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ORIGINAL RESEARCH PAPER

Optimal energy scheduling of a solar-based hybrid ship considering cold-ironing facilities

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Abstract

There are many restrictions on shipping, which reduce or prohibit the use of diesel generators for feeding the energy demand of the electric ships, especially in ports. Therefore, the use of shore power system (SPS) together with renewable energies and energy storage systems (ESSs) can lead to many environmental benefits while ships are berthing in ports. In this study, the shipboard hybrid power system (HPS) is proposed, including diesel generators, solar photovoltaic panels (PV), ESS and cold-ironing (CI) facilities for using SPS to efficiently supply the ship's electrical demand. With such HPS aboard, the solar generated power is estimated accurately based on the navigation route. By optimal energy scheduling in a real hybrid cruise ship, the use of diesel generators gets minimised, due to the utilisation of PV and ESS. In addition, using CI service instead of switching on auxiliary diesel generators in ports leads to a 3 h increase in charging and discharging times of the ESS. Furthermore, the efficient use of CI service results in less use of diesel generators even at sailing hours, reducing emissions and minimising the costs of supplying ship's energy demand. The total cost reduction of the HPS in different case studies, without the use of CI services is only 1% to 2%, while this reduction is about 6% to 7% by adding the CI facilities to the HPS. Moreover, the economic characteristics of the proposed diesel-PV-ESS-CI by adding the CI facilities to the HPS are analysed and the profitability of this HPS in reducing the daily costs with considering the share of installation costs on the target day is proved.

1 | INTRODUCTION

The energy consumption of the international shipping has increased by an average of 1.6% per year between 2000 and 2015 [1]. This increasing energy demand leads to extensive use of fossil fuels, higher energy costs and greenhouse gas (GHG) emissions [2], which has become an important issue in global energy systems [3]. Therefore, the use of hybrid power systems (HPSs) including renewable energies and energy storage systems (ESSs), as well as other practical methods of power generation on the ship is a proper solution for producing energy in a cleaner and economically viable way in the shipboard power systems. These multiple energy systems reduce the dependency on conventional diesel engines and fossil fuels [4], which results in more efficient and economic operation of ships [5].

1.1 | Literature review

Nowadays, many literatures have pointed out the applicability of new technologies, including renewable energy sources (RES), ESS as well as technologies to use the shore power supply (SPS), on the improvement of the shipboard power system operation [6]. In this regard, the cost and emissions of a hybrid PV/diesel/ESS power system was studied in [7] for an oil tanker ship. In addition, the authors in [4] proposed a hybrid renewable energy system including solar photovoltaic (PV) panels, fuel cell and diesel generator to supply the electric load of a large cruise ship in such a way that the renewable fraction was increased and the equivalent CO_2 emission was reduced. Due to the fast development of renewable energy systems, a marine vessel power system with the utilising of wind turbines, solar generation, sea wave energy and ESS was considered in [8].

TABLE 1 Comparison of relevant studies with the proposed study

			Considering CI effect on		
Ref.	**PV**	**ESS**	**Sailing hours**	**Berthing hours**	**Objective of the work**
[7]	√	√	×	×	Minimising investment & fuel costs & GHGs
[11]	√	√	×	×	Minimising fuel & capital costs & GHGs
[27]	×	√	×	×	Minimising operation cost & GHGs
[28]	×	√	×	√	Power management and GHG limitation
[30]	×	√	×	√	Energy management & components sizing
[21]	√	√	×	√	Optimal power-flow dispatching, minimising cost
This study	√	√	√	√	Minimising daily & installation costs & GHGs

Among various renewable technologies, solar PV panels are widely applied in the shipboard power systems. Because, solar energy is an enormous, free and infinite source of energy which is available in almost all parts of the world [9]. It is noteworthy that the output power of the solar panels depends on the solar radiation density which mainly effected by the geographical location and the season [10]. Likewise, the generated power by an onboard PV system varies with the position and motions of the ship, the date and the time [11]. Hence, using an accurate method to predict the output power of solar panels is a determining factor in energy management of a shipboard HPS [12]. To this end, a mathematical model is proposed in [13] to predict the output power of solar panels based on the realistic local condition. In addition, the authors in [14] have used locally available data to predict solar irradiance for scheduling energy resources in remote microgrids.

On the other hand, regarding the natural variation of solar energy, ESSs can be an effective solution for enhancing the stability and reliability of a hybrid shipboard power system as well as the quality of the output power [11]. In addition, the integration of an ESS into a microgrid, leads to balancing the onboard generation and load demand [15]. The ESS charges by absorbing the surplus power during off-peak hours and helps to manage the short time power fluctuations of the microgrid by discharging in required times [16]. Accordingly, the use of an ESS in maritime transportation, enables vessels to be fast and responsive in terms of energy requirements while enhancing their manoeuverability and safety [17]. The key challenges of utilising the ESSs in the shipboard power systems have been investigated in [18]. The authors in [19] have utilised an ESS on a hybrid PV–diesel oil tanker ship to smooth the PV power fluctuations.

When ships are berthing at ports, they use their auxiliary diesel generators to supply power for hotelling, unloading, and loading activities, so they emit huge amounts of GHGs and other air pollutants [20]. Being considered as an important source of port's air pollution, the use of onboard diesel generators in ports are restricted due to strict regulations of ports to improve the local air quality [21]. The authors in [22] stated that using SPS to supply the power demand of ships at berth could be an appropriate measure for reducing air pollution in port cities. Cold ironing (CI) is a service for connecting a ship at berth to SPS in order to supply the ship's electrical demands while the ship's main and auxiliary diesel generators are switched off. Using this service can limit the emissions of ships at berth, and also may lead to a global reduction of emissions if the SPS supply the ships by the environmentally friendly energy sources [23]. For example, it is required by the California Air Resources Board that about 50% of navies received to California ports reduce the use of diesel generators by at least 50%. This reduction could be achieved by using CI service for most of their spending time in port [24].

Optimal energy scheduling of all subsystems applied on ship's power system can reduce the fuel consumption and improve the efficiency [25]. Although, various shipboard energy management methodologies have been reviewed in [26], in most of these studies, the authors have not considered all the possible energy sources in shipboard power systems. As in [27], an optimisation problem for an all-electric ship (AES) has been solved by a genetic algorithm, aiming at calculating the optimum amount of power generated by each energy supplier as well as minimising costs. However, the considered AES only includes integrated diesel generators and an ESS. In addition, a fuzzy-based particle swarm optimisation method is proposed in [28] for power management and emission reduction of a shipboard power system which includes ESS and CI facilities. An energy management system has been proposed in [29, 30] to evaluate the investment and operation costs of a zero-emission ferry ship based on fuel cells, batteries, and CI service. Optimal energy management of a maritime PV/battery/diesel/CI hybrid energy system is described as a large-scale, global optimisation problem in [21] to sufficiently use solar energy and minimise the ship's electricity cost. However, the optimisation problem has been solved for the ship that is either just at-anchor or just under-sail.

To have a clearer comparison, some of the relevant studies are given in Table 1. These studies have been classified based on the configuration of the HPS, investigating the effect of CI service as well as the methods and aims of the study.

1.2 | Contributions

According to the above reviewed literatures, there are many studies that have investigated the various sources of energy available on ships. However, in most relevant studies, the shipboard power system does not include all the appropriate technologies. Most studies have considered the marine power system consisting of only diesel generators with ESS. Some others, focused on utilising the CI services, or investigating the renewable resources on ship. Therefore, a comprehensive research is needed, in which the ship's HPS includes all the possible, practical and cost-effective energy resources and components.

On the other hand, most of these studies have emphasised on the power management of the ship through control methods. In addition, most researchers have used conventional on land methods to estimate the output power of renewable energy sources on the ship, while this power must be determined regarding to the geographic characteristics of the ship's navigation route location. Moreover in the previous literatures, the benefits of using CI services in ports have only been examined for anchored ships. In other words, the effect of purchasing power from CI service on the output power of other components of the HPS has not been investigated properly.

This study solves the optimal energy scheduling problem of a shipboard HPS considering cost minimisation as an objective. In addition to diesel generators, the proposed hybrid configuration includes solar generation system, ESS and CI service on the ship for using SPS while berthing at port. The output power of the solar system is modelled through an accurate mathematical method according to the ship's navigation route. The proposed method of calculating the hourly output power of the solar system is a comprehensive method, which is not only specific to the intended route of this study, but can be used for any other route based on its geographical specifications. As the considered ship in this study is a cruise ship, it has a significant service demand during daily tour programme even at berthing hours, which the propulsion load demand becomes zero. Therefore, the profitability of using the CI service in supplying demands both at berthing and after berthing hours has been identified through reducing the use of diesel generator system and increasing the utilisation of ESS, which leads to minimising costs. The contributions of this study can be summarised as follows:

1. A hybrid diesel-PV-ESS-CI configuration is considered to optimally supply the propulsion and service loads of an electric ship during a daily voyage.
2. The optimal energy scheduling problem of the proposed HPS is solved to minimise the costs relevant to supply energy. To this end, all the daily costs of the hybrid ship are taken into account, such as fuel, maintenance, and emission costs of the diesel generator system as well as the cost to be paid for purchasing power from CI service and the wearing costs of the components.
3. A comprehensive mathematical method is proposed to calculate the hourly output of a solar system on ship based on the daily solar radiation density in the geographical location of the navigation route. This method is applicable for any other PV system with other locations, if the geographical specifications of the considered location could be determined.
4. The effect of using CI service on the output power of the diesel generator system and the charging and discharging states of the ESS is evaluated, both at berthing and sailing hours. Consequently, the role of CI service in reducing the daily costs of the ship is clarified.
5. A sensitivity analysis is also performed to determine the impact of several variables on the total cost. Accordingly, the most effective factor in increasing or decreasing costs is identified.
6. The economic characteristics including capital expenditure (CAPEX), discount payback period and internal rate of return (IRR) of the proposed HPS are analysed. Furthermore, the profitability of the diesel/PV/ESS/CI configuration in reducing the daily costs of the ship with considering the share of installation costs on the target day has been evaluated.

The rest of the study is organised as follows. In Section 2, each component of the shipboard HPS is modelled. Section 3 presents the formulation of the optimal energy scheduling problem. In Section 4, the problem assumptions as well as the numerical results of the proposed energy scheduling method is discussed for the various energy sources available in the shipboard power system. Finally, this study is concluded in Section 5.

2 | SHIPBOARD HPS MODEL

In this section, power generation or energy exchange model for each component of the ship's HPS is described. Furthermore, the output power of each source is formulated and the constraints related to each segment are explained.

2.1 | Diesel generator system

The diesel generator system causes a significant portion of the ship's costs because of the fuel it uses to generate power. The fuel consumption of the diesel generator system per hour is a function of the hourly generated power and the rated power, which can be written as Equation (1) [31]. Moreover, the range of the hourly output power of each diesel generator is limited by Equation (2) to the minimum and maximum outputs of that diesel generator:

$$F_h^G = m \times P_h^G + n \times P^{G,ref} \tag{1}$$

$$P_{\min}^G \le P_h^G \le P_{\max}^G \tag{2}$$

Due to reliability issues, the diesel generator system should be capable of supplying the peak demand. However, it is desirable to limit the use of diesel generators which results in less pollution and fuel costs. Therefore, an HPS is recommended for supplying the shipboard electrical demand, including renewable energy system and ESS.

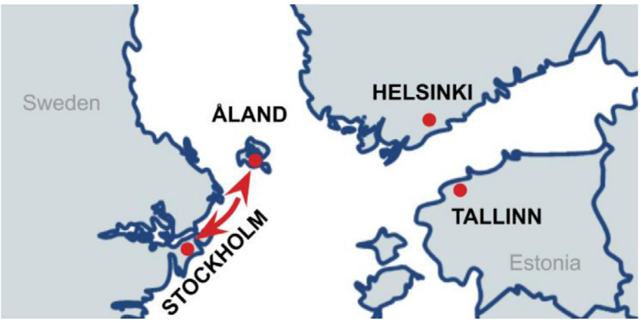


FIGURE 1 The ship's navigation route in Baltic Sea (the route is marked in red)

2.2 | Solar generation system

Given that the use of solar panels in the ship arena is more feasible than other renewable energy facilities, the solar power system is considered as another source of energy in the mentioned HPS of this study. An accurate approach for calculating the hourly output power of the solar generation system is presented below.

2.2.1 | Determining the daily solar radiation density

The amount of power generated by the solar system depends on the solar radiation, which is mainly related to latitude in addition to date, time and season [32]. The globe is divided into six zones in terms of latitude [33], in which three zones are in the north hemisphere and three are in the south hemisphere with a range of 30 degrees in latitude for each zone. Thus, depending on where the navigation route of the ship is located among the globe zones, the latitude could be determined. The considered cruise ship of this study sails daily in the Baltic Sea from Stockholm in Sweden to Mariehamn on Åland islands and vice versa [34]. Figure 1 shows the position of the ship's route in the Baltic Sea. By comparing this Figure 1 with the map of globe zones [33], it is recognisable that the route of the mentioned ship is located in zone 2 and close to zone 3. Therefore, the latitude of the ship's route assumed to be 59 degrees according to the latitude range of each zone [33]. This latitude is used to calculate the output power of the ship's solar generation system.

The daily solar radiation density for each zone can be found in [33], which is 3.72 kWh/m^{2}day in the considered zone of the ship's traveling route. Using this value, the solar radiation density per hour can be calculated as described in the following.

Given that the proposed ship is 28.6 m wide and 176.9 m long, it has an area of 5059.34 m^2 in total, where a surface area of 1500 m^2 can be used for plantation of solar panels [35]. Considering that the output power of PV panels depends on the solar radiation density, it can be estimated that for the considered solar system with about 1500 m^2 surface and efficiency of 20%, at least 1 MW daily output power can be achieved. Hence, the solar power system can be a profitable source in ship for supplying the load demand of a daily tour programme.

2.2.2 | Calculating the hourly output power of the solar generation system

As mentioned earlier, the amount of power generated by the solar panels in each hour is dependent on the hourly solar radiation density. Equation (3) presents the relationship between them [33, 36]:

$$P_h^{PV} = \sigma_\theta \times \sigma_\kappa \times \eta^{Inv} \times \eta^{PV} \times S^{PV} \times G_h \tag{3}$$

Accordingly, to calculate the output power of solar generation system, the total surface of the ship covered by the PV panels and the efficiency of the solar generation system plus the hourly solar radiation density must be determined. It is noteworthy that σ_κ is the dirtiness coefficient of the upper surface of PV panels, which is taken as 0.93 in this study. Furthermore, σ_θ= 0.9 is the coefficient related to temperature that is evolved on the PV panels [33]. Moreover, η^{Inv}refers to the efficiency of the inverter which converts the DC power from the solar system to AC power and considered 94% in this study [4].

Equation (4) is used to calculate the efficiency of the PV panels [37], where $\eta^{PV,ref}$ denotes the solar panels reference efficiency, and η^T refers to the tracker efficiency, which is assumed to be 1:

$$\eta^{PV} = \eta^{PV,ref} \times \eta^T [1 - \tau(T^C - T^{C,ref}] \tag{4}$$

Other effective parameters in calculating solar system efficiency are solar panels temperature coefficient τ and solar panels reference temperature $T^{C,ref}$, which are taken 0.048 and 25°C, respectively [38]. In addition, solar panels temperature T^C is modelled by (5):

$$T^C = T^a + \left[\frac{(NOCT - 20)}{800}\right] G_h \tag{5}$$

Given the above equation [38], solar panels temperature T^C depends on ambient temperature T^a and normal operating cells' temperature $NOCT$, which are taken 25 and 45°C, respectively. In addition, the hourly solar radiation density G_h can be calculated as follows [39], from the daily solar radiation density G_d, which is obtained in the previous subsection:

$$\frac{G_h}{G_d} = \frac{(\pi/24)(\cos\delta - \cos\omega)}{\sin\omega - (2\pi\omega/360)\cos\omega} \tag{6}$$

where ω is the sunset hour angle and δ is the hour angle, which expresses the angular displacement of the sun from the local point and is related to the apparent solar timeAST as following [40, 41]:

$$\delta = 15(AST - 12) \tag{7}$$

$$AST = LST + ET + \left(4\frac{\min}{\deg}\right)[LSMT - L_{lo}] \tag{8}$$

$$LST = LT + T_c/60 \tag{9}$$

$$T_c = 4(L_{lo} - LSMT) + ET \tag{10}$$

$$LSMT = 15^{\circ} \times t_{GMT} \tag{11}$$

where LST is the local standard time and LT is the local time. Moreover, the local standard meridian time $LSMT$ is given by Equation (11) based on time zone in GMT [41].

The equation of time ET is expressed in Equation (12) [41] which denotes the difference between apparent and mean solar times at a given longitude L_{lo}. The longitude around the navigation route of this study is about 19 degrees.

$$ET = 9.87\sin(2\beta) - 7.53\cos(\beta) - 1.5\sin(\beta) \tag{12}$$

$$\beta = 360(d - 81)/365 \tag{13}$$

where in Equation (13) [34] d is the number of days passed in a given year up to the considered date. On the other hand, the sunset hour angle ω, that is, the hour angle at which the sun sets in the west, can be formulated as below [41], where λ is the latitude and is equal to 59 degrees according to the previous subsection. Moreover, the solar declination angle α is given by Equation (15) [40].

$$\omega = \cos^{-1}(-\tan\lambda\tan\alpha) \tag{14}$$

$$\alpha = 23.44\sin\left[360\left(\frac{d-80}{365.25}\right)\right] \tag{15}$$

By the replacement of the obtained hourly solar radiation density and the efficiency of the solar energy system in Equation (3), the amount of solar power generated per hour can be calculated. Note that the power generation range of the solar panels is expressed by Equation (16) [34]:

$$0 \le P_h^{PV} \le P_{Max}^{PV} \tag{16}$$

The steps of calculating the hourly output power of the solar system in each sea voyage with a specific route location can be summarised as the flowchart shown in Figure 2.

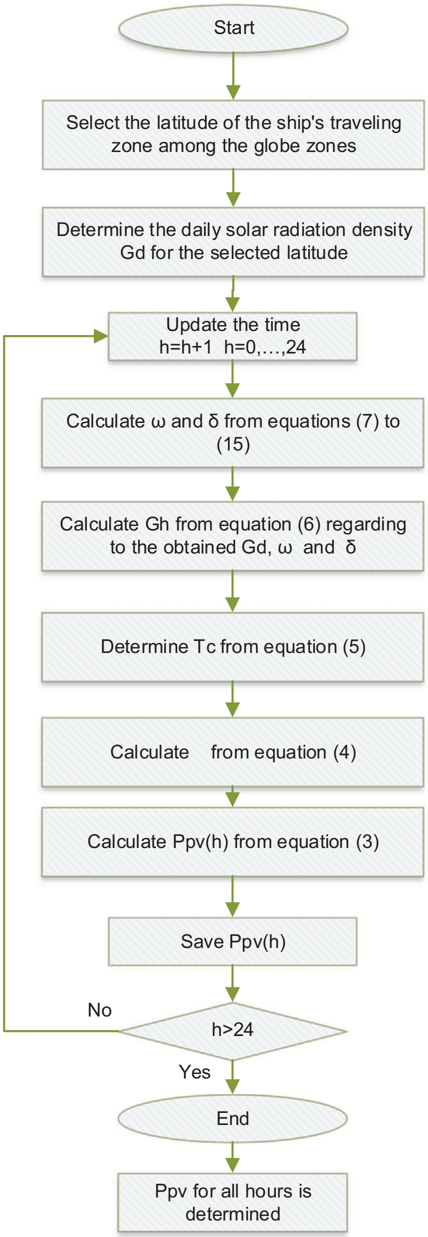


FIGURE 2 Flowchart of the proposed algorithm for calculating the hourly output power of solar panels

2.3 | CI service

There may be several ships in port at the same time and wishing to use the CI service, so there should be a limitation on the amount of purchased power from the CI service. This limitation is stated by Equation (17) and ensures that the power balance constraint of the SPS is satisfied. The amount of this power varies for different ports and different types of ships.

$$P_h^{CI} \le \upsilon_h P_{\text{Max}}^{CI} \tag{17}$$

$$\upsilon_h = 0, h \in h_{sailing} \tag{18}$$

In Equation (17), a binary variable is used to identify the berthing hours of the ship at port where it is possible to use SPS. When the ship is at sea (i.e. during sailing times $h_{sailing}$), the binary variable υ_h is set to zero as in Equation (18) as CI facilities are no longer available.

In this study, the price of electricity sold by the CI service while ships are at port is modelled according to the time of use (TOU) scheme. Thus, a high price for peak periods, an average price for standard periods and a low price for off-peak periods are defined below [42]:

$$\kappa_h^{CI} = \begin{cases} \kappa_p^{CI}, & h \in [7,10) \cup [18,20) \\ \kappa_s^{CI}, & h \in [6,7) \cup [10,18) \cup [20,22) \\ \kappa_o^{CI}, & h \in [0,6) \cup [22,24) \end{cases} \tag{19}$$

2.4 | ESS

Due to the volatility of PV generation and ship movement, the use of an ESS is essential for the proposed HPS. The ESS is charged through the surplus power generated by the solar system and diesel generators. When the ship is berthed at port, the shipboard operator may also purchase power from the SPS to charge the ESS if the price offered by the CI service is affordable. On the other hand, discharging the ESS to supply the peak load demand improves the efficiency and reliability of the HPS.

Equation (20) expresses the energy state function of an ESS [43]. Accordingly, the energy stored in the ESS per hour depends on the input and output energy as well as the stored energy at the previous hour and also the characteristics of the storage system, including efficiency. In addition, Equation (21) [43] denotes that the energy stored in the ESS at hour h should be limited to a certain range due to some technical considerations.

$$E_{h+1}^{ESS} = \left(E_h^{ESS} \times \eta^{SE}\right) + \left(E_h^{ESS,in} \times \eta^{ESS}\right) - \left(\frac{E_h^{ESS,out}}{\eta^{ESS}}\right) \tag{20}$$

$$E_{Min}^{ESS} \le E_h^{ESS} \le E_{Max}^{ESS} \tag{21}$$

The input and output energy of the ESS during charging and discharging states at each hour is limited by Equations (22) and (23), respectively [43]. The binary variables Ψ_h^{in} and Ψ_h^{out} are defined for the charge and discharge modes. Equation (24) [43] is considered to avoid simultaneous charging and discharging:

$$E_h^{ESS,in} \le \Psi_h^{in} \times E_{Max}^{ESS,in} \tag{22}$$

$$E_h^{ESS,out} \le \Psi_h^{out} \times E_{Max}^{ESS,out} \tag{23}$$

$$\Psi_h^{out} + \Psi_h^{in} \le 1 \tag{24}$$

3 | OPTIMAL ENERGY SCHEDULING PROBLEM

3.1 | Objective function

In order to supply the electrical demand of the proposed electric ship by the various energy sources in a cost-effective way, the objective function of the energy scheduling problem is formulated as below considering different technical constraints of the shipboard HPS:

$$\text{Min} \sum_{h=1}^{24} \left\{ FC_h^G + EC_h^G + MC_h^G + PC_h^{CI} + WC_h^{HPS} \right\} \tag{25}$$

where

$$FC_h^G = PF \times \left(m \times P_h^G + n \times P^{G,ref}\right) \tag{26}$$

$$EC_h^G = PE \times \left(m \times P_h^G + n \times P^{G,ref}\right) \tag{27}$$

$$MC_h^G = PM \times \left(m \times P_h^G + n \times P^{G,ref}\right) \tag{28}$$

$$PC_h^{CI} = \kappa_h^{CI} \times P_h^{CI} \tag{29}$$

$$WC_h^{HPS} = \left(w_{ESS} \times E_h^{ESS,out}\right) + w_O \tag{30}$$

According to Equation (25), the total cost includes fuel, emission and maintenance costs of the diesel generator as well as the cost to be paid for the power purchased from the CI service and the wearing cost of the HPS. Considered costs for the diesel generator system depend on the output power of the diesel generator and its rated power. In addition, PF, PE and PM are the diesel generator fuel price, emission and maintenance coefficients, respectively [43]. Moreover, m and n are the coefficients of the diesel generator fuel consumption curve.

The cost to be paid for purchasing power from the CI service during berthing hours is also affected by the objective function. Purchase cost is stated in Equation (29) [44] which depends on the electricity price provided by the CI service and the amount of purchased power per hour.

Furthermore, the wearing cost of the HPS is considered in Equation (30) [42]. The first term of the wearing cost w_{ESS} denotes the battery wearing cost and the second term $w_O$represents the hourly wearing cost of other components of the shipboard HPS. In this study, w_{ESS} and w_O are considered as 0.001 and 0.002, respectively [45].

3.2 | Constraints

The above mentioned objective function should be solved subjected to all the constraints related to the different components of the HPS. Thus, the constraints of the considered HPS, including all the equations related to the diesel generator system, solar generation system, ESS as well as CI service, which are expressed separately in the previous subsection from Equations (1) to (24) must be satisfied for solving the optimal energy scheduling problem.

3.2.1 | Power balance constraint

Due to the reliability issues and to satisfy ship's hourly load demand, the power balance of the shipboard HPS must be fulfilled as described in the following:

$$P_h^G + P_h^{PV} + P_h^{CI} + E_h^{ESS,out} - E_h^{ESS,in} - P_h^{load} = 0 \tag{31}$$

3.2.2 | GHG emissions constraint

To evaluate the GHG emissions caused by fuel consumption in the proposed hybrid ship, Energy Efficiency Operational

Indicator ($EEOI$) must be determined. As stated by Equation (32) [46], $EEOI$ is a suitable tool for measuring the ratio of the mass of CO_2emitted to the environment per the transport work of the ship.

$$EEOI = \frac{m\mathrm{CO}_2}{\text{transport work}} \tag{32}$$

It is obvious that GHG emissions are proportional to the fuel consumption of the diesel generator system, which is expressed by Equation (1). In the other words, the math of the emitted CO_2 can be calculated using a conversion coefficient c_i from the amount of fuel consumed by the i-th diesel generator [46]. $EEOI$ can be estimated as Equation (33) [25] within the time interval ΔT_j:

$$EEOI_{j,s} = \frac{\sum_i c_i \times F^G(P^G)_{ij}}{LF \times V_j} \tag{33}$$

$$V_j = \frac{Dj}{\Delta T_j} \tag{34}$$

where $F^G(P^G)_{ij}$ determines the fuel consumption of the i-th diesel generator during time interval j. Moreover, V_j is the ship average velocity which is obtained from the traveled distance Dj during time interval ΔT_j [25]. On the other hand, ship loading factor (LF) estimates based on the type of the examined ship. For passenger or cruise ships, LF is formulated as Equation (35) [25].

$$LF = \frac{PayLoad_{actual}}{PayLoad_{nom}} GT = \frac{n'_p.0.1 + n'_v}{n_p.0.1 + n_v} GT \tag{35}$$

where n'_p is the number of passengers, n_p maximum number of passengers, n'_v is the number of carried vehicles and n_v is the maximum number of the carried vehicles. Moreover, GT is ship gross tonnage. However, for the cruise ships LF is usually calculated based on the passenger capacity utilisation [47].

The following constraint must be considered in solving the energy scheduling problem of the proposed hybrid ship in order to limit the ship's GHG emissions under a certain amount:

$$\frac{\sum_i C_i \times F^G\left(P^G\right)_{ij}}{LF \times V_j} \leq EEOI_{\max} \tag{36}$$

3.3 | Economic assessment

Although the shipboard power system has been equipped with other energy components to reduce the ship's daily cost, these equipment have undeniable investment costs. Therefore, the impact of these installation costs on the amount of daily cost as well as the IRR is estimated in the following.

3.3.1 | The impact of installation costs on daily cost

To evaluate the impact of installation costs of the components on the ship's daily cost, the objective function can be rewritten as Equation (37) in the following, subjected to all the mentioned constraints of the HPS. In addition, the installation costs of the PV and ESS including both the investment and replacement costs can be calculated from Equations (38) and (39) [7]. Moreover, the cost to retrofit the vessel is stated by C^{CI}_{Ret}, which can be determined according to maximum considered capacity for the CI service.

$$\begin{aligned} \operatorname{Min} \sum_{h=1}^{24} & \left\{ FC_h^G + EC_h^G + MC_h^G + PC_h^{CI} + WC_h^{HPS} \right\} \\ & + \left(C_{INST}^{PV} \times CRF^{PV} \right) + \left(C_{INST}^{ESS} \times CRF^{ESS} \right) \\ & + \left(C_{\mathrm{Ret}}^{CI} \times CRF^{CI} \right) \end{aligned} \tag{37}$$

where

$$C_{INST}^{PV} = P_{Max}^{PV} \times \left(C_{INV}^{PV} + C_{REP}^{PV} \right) \tag{38}$$

$$C_{INST}^{ESS} = E_{Max}^{ESS} \times \left(C_{INV}^{ESS} + C_{REP}^{ESS} \right) \tag{39}$$

In the above equations, CRF is the capital recovery factor of the installation costs to the target day. This factor can be calculated from Equation (40) [34], in which q and r are the number of life span of each facility and interest rate, respectively.

$$CRF = (r \times (r+1)^q) / ((r+1)^q - 1) \tag{40}$$

3.3.2 | Long-term prospects

In order to estimate the long-term profitability, net present value (NPV) can be used as an index. NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time [33]. On the other hand, the IRR is a discount rate that makes the NPV of all cash flows from a particular project equal to zero. Consequently, IRR can be obtained through solving the following equation, while NPV is set to zero [33].

$$NPV = -C_0 + \sum_{t=1}^{T} \left[\frac{F_t}{(1 + IRR)^t} \right] \tag{41}$$

where C_0 is the total initial investment costs, F_t is net cash flow during the period t, t is the time of the cash flow and T is the total considered time. In other words, the net cash flow is the profit provided by the energy saving of the PV-ESS-CI installation. Because without using this hybrid configuration, the energy should be produced by the fuel-based diesel generators. In such situation, the profit is dependent on the cost of kWh

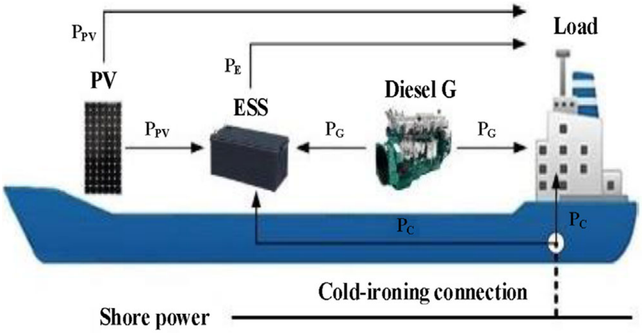


FIGURE 3 Schematic of hybrid electric ship along with cold-ironing (CI) service

produced by diesel generator system in addition to the energy produced every year by the ESS-PV-CI configuration. Therefore, the profit can be obtained from Equation (42), and the price of 1 kWh after T years is given by Equation (43) for annual fuel price increase of x% [33]:

$$\Pr(T) = \left(P^{PV}_{1-year} + E^{ESS,out}_{1-year} + P^{CI}_{1-year}\right).C_{per-kWh}(T) \quad (42)$$

$$C_{per-kWh}(T) = C_{per-kWh}(x\% + 1)^{t} \quad (43)$$

On the other hand, C_0 is calculated as follows, based on the CAPEX formula. It is noteworthy that the capital costs of PV and ESS are equal to their investment costs.

$$C_0 = CAPEX = C^{PV}_{INV}.P^{PV}_{Max} + C^{ESS}_{INV}.E^{ESS}_{Max} + C^{CI}_{\mathrm{Ref}} \quad (44)$$

4 | RESULTS

The efficiency of the proposed energy scheduling method for the various components available on the shipboard power system is evaluated in this section. The simulations are performed based on the characteristics of a real hybrid electric ship which are described as the problem assumptions in the following. By analysing the results, the efficiency of each component in supplying the ship's load demand and reducing the costs is determined. In addition, the impact of purchasing power from the CI service in reducing costs and pollution has been specified.

4.1 | Features of the shipboard power system

The structure of the proposed shipboard multiple energy system is illustrated in Figure 3 [42], which includes diesel generator system, solar energy system, ESS and CI service to supply the electrical demand. The fuel consumption curve coefficients as well as fuel price, emission and maintenance coefficients of the diesel generators are available in [7, 48]. The total capacity of the diesel generators system is 8500 kW, which is achieved by several similar diesel generators with the same characteristics.

TABLE 2 Specification of the ESS

Maximum stored energy	432 (kWh)
Minimum stored energy	216 (kWh)
Maximum charging/discharging range	1296 (kW)
Standby efficiency	98%
Charging efficiency	85%
Discharging efficiency	100%

TABLE 3 Different daily tour programmes

Tour programme	I	II
Departure from Stockholm	6:00 PM	10:00 AM
Stop at the open sea	12:00 PM to 4:00 AM	4:00 PM to 8:00 PM
Arrival to Mariehamn	6:00 AM	10:00 PM
Departure from Mariehamn	8:00 AM	12:00 PM
Arrival to Stockholm	2:00 PM	6:00 AM

On the other hand, the technical and economic specifications of the ESS are given by Table 2 [30, 43].

To carry out a more comprehensive assessment, two different tour programmes are considered in this study [34] which lead to various load profiles. According to Table 3, tour programme I is adopted for summer trips in which the trip hours have been adjusted in a way that the sailing hours does not coincide with the very hot hours of the day. Moreover, tour programme II is adopted for the ships which trips during winter days. On the other hand, the effect of the seasonal changes on the output power of the solar power generation system is also considered. It is noteworthy that the sum of the propulsion and service loads in both case studies are considered the same to compare the costs and output powers of two different conditions on the same scale.

Since the ship is considered as a cruise ship, it always has a service load demand which does not vary so much at different times of the day. However, the fluctuation of the propulsion load is much higher due to the changes in the speed of the ship during the cruising hours according to the hourly tour programme of the ship. For instance, the ship's propulsion and service loads are shown in Figure 4 for tour programme I [49].

It should be noted that, the CI connection is only feasible when the ship is berthed at port. Accordingly, the CI service can also be added to the ship's energy sources to feed the electrical demand during berthing hours. The CI service is available for using shore power at the port of Stockholm, where the ship berths three hours daily [50]. The maximum power which the CI service provides to any cruise ship is estimated to be 6000 kW in this study [51]. Therefore, within berthing hours at this port, the option of using the shore power has also been added to the ship's power suppliers. The following values are chosen as the TOU electricity prices provided by the CI service at any given

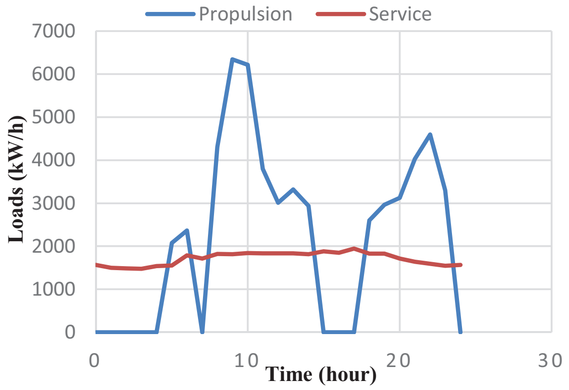


FIGURE 4 Shipboard propulsion and service loads in tour programme I

TABLE 4 Different case studies

Case studies	Tour programme	Season	CI price ($/kW)	Connected hours to shore power system (SPS)
Case #1	I	Summer	0.08948	3-5 PM
Case #2	II	Winter	0.22538	7-9 AM

time period [42]

$$\kappa_h^{CI} = \begin{cases} 0.22538\$/\text{kW}, & h \in [7,10) \cup [18,20) \\ 0.08948\$/\text{kW}, & h \in [6,7) \cup [10,18) \cup [20,22) \\ 0.04858\$/\text{kW}, & h \in [0,6) \cup [22,24) \end{cases}$$

Regarding Table 3, in tour programme I, the ship arrives at the port of Stockholm at 2:00 PM. Then, the operator of the ship can apply for using CI service until 6:00 PM in which the ship departs from Stockholm. Therefore, the operator of the ship intends to purchase power from SPS during standard hours. Consequently, in tour programme II, the ship arrives at Stockholm at 6:00 AM and leaves from there at 10:00 AM. Therefore, CI service is used in this tour programme during peak hours of the SPS.

According to the assumptions above, two case studies are applied in this study to have an accurate estimation based on various seasonal conditions, tour programmes and electricity prices. Table 4 summarises the features of these two case studies.

The aim of the optimal energy scheduling problem for the mentioned HPS is to minimise the overall costs of supplying the shipboard energy demand, which is solved as a mixed integer linear programming model (MILP) by utilising the CPLEX solver in the General Algebraic Modelling System (GAMS) software, considering all the equations and assumptions mentioned in the previous section.

GAMS is a high-level modelling software which is used to accurately analyse and easily solve the large dimension and complex mathematical and optimisation problems [52]. CPLEX is a GAMS solver that combines the high level modelling capabilities of GAMS with the power of CPLEX optimisers which are able to solve large and difficult problems quickly and with minimal user intervention. While various solving options are available, CPLEX automatically calculates and sets most options at the best values for specific problems [53]. Although there are other effective solvers such as XPRESS and Gurobi, this study is focused on CPLEX because of its unique features in solving the MILP problems [54].

4.2 | Cost comparison of different configurations of shipboard power systems

To evaluate the efficiency of the proposed HPS in providing propulsion power and service load, the ship's energy scheduling problem is solved for a diesel generator-only power system and also for an HPS including diesel generator, ESS and solar energy system to determine the optimal combination in terms of costs. Furthermore, this problem has been resolved with adding the feasibility of connecting the ship to the CI service at the berthing hours to reveal the impact of using CI services on the performance of other segments of the HPS as well as energy supplying costs.

The daily cost of the considered shipboard power system in accordance with the objective function written in Equation (25) consists of several costs. Therefore, in addition to the total cost of supplying electrical demand, the costs associated with the diesel generator system, including fuel, emission and maintenance costs as well as wearing costs and purchasing costs, are also compared in Table 5 and Figure 5 for the different types of power systems intended for the ship in one-day period of case studies 1 and 2.

Note that the purchase costs as well as the wearing costs are much lower than other costs. Therefore, their values are not well shown in Figure 5 in contrast to thousand of US dollars of diesel generators and total costs. Thus, Table 6 gives all the costs for different case studies clearly.

According to Table 5 and Figure 5, the following results can be obtained:

(i) By adding the PV panels and ESS to the diesel-only power system, the total daily cost of the ship has been reduced about $1674 and $836 in cases #1 and #2, respectively. In addition, this reduction is clearly seen in the fuel, maintenance and emission costs separately.
(ii) The difference between the amounts of cost reduction through hybridisation in cases #1 and #2 is due to the various amounts of solar radiation in summer and winter. As case 2 is related to winter, the output power of PV panels is less than case 1, so the diesel generator is used more. Thus, a lower reduction is observed in the total costs as well as the costs related to diesel generator systems of case 2 compared to case 1.
(iii) Adding the CI facilities to use SPS during berthing hours has significantly reduced the costs of the HPS. This reduction is evident in the total costs as well as the costs of the diesel generator system. For instance, the fuel cost of

TABLE 5 Daily cost comparison of different shipboard power systems

Cases	Configuration	Total cost ($)	Fuel cost ($)	Maintenance cost ($)	Emission cost ($)	Purchase cost ($)	Wearing cost ($)
#1	Diesel-only	77,078.824	16,515.227	4658.738	55,904.859	0	0
	Diesel-PV-ESS	75,404.154	16,156.013	4557.409	54,688.903	0	1.829
	Diesel-PV-ESS-CI	69,635.997	14,746.749	4159.873	49,918.474	805.946	4.955
#2	Diesel-only	77,078.824	16,515.227	4658.738	55,904.859	0	0
	Diesel-PV-ESS	76,242.259	16,335.971	4608.172	55,298.068	0	0.048
	Diesel-PV-ESS-CI	71,456.24	14,856.677	4190.882	50,290.586	2114.92	3.174

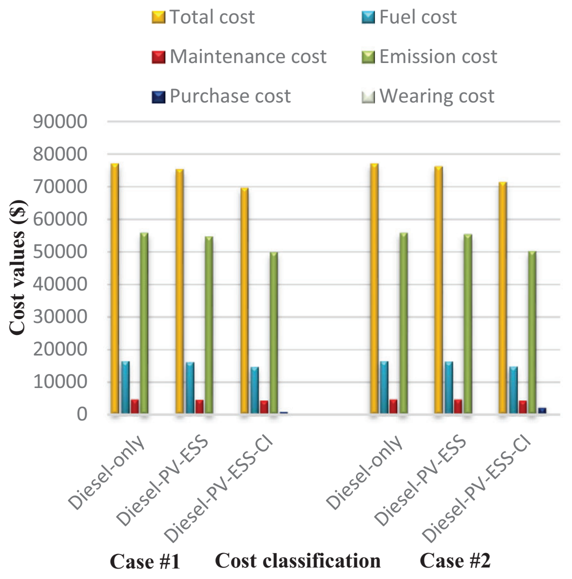


FIGURE 5 Daily cost comparison of different shipboard power systems

TABLE 6 Sensitivity analysis

Case # 1	Initial	Scenario 1 P^G + 5%	Scenario 2 $\varkappa^{CI}$ + 15%	Scenario 3 $E^{ESS,out}$ + 20%
P^G	85,931.8	90,228.4	85,931.8	85,931.8
$\varkappa^{CI}$	0.08948	0.08948	0.1029	0.08948
$E^{ESS,out}$	4906.8	4906.8	4906.8	5888.2
FC^G	14,746.7	15,481.2	14,746.7	14,746.7
EC^G	49,918.4	52,404.6	49,918.4	49,918.4
MC^G	4159.8	4367.05	4159.8	4159.8
PC^{CI}	805.9	805.9	926.8	805.9
WC^{HPS}	4.95	4.95	4.95	5.93
Total cost	69,635.9	73,063.8	69,756.8	69,636.9
Total cost changes (%)	–	4.92%	0.17%	0.0014%

case 1 has been reduced by about $359 through adding PV and ESS to the ship's power system. However, the co-operation of the CI service along with the mentioned HPS reduced the fuel cost by about $1409, which means much more cost savings.

(iv) The cost to be paid for purchasing power from CI service in case #2 is 2.5 times higher than the one for case #1 in which the price of electricity provided by the CI service is lower than case #2. This means that the total cost reduction caused by using CI facilities is much higher in case #1. However, the higher price of the CI service does not mean that it will not be affordable for the ship to use this service. Because the prices of this service for all periods of the day are considered lower than the normal prices of the shore grid to encourage ship owners to make more use of CI and reduce the use of auxiliary diesel generators with high amounts of costs and pollution.

(v) Despite the above statement, in order to reach to the minimum costs, it is better to adjust the ship's hourly tour programme in such a way that the ship can be connected to the grid during off-peak or standard hours to purchase more power from the CI service with low prices.

(vi) Moreover, the reduction in the emission and maintenance costs of the HPS equipped with the CI service are approximately 3.5 times more than the mentioned cost reductions in the HPS of case #1 without this service.

(vii) It is noteworthy that the total cost reduction by an HPS without using the CI service is only about 2% and 1% in cases #1 and #2, respectively. However, this reduction is about 7% in case #1 and 6% in case #2 through using the HPS and the CI service.

(viii) The wearing costs of battery and other components of the HPS are increased by adding the CI facilities due to more battery usage which increases the total cost. However, such incremental cost is negligible compared to the benefits gained by the use of such hybrid electrification solution.

(ix) Given the above comparisons, it can be found that the co-operation of the CI service with a renewable based HPS can leads to reducing diesel generator costs as well as the total costs. As in the two cases discussed above, using an HPS coupled with the use of CI service has reduced the ship's total costs by 9.6% and in the worst case by 7.2%. This means that using this shipboard HPS, complemented by the CI service, is an optimal and cost-effective way to supply the propulsion and service load demand of the considered ship.

4.3 | Sensitivity analysis

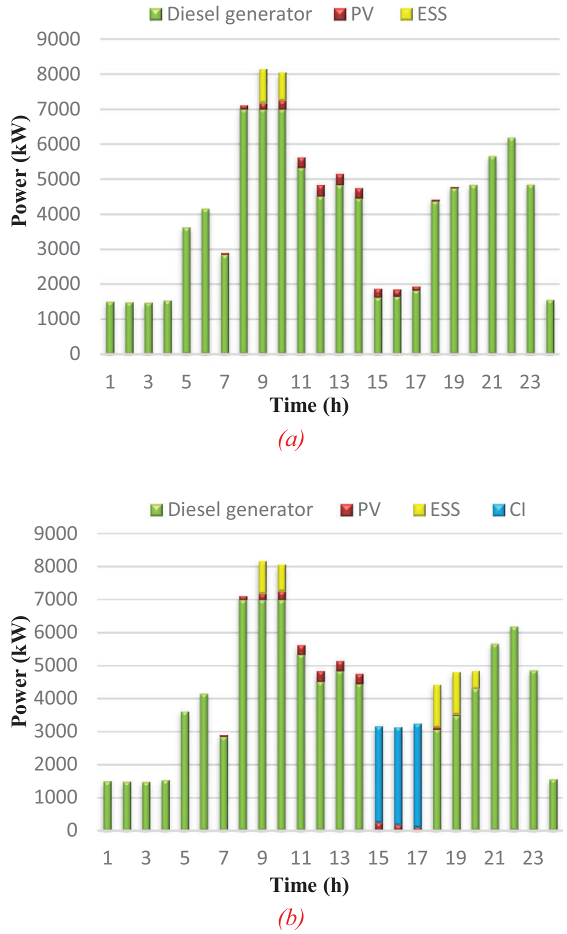
According to the objective function given in Equation (25), the total daily cost of the proposed shipboard HPS depends on several variables such as the costs related to the diesel generator system, purchase cost and wearing cost. The fuel, emission and maintenance costs of the diesel generator system are affected by the fuel consumption which is a function of the generated power. Therefore, the output power of the diesel generator system is a determining factor in calculating the diesel generator's costs as well as the total cost. On the other hand, both the price and the amount of purchased power are important in determining the purchase cost. Moreover, the wearing cost is related to the output energy of the ESS. Accordingly, the output power of the diesel generator system, the electricity price or the amount of purchased power from SPS and the output energy of the ESS are the key factors upon which the total cost depends.

The impact of each of the abovementioned variables on the total cost of diesel-PV-ESS-CI configuration for case 1 is clarified in Table 6, with the help of sensitivity analysis. It is clearly observed, the total cost of the HPS depends heavily on the output power of the diesel generator system. As in scenario 1, a 5% increase in diesel generator output power has led to a 4.92% increase in total cost. However, further changes in the price of the CI service and the output energy of the ESS do not have a significant impact on the total cost. A 15% increase in the price of the CI service in scenario 1, and a 20% increase in the output energy of the ESS in scenario 2, will only increase the total cost by 0.17% and 0.0014%, respectively. Therefore, in order to reduce the total cost, an approach must be taken to decrease the use of the diesel generator and consequently its output power. According to the results of solving the proposed energy scheduling problem in the next section, although the application of the HPS equipped with CI facilities has added the purchase and wearing costs to the total cost, it has led to a further reduction in the output power of diesel generators. As a result, due to the high dependence of the total cost on the output power of the diesel generator system, the total cost has also been decreased.

4.4 | The results of energy scheduling for the proposed HPS

Figure 6 illustrates the contribution of each component of the HPS in supplying the ship's electrical load demand in the 24-h journey scheduling of case 1. To clarify the effect of the CI service on the output power of other components (especially the diesel generator system), Figure 6(a) displays the energy scheduling of the HPS without connecting to the CI service and Figure 6(b) shows the energy scheduling of the HPS with the connection of CI service.

Since the main power source of the ship is the diesel generator system, its output power is largely dependent on the hourly load variation. As shown in Figure 6, the diesel generator output power is increased during hours 5:00–10:00 AM in which the propulsion load is also increased regarding to Figure 4.



(a)

(b)

FIGURE 6 Energy scheduling of hybrid power system (HPS)–case #1 (a) HPS without CI, (b) HPS with CI

Considering Figure 6(a), while the ship is berthed at port during hours 3:00–5:00 PM, the ship's propulsion load demand is zero but diesel generator system is still in use to supply the service load of the HPS without CI connection. Moreover, the diesel generator output power is decreased during hours 11:00 AM to 2:00 PM. This reduction is due to the increasing output power of the PV panels because of high sunlight at mid-day, in addition to low-load during these hours. Therefore, the effect of solar generation system on reducing the use of diesel generators and also decreasing the costs of HPS can be concluded. In other words, by the optimal energy scheduling of the HPS, the amount of diesel generators output power and the input or output energy of the ESS is determined, depending on the amount of load and the solar power produced per hour. Regarding Figure 6(b), in the HPS with CI service, the operator of the ship is completely switched off its diesel generators during the berthing hours at the port of Stockholm to supply energy from the most economic sources. It means that the operator is preferred to use other sources of the shipboard HPS such as CI service, rather than turning the diesel generators on, which results in high cost and pollution.

Considering the TOU electricity prices for the CI service, these three hours are within the standard range in case #1 and the electricity price is relatively low. Therefore, the ship has received considerable power from the CI service while berthing at the port of Stockholm. Although there is no restriction on the use of diesel generator, by solving the optimal energy scheduling

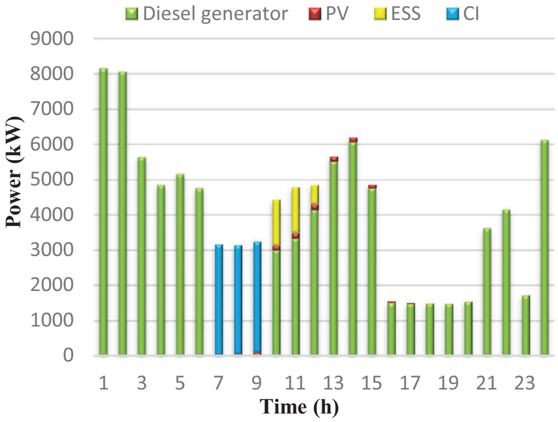


FIGURE 7 Energy scheduling of HPS with CI–case #2

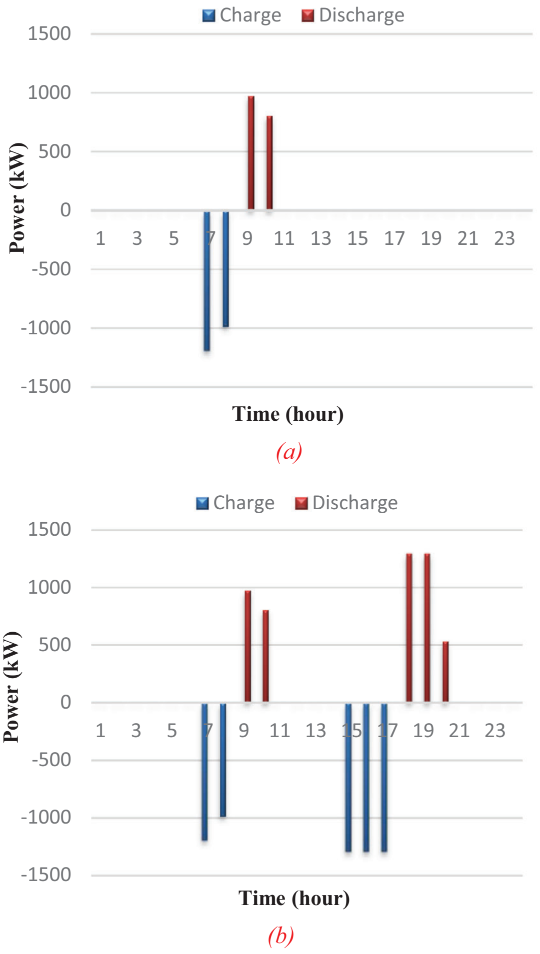
problem, there is no use of diesel generator system during ship connection hours to the CI service. Thus, it can be found that it is more economic to purchase power from the CI service at a reasonable price than to use diesel generator and pay for its various cost terms.

In addition, by comparing Figures 6(a) and (b) it is obvious that, the output power of diesel generator is also reduced at hours 6:00–8:00 PM after the ship leaves the port of Stockholm. According to Figure 6(b), due to the reasonable electricity price of SPS, the amount of purchased power from the CI service is higher than the demand required during these hours, which shown in Figure 4. This additional amount stored in the ESS and used accordingly to provide the increased propulsion load demand during the departure hours of the ship from Stockholm port. Thus, the amount of diesel generator output power and its associated costs are decreased.

It is concluded that the use of CI service in the HPS has stopped the use of the diesel generators within three berthing hours and has also decreased its usage in the next three hours with the help of ESS, which has reduced the costs associated with the diesel generator system as well as the total cost of the shipboard power system.

Furthermore, the energy scheduling of different components of the proposed HPS with connecting to the CI service is given by Figure 7 for case #2 to clarify the effect of electricity price of CI service on the amount of power purchased and also the effect of seasonal changes on the potential of solar power generation. As illustrated in Figure 7, the purchased power from CI service has not decreased in case #2 compared to case #1, despite the higher price of electricity during the ship's berthing hours in case #2. This is due to the reasonable price of electricity provided by the CI service to the ships, even at peak hours of the shore grid, in order to encourage ship owners to purchase power from the exist grid, instead of using additional diesel generators.

In addition, in case 2, similar to case 1, using CI service reduces the use of the diesel generator both during the berthing hours and in the early departure hours of the ship from port of Stockholm. Thus, the efficiency of connecting the ship to the CI service in the port is provable both for the standard and peak periods. On the other hand, the output power of the solar generation system has decreased in all hours of the day in case #2 compared to case #1, which is due to the fact that the amount of solar radiation in winter is less than in summer.



(a)

(b)

FIGURE 8 Charging and discharging states of the energy storage system (ESS)–case #1 (a) without CI, (b) with CI

4.5 | Charging and discharging states of ESS

Figure 8 represents the charging and discharging states of the ESS in the HPS of case #1, with and without connecting to the CI service, to emphasise how the ESS contributes in providing the load demand of the ship in different structures. It should be noted that the ESS behaviour is significantly affected by the amount of purchased power from CI service in addition to the power generated by the solar generation system and diesel generators, as well as the hourly load profile. As illustrated in Figure 8(a), the ESS gets charged at hours 7:00–8:00 AM, so as to be able to discharge during hours 9:00–10:00 AM, in which the propulsion load demand of the ship is very high. Thus, the impact of the ESS on supplying the energy demand of the ship is proven, especially during peak load hours. Furthermore, due to the high amount of solar power generated in the middle of the day, there is no need to discharge the storage system to supply the load demand during these hours.

On the other hand, using the CI service along with other energy sources of the HPS has increased the charging and discharging hours of the ESS according to Figure 8(b). It is obvious that by connecting the ship to the CI service at berthing hours, in addition to supplying major part of service loads by SPS during hours 3:00–5:00 PM, the shipboard operator purchases power from the CI service to charge the ESS. This enables ESS to discharge during hours 6:00–8:00 PM which helps to supply the ship's increased propulsion load demand at these hours. Consequently, using the CI service during the berthing hours has resulted in more contribution of the ESS in supplying the load demand of the ship, a reduction in the use of diesel generators and thus lower costs.

4.6 | Obtained values for *EEOI* in different configurations of the shipboard power system

To calculate the *EEOI* for the proposed hybrid ship, LF must be determined from Equation (35) based on the weight of the ship in different structures. To this end, the weight of the diesel-only cruise ship, with a capacity of 2800 passengers is considered 74,250 tons in this study [46].

For more accuracy, the weight of the added components to the shipboard power system including PV panels, ESS, and CI facilities must be considered in calculating the *EEOI* of the ship. In this study, the weight of the proposed solar generation system is 11.9 tons (based on a total of about 623 solar panels with the weight of 19.1 kg per panel) [10]. On the other hand, the ESS weights 18 tons based on the specifications stated in Table 2. Furthermore, the CI facilities have approximately 9 tons weight, regarding transformer as well as other equipment such as cable reel, shore connection switchgear and main switchboard. Therefore, the weight of considered ship reaches to about 74,279.9 and 74,288.9 tons for diesel-PV-ESS and diesel-PV-ESS-CI configurations, respectively, taking into account the weight of the added equipment. On the other hand, LF is considered to be 0.76GT (assuming $n'_p = 2150$) for the mentioned cruise ship [47].

Thus, for the diesel-only, diesel-PV-ESS and diesel-PV-ESS-CI hybrid configurations, LF is approximately 56,430; 56,452.72; and 56,459.56, respectively.

The considered cruise ship sails from Stockholm to Mariehamn and then sails back from Mariehamn to Stockholm. The sea distance between Stockholm in Sweden and Mariehamn in the Aland Islands is equal to 91 nautical mile (nm). Therefore, the navigated distance in this study is 182 nm, and its average speed is calculated about 0.012 kn/h. Moreover, the conversion coefficient c_j is considered 3.206 based on the fuel type [55].

The obtained values for *EEOI* from solving the energy scheduling problem based on the above-mentioned assumptions are given in Table 7 for different configurations. As the obtained results for *EEOI* confirm, although equipping the ship with various power generation components, has slightly increased the ship's weight, it has led to less emissions.

TABLE 7 Obtained values for Energy Efficiency Operational Indicator (*EEOI*)

Cases	Configuration	*EEOI* ($gCO_2/tn.kn$)
#1	Diesel-only	7.27
	Diesel-PV-ESS	7.11
	Diesel-PV-ESS-CI	6.48
#2	Diesel-only	7.27
	Diesel-PV-ESS	7.18
	Diesel-PV-ESS-CI	6.53

TABLE 8 Economic characteristics of the PV-ESS-CI

Facility type	Life span (year)	Investment cost ($/kW)	Replacement cost ($/kW)	Retrofitting cost ($)
PV	25	1500	1000	
ESS	15	506	506	
CI	10	–	–	550,000

By comparing the values of *EEOI* for different configurations of both cases in Table 7, it can be found that due to the reduced use of diesel generators, the fuel consumption has decreased by hybridisation of the shipboard power system, which leads to a reduction in *EEOI* values. This reduction is more evident in both cases when the HPS is also equipped with CI service. For instance, in case #2, the *EEOI* is reduced from 7.27 to 7.18 by utilising PV and ESS, while this index is decreased to 6.53 by adding the CI facilities to the HPS. This proves the effectiveness of the diesel-PV-ESS-CI configuration in reducing the pollution caused by the ship's diesel generators.

4.7 | Economic assessment results

The objective function rewritten in Equation (37) includes installation costs of PV panels, ESS and CI facilities, in addition to fuel, emission, maintenance, wearing and purchase costs. To solve this function, the economic characteristics of PV, ESS and CI service are given in Table 8 [51, 56, 57]. Moreover, the interest rate for all equipment has been considered 0.6.

The results related to the daily costs of various configurations of HPS for both case studies are represented in Table 9. Regarding to this table, it can be found that the total daily cost of the hybrid ship is decreased in both case studies compared to the diesel-only power system even taking into account

TABLE 9 Daily total costs considering the share of installation costs

Cases	Configuration	Total cost ($)
#1	Diesel-only	77,078.824
	Diesel-PV-ESS	76,204.151
	Diesel-PV-ESS-CI	70,526.469
#2	Diesel-only	77,078.824
	Diesel-PV-ESS	77,042.256
	Diesel-PV-ESS-CI	72,346.712

TABLE 10 Obtained amounts of internal rate of return (IRR) over the years for various fuel price increases

15% fuel price increase	**Years**	**1**	**5**	**10**	**17**	**21**
	IRR (%)	–87.7	–26.4	–8.02	0. 83	3.5
30% fuel price increase	**Years**	**1**	**5**	**9**	**10**	**15**
	IRR (%)	–86.**09**	–16.**8**	1.41	3.96	12
50% fuel price increase	**Years**	**1**	**5**	**6**	**7**	**10**
	IRR (%)	**–83.9**	**–4.06**	3.35	9	19.95

the share of installation costs on the target day. In addition, the CAPEX of the hybrid diesel-PV-ESS-CI has been obtained about $3,069,000 from Equation (44). On the other hand, $C_{per-kWh}$has been considered $0.066 /kWh and the average amounts of $P^{PV}, E^{ESS,out}, P^{CI}$have been estimated about 221,634; 1,445,760; 3,310,200 kWh/year, respectively, based on the daily solar radiation density [33] and the obtained results of one-day scheduling for two case studies.

Table 10 illustrates the amount of IRR over the years for 15%, 30% and 50% annual increase in fuel price (as the increase in fuel price from 1990 until 2009 is calculated to be about 15% [33], this amount in this study cannot be lower than 15%).

As it can be seen in Table 10, for the fuel price increase of 15%, the IRR will be positive after about 16 years and the discount payback period is equal to about 21 years based on the discount rate of 3.5% (the rate of return that could be earned on an investment in the financial markets with small risk). However, for the fuel price increase of 30% and 50%, the IRR will be positive in less than nine and six years, respectively. Furthermore, the payback period for the discount rate of 3.5% is estimated to be 10 years for 30% fuel price increase and six years for 50% fuel price increase.

Based on this economic analysis, it can be found that the profitability of the installations is dependent on the annual increase of the fuel price in addition to the produced power by the PV-ESS-CI configuration. In other words, the further increase of fuel price each year as well as large amounts of total power produced by PV-ESS-CI leads to the shorter payback period of the investment and higher IRR.

5 | CONCLUSION

In this study, the optimal energy scheduling problem of a hybrid shipboard power system was solved to supply the ship's electrical propulsion and service loads in an optimal and cost-effective way. The proposed hybrid configuration included diesel generators, solar generation system, ESS and the CI facilities to use shore power system (SPS), when the ship was berthed at port. The output power along with the technical and economic constraints relevant to each energy source or power system component were extracted. In addition, the hourly output power of the PV panels was calculated using a mathematical model according to the geographical location of the ship's navigation route. Moreover, the electricity prices offered by the CI service were stated for different time periods of day, and the constraints related to purchasing power from SPS were modelled. To deal with different seasons and various prices of CI service, two case studies with different tour programmes were considered, in which case #1 refered to summer with higher amounts of solar radiation and lower price of CI service due to the standard time period of use. On the other hand, case #2 refered to winter with low amounts of solar radiation and high price of CI service due to the use of SPS during peak periods.

The results obtained from solving the optimal energy scheduling problem for a cruise ship during the 24-h traveling period, indicated that the total cost of the ship was effectively reduced (about $1674 and $836 in cases #1 #2), through adding PV panels and ESS into the diesel generator-only power system. This reduction was evident in the maintenance, emission and fuel costs because of decreasing the use of diesel generators. On the other hand, connecting the ship to the CI service at berthing hours, along with using the aforementioned HPS, ended in reducing the use of diesel generators both at berthing and after berthing hours, further use of ESS, less fuel consumption as well as higher cost reduction. Furthermore, the total cost reduction gained by the HPS without using the CI service was only about 1% to 2% in different cases. However, this reduction was about 6% to 7% using the HPS together with the CI service.

In addition, the effectiveness of the proposed diesel-PV-ESS-CI configuration in reducing the GHG emissions was proved because of the reduction in $EEOI$ values due to the reduced usage of diesel generators. Therefore, it can be concluded that utilising the CI service in a shipboard HPS provided the optimal, economically efficient and environmentally friendly way of supplying the ship's electrical demand. Furthermore, the economic assessments emphasised that although utilising the hybrid configuration caused high installation costs, the total daily cost of the HPS was also decreased even with considering the share of installation costs on the target day. Moreover, regarding the increasing fuel price in the next years, the discount payback period of the proposed HPS could be decreased to about six years with the high amounts of IRR. Of course, more detailed economic analyses in the field of planning has required to determine all the long-term economic aspects of the proposed shipboard HPS.

Nomenclature

h	index for scheduling time (hour).
$P^{\mathrm{CI}}_{\mathrm{Max}}$	maximum purchased power from the CI service (kW).
$\varkappa^{\mathrm{CI}}$	electricity price of the CI service ($/kW).
η^{SE}	efficiency of the ESS.
η^{ESS}	standby efficiency of the ESS.
$E^{\mathrm{ESS}}_{\mathrm{Min/Max}}$	minimum/maximum stored energy in the ESS (kWh).
$E^{\mathrm{ESS,in}}_{\mathrm{Max}}$	maximum input energy of the ESS (kWh).
$E^{\mathrm{ESS,out}}_{\mathrm{Max}}$	maximum output energy of the ESS (kWh).
P^{load}	electrical load of the ship (kW).
T^{C}	solar panels temperature (°C).

$T^{\mathrm{C,ref}}$	solar panels reference temperature ($°C$).
η^{T}	tracker efficiency.
η^{PV}	solar panels efficiency.
$\eta^{\mathrm{PV,ref}}$	solar panels reference efficiency.
G	solar radiation density (kW/m^2).
α	the solar declination angle (degree).
S^{PV}	surface area intended for solar panels (m^2).
δ	the hour angle (the angular displacement of the sun from the local point) (degree).
ω	the sunset hour angle (the hour angle at which the sun sets in the west (degree).
$P^{\mathrm{PV}}_{\mathrm{Max}}$	maximum output power of solar panels (kW).
$C_{\mathrm{INV/REP}}$	investment/replacement costs of the components ($).
$C^{\mathrm{CI}}_{\mathrm{Ret}}$	the cost to retrofit the vessel for using CI service ($)
FC^{G}	fuel cost of the diesel generator ($).
EC^{G}	emission cost of the diesel generator ($).
MC^{G}	maintenance cost of the diesel generator ($).
PC^{CI}	purchase cost from the CI service ($).
$WC^{\mathrm{HPS}}_{\mathrm{h}}$	the wearing cost of the hybrid power system ($).
F^{G}	diesel generator fuel consumption (L).
P^{G}	output power of the diesel generator (kW).
P^{CI}	purchased power from CI service (kW).
E^{ESS}	the amount of energy stored in the ESS (kWh).
$E^{\mathrm{ESS,in/out}}$	input/output energy of the ESS (kWh).
$\Psi^{in/out}$	binary variable for charging/discharging state.
υ	binary variable for using CI service.
m,n	diesel generator fuel consumption curve coefficients (L/kW).

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