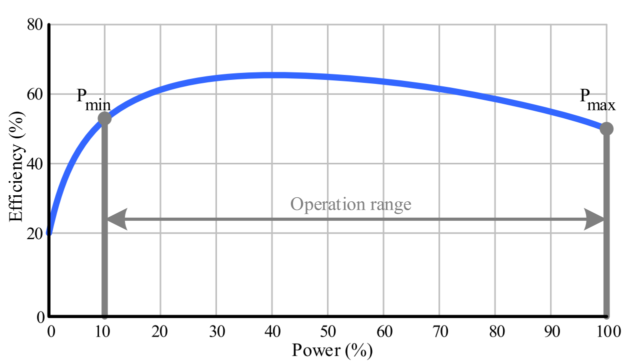

Fig. 5. Efficiency to output power diagram of the HD7-100 fuel cell.

of the proposed method. As the trip lasts for 24 hours, the daily investment costs are regarded. Therefore, by considering $\mathrm{iic}_{\text{feul cell}}$ and $\mathrm{lt}_{\text{feul cell}}$ as the initial investment cost and lifetime of fuel cells, respectively, the daily investment cost for fuel cells can be calculated as follows:

$$\mathrm{IC}_{\text{feul cell}} = \frac{(P_{\mathrm{FC}} * \mathrm{iic}_{\text{fuel cell}}) * \mathrm{ot}}{\mathrm{lt}_{\text{fuel cell}}} \qquad (2)$$

where $\mathrm{IC}_{\text{feul cell}}$ represents the daily investment cost of the fuel cell and ot is the fuel cell operation time in the obtained energy management.

The other consideration for fuel cells is the available H_2 in tanks. Thus, in power management modeling of the zero-emission boat, the limitation of available H_2 must be considered.

B. Battery

Considering the high cost of batteries, their lifetime is a very important parameter. Subsequently, in order to increase batteries' lifetime, some limitations must be considered during utilization.

The first limitation is defined in the form of the maximum charging and discharging of batteries in a specific period of time. Too much charging or discharging of a battery in a period of time causes the battery to warm up, which has negative effects on the battery's lifetime [25]. Therefore, two parameters $P^{\max}_{\text{Charge}}$ and $P^{\max}_{\text{Discharge}}$ are defined here with the concept of the maximum allowed charge and discharge power of batteries in one hour.

The other limitation is related to the maximum and minimum energy stored in batteries. Based on the research works on batteries [11], in order to increase the battery's lifetime, it is better to keep the battery's state of the charge (SOC) in a specific range. The situation of the SOC higher and lower than the suggested range is called overcharge and overdischarge, respectively. Accordingly, by defining α_M and α_m as the maximum and minimum coefficients of the SOC, respectively, the following equation must be satisfied:

$$\alpha_m * P_{\text{Battery}} \leq \text{SOC} \leq \alpha_M * P_{\text{Battery}}. \quad (3)$$

The other consideration in the modeling of the batteries is about the charge and discharge losses. These losses are modeled in the calculation of the SOC with charge and discharge coefficients (η_c and η_d). Therefore, the SOC of the batteries at the beginning of hour *i* is calculated as follows:

$$\text{SOC}^i = \text{SOC}^{i-1} + \eta_c P^{i-1}_{\text{Charge}} - 1/\eta_d P^{i-1}_{\text{Discharge}} \quad (4)$$

where P^{i-1}_{Charge} is equal to the summation of the transferred power from fuel cells and cold-ironing to the batteries in hour $i-1$. Besides, $P^{i-1}_{\text{Discharge}}$represents the value of the supplied loads by batteries in hour $i - 1$.

The utilization cost of the batteries, which represents the maintenance cost, has a direct relationship with the power they inject. Therefore, the operation cost of batteries can be defined in form of a utilization constant coefficient (c_b) in batteries' power output. Therefore, the batteries' operation cost in hour *i* can be modeled as follows:

$$\text{OC}^i_{\text{battery}} = c_b * E^i_b \quad (5)$$

where E^i_b is equal to the transferred power from batteries to the load in hour *i*.

In order to calculate the investment cost of batteries, the initial investment cost and lifetime of batteries are represented by $\text{iic}_{\text{battery}}$ and $\text{lt}_{\text{battery}}$, respectively. So, the batteries' daily investment cost can be computed as follows:

$$\text{IC}_{\text{Battery}} = \frac{(E_{BA} * \text{iic}_{\text{battery}}) * \text{nc}}{\text{lt}_{\text{battery}}} \quad (6)$$

where $\text{IC}_{\text{battery}}$ indicates daily investment cost of battery and nc illustrated the number of cycles that batteries are charged and discharged in the obtained energy management.

C. Cold-Ironing

As mentioned earlier, the connection to onshore power network is optional for a zero-emission boat. This decision must be taken based on the boat power requirements and the power cost of the onshore network. The cost of the cold-ironing is related to the time of connection to the onshore network and is presented as follows:

$$\text{cost}^i_{\text{cold-ironing}} = \begin{cases} \rho_{\text{on}} * E^i_c & t \in [7,10) \cup [18,20) \\ \rho_{\text{mid}} * E^i_c & t \in [6,7) \cup [10,18) \cup [20,22) \\ \rho_{\text{off}} * E^i_c & t \in [22,6) \end{cases} \quad (7)$$

where ρ_{on}, ρ_{mid}, and ρ_{off} are equal to the price of cold-ironing energy in on-peak, mid-peak, and off-peak periods, respectively. Furthermore, E^i_c is equal to the transferred power from cold-ironing to the load and batteries in hour *i*.

IV. Power Management

The different types of power management strategies can be categorized in two points of view: objectives [26] and methods [27]. Based on the first viewpoint, the objectives of different strategies could include one of the following:

1) the load satisfaction;
2) technical decision factors;
3) economic decision factors;
4) both technical and economic decision factors.

The objectives of the proposed strategy in this article are categorized in the fourth type. Also, in the viewpoint of methods, the available techniques are the following:

1) classical methods;
2) metaheuristic approaches;
3) artificial intelligent methods;
4) stochastic and robust programming approaches;
5) MPCs.

Based on the utilized optimization method presented in this article, the proposed strategy's method is considered as a metaheuristic approach.

The power management issue in this study is to minimize the cost of the system operation in the form of an hourly power dispatch problem for a period of 24 hours. The aim is to determine the best amount of generated or stored power of each energy source in each hour to satisfy the loads. Accordingly, the improved SCA optimization algorithm is used here to find the best optimal solution. The power transfers among energy resources and loads are the optimization parameters, and the total cost is the cost function.

A. Improved SCA

The stochastic optimization SCA algorithm is based on the mathematical sine and cosine functions [28]. The algorithm uses different candidate search agents and moves them toward or outward the best one by a mathematical model. This algorithm has been used in different research topics with highly acceptable results [29], [30].

In SCA, a search agent is moved based on random and adaptive variables; therefore, there is no guarantee to find a desirable search agent. Therefore, it may result in a poor search ability for some complex problems, which may lead the algorithm to premature convergence. To overcome this weakness, a new improvement is applied to the SCA algorithm. This improvement is obtained by adding the improvisation approach established in the HS to the SCA. As a result, each candidate point is ameliorated based on three factors: memory consideration, pitch adjustment, and random selection. Also, a hybrid variant of SCA that incorporates a wavelet-theory-based mutation mechanism is applied [9]. In this regard, every component of a search agent has a possibility to mutate by a specified probability. Therefore, the component experiences mutation by a new wavelet operation enhanced by the sine and cosine functions.

The pseudocode, as employed in the ISCA algorithm, is demonstrated in Algorithm 1.

Two main differences between the proposed optimization ISCA algorithm and the classic power system optimization algorithms, which leads to choose and apply it on the current problem, are its simplicity of implementation and also its potential to solve challenging real problems that are highly

TABLE II
CONSTRAINT EQUATIONS

Position	Constraint	Eq. #
On sail	$\max\left[\left(P^i_{Load}-P^{\max}_{Discharge}\right),0\right]\le P^i_{F-L}\le\min\left[P^{\max}_{FC},\left((1-\beta)*\left(P^i_{Load}\right)\right)\right]$	(8)
	$P^i_{B-L}=P^i_{Load}-P^i_{F-L}$	(9)
	$\max\left[0,\left(P^{\min}_{FC}-P^i_{F-L}\right),\left(\left(\alpha_m*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}\right)\right)\right]\le P^i_{F-B}\le\min\left[P^{\max}_{Charge},\left(\left(\alpha_M*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}\right)\right)\right]$	(10)
	$P^i_{C-L}=P^i_{C-B}=0$	(11)
At anchor	$0\le P^i_{C-L}\le P^i_{Load}$	(12)
	$\max\left[0,\left(\left(\beta*\left(P^i_{Load}-P^i_{C-L}\right)\right)-P^i_{C-L}\right)\right]\le P^i_{B-L}\le\min\left[P^{\max}_{Discharge},\left(P^i_{Load}-P^i_{C-L}\right)\right]$	(13)
	$P^i_{F-L}=P^i_{Load}-\left(P^i_{C-L}+P^i_{B-L}\right)$	(14)
	$\max\left[0,\left(P^{\min}_{FC}-P^i_{F-L}\right),\left(\left(\alpha_m*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}\right)\right)\right]\le P^i_{F-B}\le\min\left[P^{\max}_{Charge},\left(\left(\alpha_M*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}\right)\right)\right]$	(15)
	$\max\left[0,\left(\left(\alpha_m*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}+P^i_{F-B}\right)\right)\right]\le P^i_{C-B}\le\min\left[\left(P^{\max}_{Charge}-P^i_{F-B}\right),\left(\left(\alpha_M*P_{Battery}\right)-\left(SOC^{i-1}-P^i_{B-L}+P^i_{F-B}\right)\right)\right]$	(16)

constrained and have a completely unknown search space [28]. So, by considering the large number of constraints in this article, which are explained in the following section, beside the novelty, the selection of ISCA algorithm for this type of problems is highly reasonable with completely acceptable results.

B. Constraints

One of the important differences of ships' energy management in comparison with other situations is about the high complexity of the energy management's constraints. These complexities come from the time and location-based limitations of refueling, the location-based differences in power generation profile, and etc.

All the constraints that rule over this problem are presented in Table II [see (8)–(16)]. The explanations related to these constraints are presented in this section.

1) Power Supply Constraint: Based on the power supply constraint, the value of the loads and the summation of generated powers in each hour must be equal. This constraint is analyzed in two different states. In "on sail" state, the loads are supplied only by fuel cells and batteries. At first, a part of the loads is supplied by fuel cells (P^i_{F-L}) in its allowed range according to (8). Then, the remaining loads are supplied by batteries (P^i_{B-L}) according to (9). In the "at anchor" state, besides the fuel cells and batteries, the cold-ironing can be used to supply the loads too. Therefore, the parts of the loads are supplied by cold-ironing (P^i_{C-L}) and batteries (P^i_{B-L}) in their allowed ranges according to (12) and (13). After that, the fuel cell power (P^i_{F-L}) is used to supply the remaining loads following (14).

2) Batteries' Maximum Charge and Discharge Constraints: Batteries have limitations in the amount of charge and discharge in a period of time. As mentioned earlier, these limitations are modeled by $P^{\max}_{\text{Charge}}$ and $P^{\max}_{\text{Disharge}}$. The term $P^{\max}_{\text{Charge}}$ in (10), (15), and (16) shows the constraints of maximum battery charge by fuel cells and cold-ironing. Moreover, the term $P^{\max}_{\text{Disharge}}$ in (8) and (13) represents the constraints of maximum battery discharge to the loads.

3) Batteries' Overcharge and Overdischarge Constraints: In order to avoid overcharge and overdischarge of the batteries, two coefficients α_M and α_m are defined, respectively. So, the term $\alpha_m * P_{\text{Battery}}$ in (10), (15). and (16) guarantees the system to avoid overdischarge of batteries with charging them by fuel cells or cold-ironing. Also, the overcharge phenomenon is prevented by term $\alpha_M * P_{\text{Battery}}$ in (10), (15), and (16).

4) Fuel Cells' Maximum and Minimum Power Constraints: In order to apply these constraints, two parameters $P^{\min}_{\text{FC}}$ and $P^{\max}_{\text{FC}}$ are defined here. Hence, these two parameters in (8), (10), and (15) certify that the power outage of fuel cells stays in their allowed range.

5) Constraint of Different Dynamics of Fuel Cells and Loads: It has been said that one of the reasons for using batteries with fuel cells is to fix the problem of fuel cells' slow dynamic response. For this purpose, the parameter β has been defined as a percentage of the loads, which is supplied by batteries or cold-ironing. So, the term $(1-\beta) * P^i_{\text{Load}}$ in (8) and (13) guarantees that at least β percentage of loads remains for batteries or cold-ironing.

6) Constraint of H_2 Tank: This constraint is modeled as a penalty function in the cost function of the optimization problem.

C. Cost Function

The cost function of the problem covers the summation of energy resource costs and the penalty function of the H_2 tank constraint. Because of the different energy resources in "on sail" and "at anchor" states, two individual cost functions are defined for each state. Based on energy resources in each state and the penalty of H_2 tank constraints (PF_{H_2}), the cost function is presented as follows:

$$\text{cost}^i = \begin{cases} \text{cost}^i_{\text{fuel cell}} + \text{cost}^i_{\text{battery}} + \text{PF}^i_{H_2} & \text{on sail} \\ \text{cost}^i_{\text{fuel cell}} + \text{cost}^i_{\text{battery}} & \\ \quad + \text{cost}^i_{\text{cold-ironing}} + \text{PF}^i_{H_2} & \text{at anchor} \end{cases}. \tag{17}$$

Algorithm 1: The Pseudo-Code of the ISCA Algorithm.

```
begin ISCA algorithm main
    initialize a set of search agent
    while t<T
      evaluate each search agent by the objective function
      update the best solution obtained so far
      for each search engine
        update the position of the search agent
      end
      perform the harmony search and wavelet mutation
       operators
      update the search agent
    end
    return the best solution so far
end
```

V. Numerical Results

In this article, the power management problem is modeled in MATLAB R2014a software. The experimental steps used in MATLAB are as follows.

Step 1: Define the optimization parameters and the objective function.

Step 2: Specify the allowed searching space for all the parameters.

Step 3: Determine the random initial agents (by considering the impressibility of some parameters, such as SOC, from the previous situation [see (10), (15), and (16)], the determination is done hour by hour);

Step 4: Calculate the objective function for all the agents.

Step 5: Update the agents by the ISCA's equations.

Step 6: Check out the parameters to be in the permissible range (hour by hour).

Step 7: Back to the fourth step until the convergence condition is satisfied.

Step 8: choose the best solution as the optimal energy management plan.

The settings of all parameters are presented in Table III.

The power dispatch results, including the contributions of each energy resources in load supply as well as the total loads in each hour, are presented in Fig. 6. The figure shows that all loads in each hour are completely supplied; so, the optimization could correctly satisfy the power supply constraint.

The ship's attendance time on points "A" and "B" (with cold-ironing points) is in mid-peak or off-peak hours. As a result, the energy cost of the cold-ironing is almost equal or less than fuel cells' energy cost. Therefore, in order to avoid the lack of the H_2 in on sail state, the optimization method decided to use cold-ironing energy instead of the fuel cells on points "A" and "B" and keep the H_2 for the next sailing.

The power profile of the fuel cells in 24 hours is presented in Fig. 7. The figure illustrates the hourly transferred power from fuel cells to the loads and batteries. Also, the remaining percentage of the H_2 after each hour has been shown. It can be seen that the used power of the fuel cells in each hour is

TABLE III
System Parameters

Equipment	Parameter	Value
Fuel cells	P_{FC}^{max}	700 kW
	P_{FC}^{min}	10 kW
	β	0.1
	c_f	0.15 $/kWh
	$iic_{\text{feul cell}}$	40 $/kW
	$lt_{\text{feul cell}}$	40,000 hours
Batteries	$P_{Battery}$	400 kW
	$P_{Charge}^{max} = 0.3 * P_{Battery}$	120 kW
	$P_{Discharge}^{max} = -0.3 * P_{Battery}$	-120 kW
	α_m	0.3
	α_M	0.9
	η_c	85%
	η_d	100%
	c_b	0.06 $/kWh
	iic_{battery}	17.8 $/kWh
	lt_{battery}	1460 cycles
Cold-ironing	ρ_{on}	0.32 $/kWh
	ρ_{mid}	0.16 $/kWh
	ρ_{off}	0.07 $/kWh

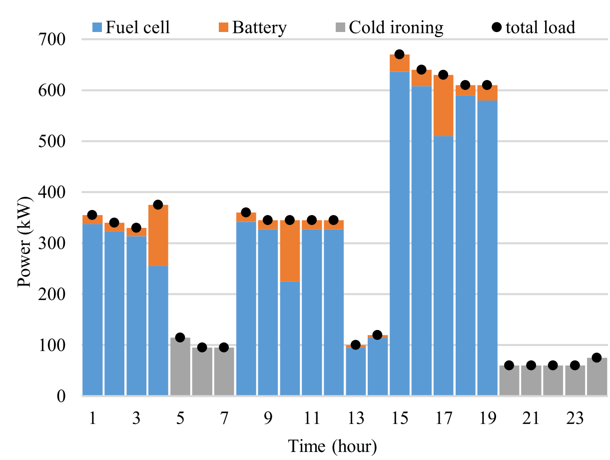

Fig. 6. Power dispatch of 24 hours.

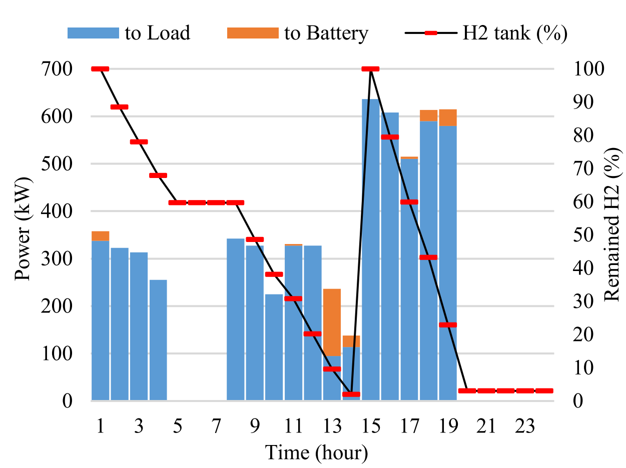

Fig. 7. Power profile of fuel cells and remained H_2 in 24 hours.

TABLE IV
COMPARATION OF TOTAL COST AND EMISSION FOR DIFFERENT ENERGY SYSTEMS

Equipment	Operation cost ($/day)	Investment cost ($/day)	Total cost ($/day)	Emission (g/kWh)
Proposed system	**~ 1150**	Batteries: 7.4 Fuel cell: 11.2 **Total: 18.6**	**~1168.6**	**0**
Diesel generator	~ 1020	Diesel generator: 13.9	~ 1033.9	13.5
Diesel generator + battery	~ 1110	Diesel generator: 9.6 Batteries: 6.6 Total: 17.2	~ 1127.2	12

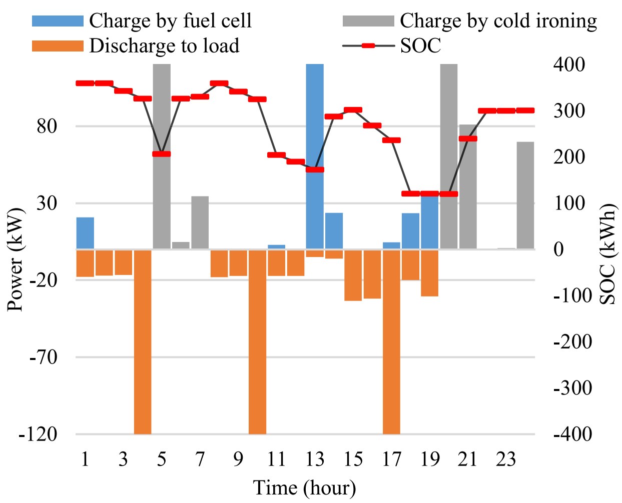

Fig. 8. Power profile and SOC of batteries in 24 hours.

in its allowed range. Also, the optimization problem accurately utilized fuel cell's power to avoid the lack of the H_2 at the time of sailing. H_2 completion at the end of hour 14th shows the refueling in point "C."

The 24-hour battery power profile is shown in Fig. 8. The battery charge by fuel cells and cold-ironing, battery discharge to loads, and the SOC of batteries are presented here. The maximum charge and discharge in each hour are 120 kW, which is equal to 30% of the total battery power. It shows that the batteries' maximum charge and discharge constraints are satisfied. On the other hand, the SOC of the batteries just changes between 120 and 360 kW, which shows that the batteries do not enter in overcharge and overdischarge states.

In order to validate the efficiency and performance of the proposed energy system, it is compared with the following two other energy systems:

1) the current energy system of the boat based on the diesel generator;
2) the diesel boat with a storage energy system based on batteries as energy storage devices.

It is not required to have energy management in the first scenario since it has only one energy supplier, diesel generator, which is able to provide all loads with electric power.

In the second scenario, the existence of the battery storage system makes it possible to use a smaller diesel generator. In this system, the batteries are charged in low-peak times and then the storage power in batteries helps the diesel generator in high-peak times. This combination can help to increase efficiency and reduce emissions.

In both these scenarios, the ability to connect to the onshore network and the mandatories of using the cold-ironing energy for nonzero-emission ships is considered.

The results of the proposed method and two other compared scenarios are presented in Table IV, which include the costs (operation and investment costs) and emission of three systems.

Based on Table IV, the proposed method has a completely acceptable cost in comparison with other methods, which shows that the proposed system is highly applicable and can be the future of this industry. It should be mentioned that the presented costs in this table only cover the energy and investment costs, while there are some penalty costs for nonzero-emission ships, which are not considered here. Additionally, the efficiency of the fuel cells is getting better every day, and the strictness and penalty cost related to pollution are getting higher; so, in near future, the proposed zero-emission energy system would be more affordable than traditional systems.

VI. CONCLUSION

Based on the increasing effects of ships pollutions on the environment and the implemented preventive laws in this context, which are getting stricter every day, the necessity of assessment of all-electric zero-emission marine vessel systems is increased. In this article, the feasibility and challenges of using a zero-emission hybrid energy system in a ferry boat were assessed. In order to obtain an efficient energy system with high quality and acceptable mass and volume, a hybrid system based on the fuel cells, batteries, and cold-ironing was proposed. It was seen that the implementation of the energy management on such a hybrid energy system had a verity of constraints with a high level of complexity. In order to improve the cost optimization results, we tried to model the constraints in the form of mathematical equations in the determination and update the optimization parameters. The H_2 tanks constraint was the only one that was modeled as a penalty function. It was seen in hourly power dispatch results that the proposed energy management method correctly satisfies the constraints. Based on the results, the utilization of the proposed zero-emission hybrid energy system on the studied boat is completely applicable. Owing to the great advancement in fuel cell efficiency as well as establishing stringent regulation on environment issue, the employment of such energy systems is more likely to increase in the ship industry.

As a future subject of research, the performance and applicability of other green energy resources, such as PV and hybrid energy storage systems, can be assessed in all electric ships.

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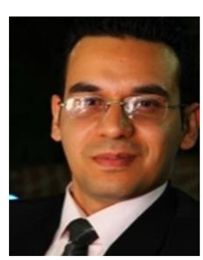

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