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Research Paper

Two-stage energy management framework of the cold ironing cooperative with renewable energy for ferry

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ABSTRACT

The cold ironing system is gaining interest as a promising approach to reduce emissions from ship transportation at ports, enabling further reductions with clean energy sources coordination. While cold ironing has predominantly been applied to long-staying vessels like cruise ships and containers, feasibility studies for short-berthing ships such as ferries are limited. However, the growing demand for short-distance logistics and passenger transfers highlights the need to tackle emissions issues from ferry transportation. Incorporating electrification technology together with integrated energy management systems can significantly reduce emissions from ferry operations. Accordingly, this paper proposes a cooperative cold ironing system integrated with clean energy sources for ferry terminals. A two-stage energy management strategy combining sizing and scheduling optimization is employed to reduce the port's emissions while minimizing system and operational costs. The proposed system configuration, determined through the sizing method, yields the lowest net present cost of $9.04 M. The applied energy management strategy managed to reduce operational costs by up to 63.402 %, while significantly decreasing emissions from both shipside and shoreside operations. From the shipside, emissions reductions of 38.44 % for CO_2, 97.7 % for NO_X, 96.69 % for SO_2, and 92.1 % for PM were achieved. From the shoreside, the approach led to a 28 % reduction across all emission types. Thus, implementing cold ironing powered by clean energy sources is a viable solution for reducing emissions generated by ferry operations. The proposed energy management approach enables emissions reduction and delivering cost-effectiveness at ferry terminals.

Nomenclature.

Abbreviations	
EMS	Energy management system
ESS	Energy storage system
HFO	Heavy fuel oil
MDO	Marine diesel oil
MGO	Marine gas oil
NPC	Net present cost
PV	Photovoltaic
S2S	Shore to ship
QCP	Quadratic constrained programming
Sets	
F	Set of the ferry, $F \in \{1,2,3,4,5\}$

(*continued on next column*)

(*continued*)

Abbreviations	
EMS	Energy management system
T	Set of time, $T \in \{1,2..24\}$
B	Set of building
Index	
f	Index of the ferry, $f \in F$
t	Index of time, $t \in T$
b	Index of building, $b \in B$
Variables	
TL_t	Total port load at time t (kW)
P_{PV}	Output power from PV (kW)
C_{sys}	Cost of the system ($)

(*continued on next page*)

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Abbreviations	
EMS	Energy management system
$Cost_d^{op}$	Cost of operation for day, d ($)
P_t^{grid}	Power grid purchased at time t (kW)
P_t^{PV}	Power from PV at time t (kW)
SOE_t^{ESS}	State of energy ESS at time t (kW)
$P_t^{dis,ESS}$	Power discharge from the battery at time t (kW)
$P_t^{char,ESS}$	Power charge from the battery at time t (kW)
SOE_t	State of energy of the ESS at the time t (kW)
SOE_{t-1}	State of energy of the ESS at previous time t (kW)
Parameters	
$PD_{B,t}$	Power demand from building B at time t (kW)
$PD_{L,t}$	Power demand from lighting L at time t (kW)
$PD_{CI,t}$	Power demand from cold ironing at times t (kW)
$S_{aux,t}$	Ferry auxiliary load at time t (kW)
$h_{berth,t}$	Duration of the ferry stay at the port (h)
$f_{call,t}$	Frequency of port calls at the port
δ_d	Daily perturbation value
δ_{ts}	Time step perturbation value
γ_{PV}	Rated capacity of the PV array
α	Load random variability
PL_T^{avg}	Average power load (kW)
PL_T^{peak}	Peak power load (kW)
C_{ins}^{PV}	The installation cost of PV($)
C_{ins}^{ESS}	The installation cost of ESS ($)
C_{ins}^{CI}	The installation cost of cold ironing facilities at the port ($)
C_{ins}^{ship}	The installation cost of the cold ironing power receiver at the ferry ($)
C_{ins}	Total installation cost ($)
$C_{capital}$	Cost of capital ($)
$C_{replacement}$	Cost of replacement ($)
$C_{O\&M}$	Cost of operation and maintenance ($)
RTP_t	Real-time price of the local grid at time t ($)
$load^{max}$	Maximum load (kW)
$load_t^{total}$	Total active power consumption of port terminal at time t (kW)
f_{PV}	Derating factor
$\overline{G_T}$	Solar radiation incident of the array in the current time step
$\overline{G}_{T,STC}$	Incident radiation at standard test conditions
α_P	Temperature coefficient of power
T_C	PV cell temperature in the current time step
$T_{C,STC}$	PV cell temperature under standard test condition
$l_t^{terminal}$	Load from the port terminal at time t (kW)
l_t^{CI}	Load from cold ironing at time t (kW)
P_t^{PVmin}/P_t^{PVmax}	The lower and upper bound of PV at time t (kW)
$SOE_t^{ESSmin}/SOE_t^{ESSmax}$	The lower and upper bound of state of the energy battery at the time t (kW)
$P_t^{dismin}/P_t^{dismax}$	The lower and upper bound discharge power from the battery (kW)
$P_t^{chargmin}/P_t^{chargmax}$	Lower and upper bound charging power from the battery (kW)
η_c/η_d	Charging/discharging efficiency rate (%)
Δt	Difference between the two measured times
LF	Load factor

1. Introduction

Coastal areas and ports play a crucial part in the local socio-economic development due to their role in transportation and tourism. Ports facilitating ferry services for short sea crossings act as central gateways to access various destinations. Nations bordered by major water bodies experience intense maritime traffic, with ferries, shipyards, and cruise vessels contributing significantly to high volumes of sea transportation [1]. Turkey exemplifies this scenario, surrounded by the Black Sea and the Mediterranean Sea. It receives between 23 and 41 million visitors annually, heavily relying on water-based transportation modes [2]. Although it brings economic advantages to the nation, the regular ferry journeys conducted in daily operations have a detrimental impact on the coastal areas and local environment due to the pollution emitted by the dirty fuel from the auxiliary engines of ships. Additionally, the ship's noise and vibration pollution also cause discomfort for those who are nearby. These negative environmental impacts triggered by ferry activities are a serious problem, particularly for ferry terminals in proximity to populated areas. Thus, the decarbonization of ferry ships is an inevitable action toward reducing the sector's adverse environmental impact. Due to this, a sustainable strategy for medium-sized ports and ferry ships is required to tackle the carbon footprint issue while also improving the port's operating performance.

Several decarbonization solutions have been introduced to the shipping lines including low sulfur fuel oil (LSFO) utilization, scrubber cleaning system, and cold ironing technology [3]. All these alternatives share the common goal of reducing emissions from shipping activities, but what sets them apart is their varying levels of effectiveness in eliminating emissions. Scrubber systems and LSFO utilization incapable to eliminate vibration and noise pollution, and they still permit the use of sulfur fuel oil by the ships. Meanwhile, cold ironing emerges as a transformative advancement in the maritime industry, replacing fossil fuel-powered generators with electricity-based technologies. This transition eliminates fuel, vibration, and noise pollution associated with conventional methods. Accordingly, cold ironing as a shore power system is growing in widespread acceptance as a solution for decarbonizing ships. It enables ferry vessels to power their onboard electrical loads directly from the port terminal, eliminating the need for fossil-fuel engines while berthed. However, the existing research literature on cold ironing applications primarily focuses on large terminals serving vessels with long berthing times, such as cruise ships and container ships. Limited studies are available for short berthing ship such as ferry transportation. One major obstacle to implementing cold ironing is the substantial investment cost for ship owners and port operators [4]. The high expenditure on port infrastructure upgrades and ship retrofitting poses a significant barrier to the wider adoption of the system. Due to this, ships with longer berthing durations are more favorable candidates for cold ironing installations, as it justifies the maximization of the system's usage over its expensive upfront cost. Consequently, there is an urgent need for a reliable economic strategy that avoids unnecessary expenses while ensuring that medium-sized ports and ferry operators can benefit from carbon footprint reduction practices through cold ironing.

Apart from the substantial investment costs, another challenge in employing cold ironing is the burden of purchasing electricity, particularly in areas with high electricity prices [5]. There is a necessity for an investigation into an energy solution that can meet the demand for cold ironing while reducing grid consumption and offering flexibility of energy. The concept of an energy mix incorporating renewable sources and energy storage systems, supported by an applicable energy management strategy, warrants further investigation. This approach could enable economical operational practices while enhancing the emission-free cold ironing system on both ships and shore-side facilities. Therefore, to boost the ferry terminal's carbon neutrality and reduce both system and operational costs at the port, this study proposes a port system structure that incorporates a cold ironing technology solution along with clean energy alternative at the ferry terminal, supported by an energy management system. Accordingly, this paper presents a novel two-stage energy management framework for cold ironing as a ferry charger integrated with renewable energy and storage system, with the following scientific contributions to the class of problems and methodological knowledge:

1) Providing the feasibility study of cold ironing with an innovative energy system configuration for short-berthing ferry ships at a medium-sized port terminal. The benefits of transitioning from fuel-based auxiliary engines to clean shore-side electricity energy concept are assessed in terms of environmental aspects from both the shipside and shoreside perspectives. This evaluation aims to motivate port operators and shipping lines, as the main stakeholders, to pursue sustainable implementation by validating the potential emissions benefits.

2) Development of a novel two-stage energy management system (EMS) framework that integrates: (a) System sizing for the optimal capacity of the component in the proposed system and (b) Operational optimization for economic scheduling of energy distribution. This framework tackles the challenge of high electricity costs associated with cold ironing adoption. The integrated EMS focuses on enabling economically viable and environmentally sustainable for the technology adoption of cold ironing at ferry terminal.

The rest of this research is structured as follows. Section 2 provides a literature review of the relevant studies, establishing the research context addressed in this work. Section 3 is dedicated to presenting the research methodology for the proposed system configuration and EMS framework. Meanwhile, section 4 analyzed and discussed the outcomes from the simulation result in terms of energy, financial and environmental aspects. Finally, the important findings are summarized in Section 5.

2. Literature review

The predominant gases produced by ships' burning fuel are CO_2, NO_x, SO_x, and PM, with CO_2 contributing to global climate change and the rest being harmful to people's well-being. Emissions emitted from ships depend on the fuel type used, such as heavy fuel oil (HFO), marine diesel oil (MDO), or marine gas oil (MGO), as well as the fuel's sulfur concentration (e.g. 3.5 %, 2.7 %, 0.1 %, 0.5 %). The emissions factors for each pollutant (in g/kWh) differ based on the fuel characteristics, with typical values provided in [3]. Shore-to-ship power system of cold ironing can be applied to the ferry ships as a ferry charger, allowing the ferry's onboard load to be powered directly from the port terminal and eliminating the use of fossil-fuel engines.

The study by [6] gathered a list of large ports throughout the world with cold ironing installations where most of them applied in cruise or container terminals. Cold ironing is initially focused on large port implementation with cruise and container service as a priority due to several factors. One of them is the berthing duration factor whereby long berthing at the port is favorable [7]. The experiment conducted for the cruise case study by [8] revealed that the minimum, average, and maximum berthing duration for the cruise ships consumed 4 h, 8.68 h, and 24 h, respectively. Meanwhile, depending on the volume of goods to be handled, container ships can berth for up to several days at port [9]. Berthing duration has an important influence on cold ironing usage since it suggests longer berthing periods potentially demand more shoreside electricity. The study conducted by [10] performs a data-driven approach to evaluate the energy demand from the ship generators. The correlation analysis in the study determines various factors that may influence the fluctuation of energy demand in the ship as well as reflect the required electricity from the cold ironing during the berthing mode. Additionally, longer berthing duration also implies the ship may cut the emission from its engines during that long period by switching to cold ironing power, which justifies the necessity to employ the technology. Facilitating cold ironing service in port requires high upfront costs for facility establishment and ship retrofitting. It becomes another factor for maximizing the utilization of the facilities. Due to the same rationalization, most of the existing research literature for cold ironing applications is oriented in large terminals with big ship consumption either cruise or container ship. Limited studies are available for short-berthing ferry applications, demanding further academic research to fully explore its potential.

Cold ironing's effectiveness in emission mitigation has been proven in numerous research investigations. Recent published work on shoreside power [11] compares the emission level of a berthed ship that utilized cold ironing while staying in port for three consecutive years in 2019, 2020, and 2021. The result shows that emissions have decreased considerably from 82 % in 2019, 76 % in 2020, and 50 % in 2021 due to continuing improvements in the charging system from time to time. Following the existing research literature, many cases consider power grid emission for cold ironing as it becomes the main supply to the system. It has been argued that cold ironing only resolves the emission from the ship's perspective [12]. It does not eliminate the emitted gases entirely when the pollution produced by the power plant that feeds cold ironing is considered. Hence, the emission assessment for the cold ironing case study typically compares the emission factor from the grid and the emission factor from the fuel auxiliary engines of the ship. It also implies that the actual scale of the pollution mitigated by cold ironing is largely dependent on the end source of power generation. Thus, this charging system has the potential to be improved more by incorporating renewable energy and raising its share in the energy configuration. This energy mix concept is proven practical to be used from a research study in [13], which conducted four different renewable energy capacities to feed the cold ironing range from 2100 kW to 6400 kW of photovoltaic (PV) size plant. The simulation result reveals that the maximum size of PV share eliminates the most carbon, with a total CO_2 removal rate of approximately 87.4 %. In addition, on-site renewable energy production is advantageous over a utility grid not only in terms of emissions but also in terms of energy scheduling flexibility and economic operating costs of purchasing energy [14]. Study in [15] demonstrated that integrating cold ironing with the renewable energy and energy storage system resulted in considerable daily cost savings of 7 % and less fuel use. These numerous benefits become the main motivation for this research work, which aims to boosting the ferry terminal's carbon neutrality by integrate the cold ironing technology solution with on-site renewable energy generated at the terminal and energy storage system.

One obstacle to its implementation that hinder wider adoption to the system is the high expenditure on infrastructure and retrofitting for the shipowners and port operators [4]. Highlighting the issue, a reliable strategy to avoid unnecessary expenses while guaranteeing port benefits from carbon footprint practices is demanded. One of the applicable methods is by performing a sizing technique. This is an essential technique for managing oversizing and under-sizing issues and delivering the system with the lowest net present cost (NPC) to lessen the financial burden of infrastructure expense. The study by [16] executes the sizing technique for their energy topology to maximize the system's advantages and minimize expenses. The Pareto optimal solution obtained from the simulation provides the organization with a range of investment value while ensuring the main criteria for the load is satisfied. This decision-making indicator enables the organization to invest within its budgetary constraints. Another challenge of employing cold ironing is the rise on operational cost due to the purchasing electricity expenses [5]. The operation optimization method is a commonly used approach to solve this kind of problem in the energy network. Its algorithm capable to schedule energy distribution between port demand and supply by optimally exploit the flexible nature of the energy mix in a cost-effective manner. Research study by [17] integrated quadratic constrained programming (QCP) optimization model for the cold ironing case study with four environmental dispatch strategies. The simulation findings show that, depending on the priority of the decision maker's objective function, each technique offers different benefits. Both sizing technique and optimization are modules within the energy management system (EMS) framework. The EMS is a computer-aided system that monitors and controls all unit's flow in the network in an economical, reliable, and sustainable manner. Sizing is an EMS module in determining the system's resource coordination and measuring the right capacity of the component to fulfill the load demand while minimizing its costs. In the meantime, optimization is required to ensure that the system operates at optimum state, maximizing economic benefit, while minimizing operation cost. Sizing and optimization are inextricably linked and complement each other. The proposed energy management system in this study will incorporate both sizing and optimization techniques, which will be elaborated in the subsequent section.

3. Methods

The case study is conducted on the Eskihisar-Tavşanlı ferry line, an active water transportation service operated by the Negmar company. This ferry line offers a shorter travel distance, affordable pricing, and a traffic-free mode of transportation. This waterbus is mainly used to transport automobiles and pedestrians across the Sea of Marmara. The ports handle more than 5 million passengers and 730 thousand vehicles annually including motorcycle, car, truck, bus, and pedestrian passengers. The operation is carried out 24 h a day where the ferry runs every 15 min during peak hours with up to 5 working ferries. Meanwhile, the trip runs every 1 h during off-peak hours (midnight to dawn) when only 2 ferries are operating. Fig. 1 shows the route between the two terminals and the distance is approximately 9 km. The voyage journey takes an average of 30 min one way. Both the ferry terminals at Eskihisar Port and Tavşanlı Port provide 2 berths facilities for the ferries to dock. The main power source for the port loads, particularly the building operations within the port area such as port authority's buildings, coast guard stations, and administrative offices, are supplied by the national utility grid.

The type of ship investigated in this work is the ferry ship, with its single-line structure depicted in Fig. 3. This ferry features four auxiliary diesel generators with 300 L of diesel usage on average per day to serve the onboard loads. Table 1 shows the detailed specification of the ferry. The berthing duration at each stop for loading and unloading the cars and passengers is 15 min. It requires 85 kW-90 kW for the hydraulic ramp to be rolled on and off from the ferry when in port. Meanwhile, it requires 30 kW-40 kW to maintain service load during voyage activities. The other onboard load that consumed energy during the berthing mode of operation are including the ferry's small cafeteria, lighting, communication devices, and ventilation. The power demand of these service loads varied depending on the consumption behaviors, the frequency of the trip per ship, and the time of operations. Ferries are recognized by a consistent frequency of port calls with a medium energy requirement as compared to cruise and container due to their shorter stay and fewer onboard loads [13]. This regular port calls character qualifies it for cold ironing installation. However, the traffic frequency increases slightly in summer due to high demand from tourist activities and long daylight.

3.1. The proposed framework

Waterbus operations that mainly utilize impure diesel fuel are held accountable for the deterioration of air pollutants in the port radius area. Therefore, cold ironing and green energy sources are viewed as an optimistic solution for environmental preservation. The objective of this study is to propose an electrified power solution for ferries in mitigating the emission and to demonstrate the benefits of on-site electricity generation in terms of energy, environment, and financial aspect.

The execution of the cold ironing system involves both sides of the port operator and ship owner. This is because the ship must be retrofitted with a cold ironing power receiver while the port operator is responsible for providing shore power facilities. As for the shore power infrastructure at berth, a portable container can house the cold ironing facilities equipment such as a high voltage switchboard, transformers, and cable connections. It is lightweight and consumes less space thus it does not interfere with the existing port operation. Fig. 2 (a) and (b) show the proposed cold ironing and solar installation areas at the ports of Eskihisar and Tavşanli.

The proposed solar-powered cold ironing is a grid-connected system to enhance emission neutrality and support the additional load of cold ironing. The study by [18] found that Turkey's geographical region with solar radiation amounts ranging from 3.13 to 5.26 kWh/m2/day and its sunny climate has a high potential for solar energy generation. Eskihisar Port has an open space of roughly 2800 m^2, while Tavşanli Port has an open area of approximately 960 m^2. The current function of this open space area is to serve as the parking lot for land vehicles. These areas become the potential site for solar panel installation where a high rooftop with a sunshade cover can be constructed to avoid affecting the current use of the area while also benefiting from solar power extraction for the port load.

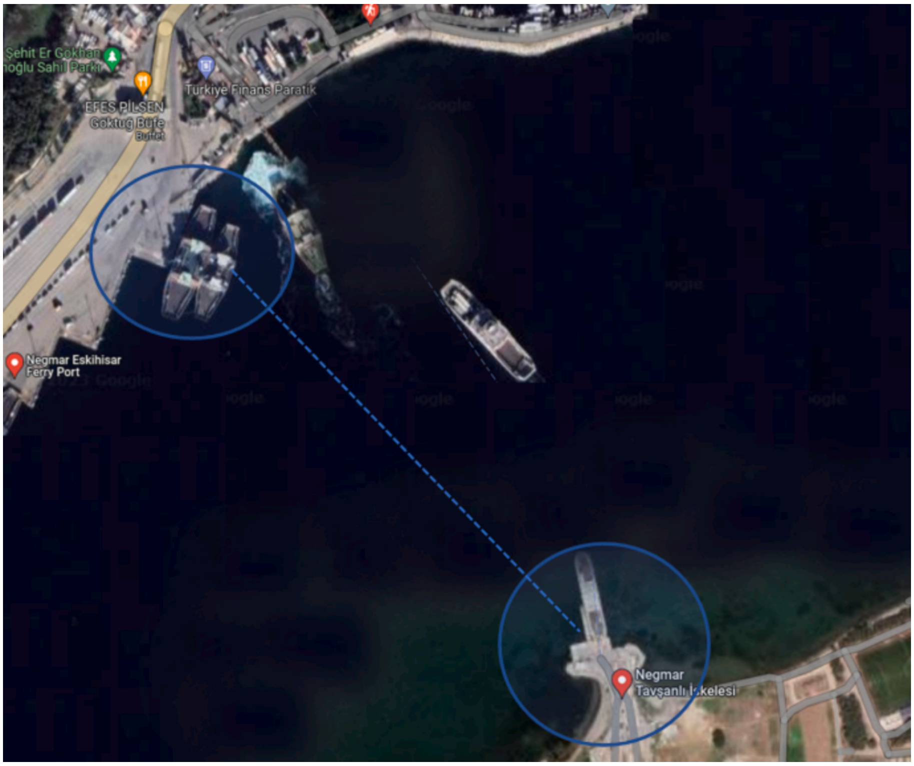
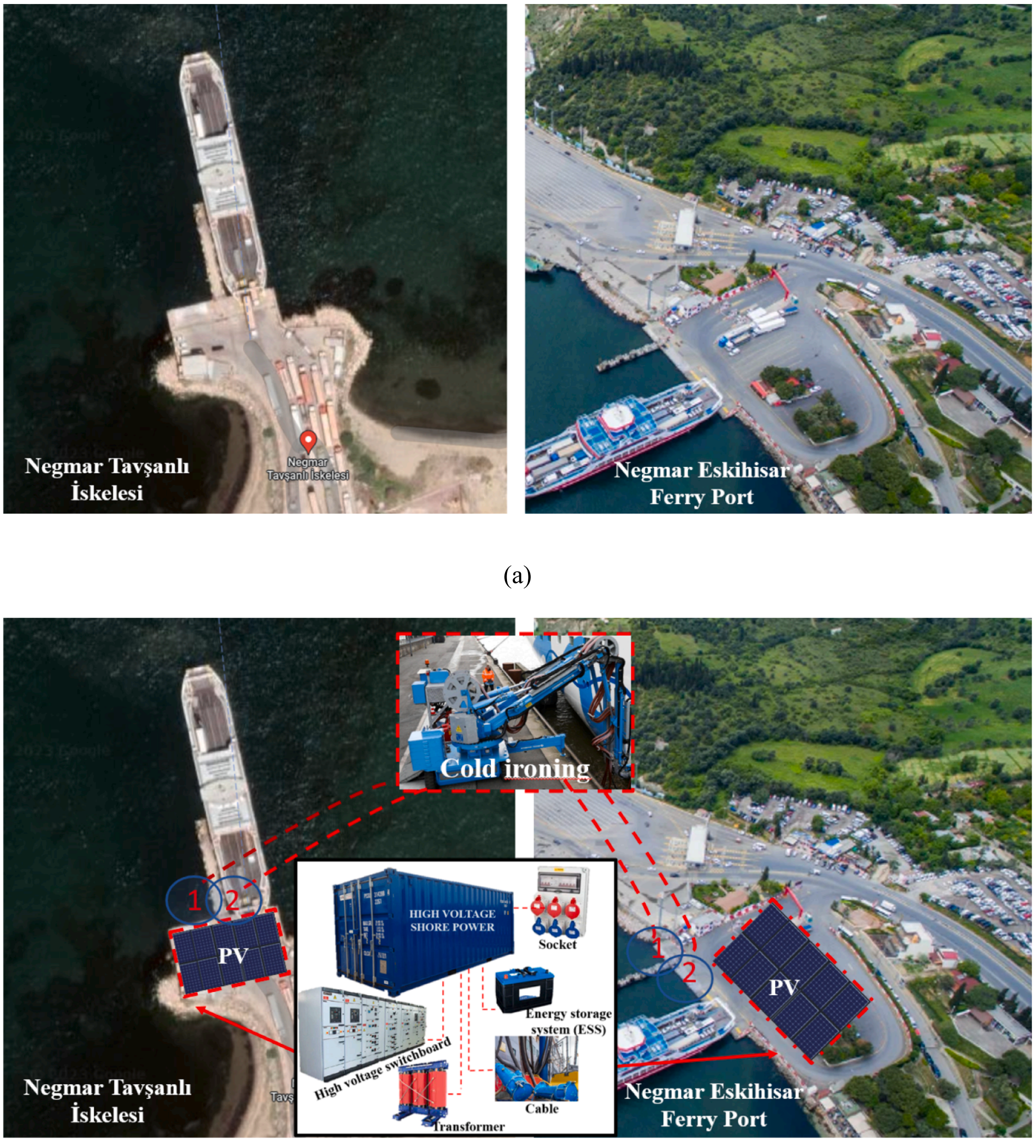


Fig. 1. Ferry routes between Eskihisar and Tavşanli terminal.



(a)

(b)

Fig. 2. (a) Existing port area condition (b) Proposed cold ironing and solar panel installation.

Fig. 3 illustrates the port's power generation-consumption architecture as well as the proposed EMS framework for the system operation. The proposed energy configuration supports the green transition as it is designed for a grid-connected power system that includes renewable energy from solar panels and energy storage systems. As for the consumption, the identified existing port load comes from the administrative port buildings and lighting system (lightings for building/street/deck) which is mainly used during night operation. Meanwhile, cold ironing will be the new port load and add the burden to the existing load in the network. Thus, the service load demand from the ferries during berthing must be identified since it is the main consumer of cold ironing.

Power generation and consumption are both crucial aspects of the energy network. The imbalance between these two aspects can lead to power outages during operation, resulting in corporate losses and operational delays. This is possibly due to poor component sizing and lacking a competent management system. Hence, an EMS strategy needs to be developed to ensure that the operation runs at its optimum performance. To fulfill the gap, this paper presented a two stages EMS framework for the ferry's terminals. The first stage determines the optimal size for the onsite PV generating and energy storage system (ESS) installation capacity to minimize investment costs. The second stage performs operation optimization where the problem formulation model is developed by considering various operational constraints at the port to minimize the operation cost.

3.2. Stage 1: Sizing

Sizing is one of the modules in the EMS framework that determines the port's resource coordination with sufficient capacity on its component to satisfy load demand while reducing investment costs. Several steps are taken at this phase as follow:

(1) Identify the energy consumption

(2) Analyze the potential production of renewable energy at the site location

(3) Economical assessment.

The analysis of the annual consumption portfolio is used to perform a power-generating sizing strategy. The pattern in consumption gives access to the average, low, and peak demand values. This step is important for maintaining power balance during peak and off-peak demand. In this case study, the demand portfolio is developed through

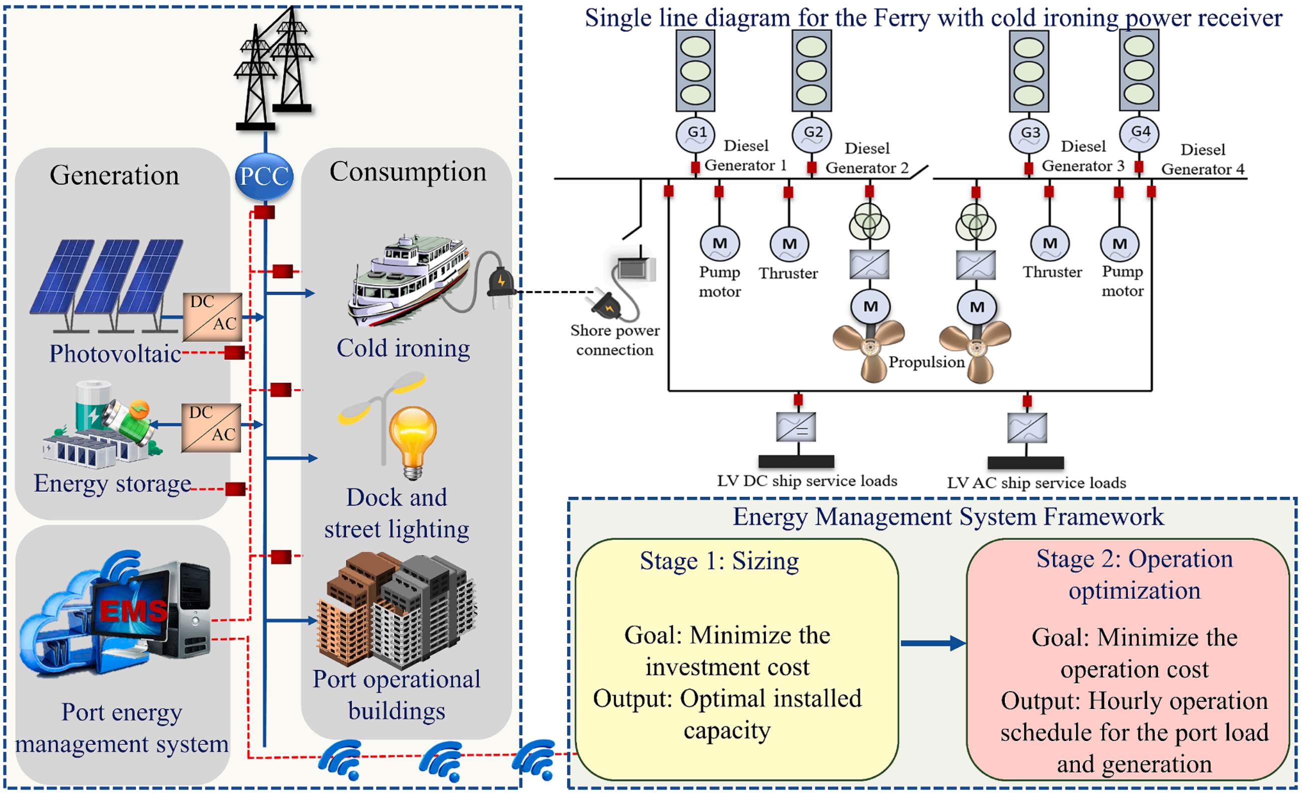


Fig. 3. The proposed ferry port's EMS framework for the solar-powered cold ironing system.

Table 1
The specification of the ship.

Parameter	Value
Name/IMO	HAMIDIYE/ 9,717,577
Area	BSEA – Marmara Sea
Type of ship	Ferry
Speed recorded (Max / Average)	9.3 knots / 8.8 knots
Distance between two ports	9 km approximately
Duration voyage	30 min
Duration berthing at the port	15 min
Operation hour	24 h
Draught	2 *m*
Length	90 *m*
Width	18 *m*
Capacity	1247 gross tonnage
Auxiliary engines	4

a simulation-based technique utilizing the following equations:

$$TL_t = \sum_{b=1}^{n} PD_{B,t} + PD_{L,t} + PD_{CI,t} \forall t \tag{1}$$

$$PD_{CI,t} = \sum_{f=1}^{5} S_{aux,t} h_{berth,t} f_{call,t} \tag{2}$$

$$\alpha = 1 + \delta_d + \delta_{ts} \tag{3}$$

$$LF = \frac{PL_T^{avg}}{PL_T^{peak}} \tag{4}$$

Equation (1) indicates that the total port load at each hour (TL_t) mainly come from the electrical appliance from buildings at port ($PD_{B,t}$), lightings system ($PD_{L,t}$), and cold ironing ($PD_{CI,t}$). As for the cold ironing load, the power needed is estimated based on the ferry's auxiliary generators used during berthing ($S_{aux,t}$), duration of stay at port ($h_{berth,t}$), and frequency of port call ($f_{call,t}$) considering all ferries that actively operate at time *t*. Meanwhile, the Eq. (3) and Eq. (4) are used to determine the load random variability and load factor for realistic data

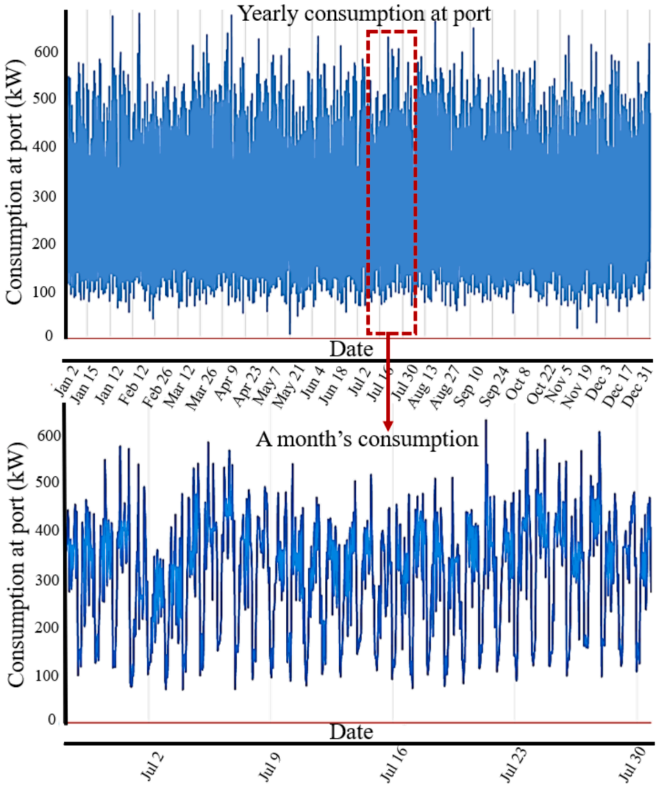


Fig. 4. Annual energy consumption and a one-month sample of load profile.

generation. Fig. 4 shows the generated load profile over one year period where a sample of a one-month consumption period is zoomed out for a clearer trend. The load profile shows that the average daily energy consumption is 6863 kWh, with an average power per hour of 285.96 kW, a peak load of 628.85 kW, and a load factor of 0.45.

In the second step, climatic conditions are observed to analyze the potential production of solar energy at the site location. A year of data is accessed from the NASA Prediction of Worldwide Energy Resources (POWER) database. The data obtained corresponds to the designated site location by the port coordination of latitude 40.75 and longitude 29.25, making the simulation's approximation of the PV output power more precise. The bar chart in Fig. 5 displays one-year data for the radiation, clearness index, and monthly average temperature of the site location.

The output generation of PV is subject to the space constraint where the rated capacity depends on the available open space area for the installation. The PV output power is generated with the following equation:

$$P_{PV} = \gamma_{PV} f_{PV}\left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right)\left[1+\alpha_P\left(T_C - T_{C,STC}\right)\right] \tag{5}$$

Where γ_{PV} is the rated capacity of the PV array in kW, $\overline{G_T}$ is the solar radiation incident of the array in the current time step (kW/m^2), $\overline{G}_{T,STC}$ is the incident radiation at standard test conditions (1 kW/m^2), T_C is the PV cell temperature in the current time step (°C), and $T_{C,STC}$ is the PV cell temperature under standard test condition (25 °C). The installed solar panel is a monocrystalline module type with a temperature coefficient of power, α_P is -0.46 %/°C and PV derating factor, f_{PV} is 80 %. Meanwhile, the ESS adopt in this configuration is to store the surplus energy from PV generation and discharge to serve port load when the production is deficit.

In the third step, the optimal capacity of the system component is implemented with the financial consideration aspect. The objective of this stage is to minimize the investment cost for the system (C_{sys}) planning with the following equation;

$$\min C_{sys} = C_{ins}^{PV} + C_{ins}^{ESS} + C_{ins}^{CI} + C_{ins}^{ship} \tag{6}$$

The minimization system cost involves the installation cost of PV (C_{ins}^{PV}), ESS (C_{ins}^{ESS}), cold ironing facilities (C_{ins}^{CI}), and shore power receiver at ship (C_{ins}^{ship}).

$$C_{ins} = C_{capital} + C_{replacement} + C_{O\&M} \tag{7}$$

The installation cost (C_{ins}) of each component is calculated by considering three types of costs which are the cost of capital $(C_{capital})$, cost of operation and maintenance $(C_{O\&M})$, and cost of replacement $(C_{replacement})$. Table 2 listed the cost parameters used in the simulation for each component.

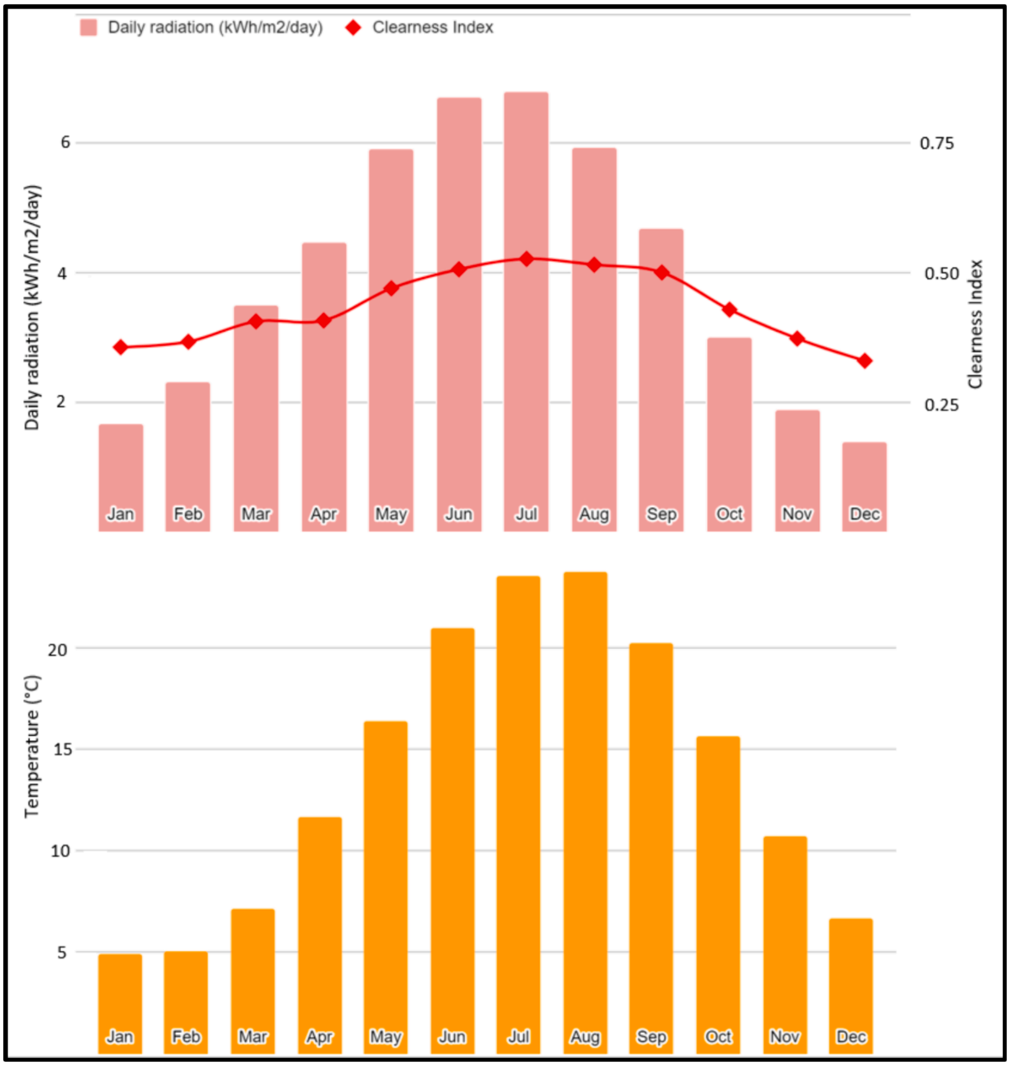


Fig. 5. Solar GHI and temperature resources (Downloaded on 20/6/2023 at 2.57 pm from NASA Prediction of Worldwide Energy Resources (POWER) database).

Table 2
Cost parameters for the system components.

Components	Lifetime (years)	Cost		
		Capital	O&M	Replacement
PV	25	2.5 k ($/kW)	10 ($/year)	2.5 k($/kW)
ESS	15	70 k ($/unit)	1 k ($/year)	70 k ($/unit)
Cold ironing facilities (berth)	25	800 k ($/berth)	3.5 k ($/kW)	800 k ($/berth)
Cold ironing power receiver (ship)	25	100 k ($/ship)	1 k ($/year)	100 k ($/ship)

3.3. Stage 2: Operation optimization

After the installation, it is important to ensure that the operation run in an optimal performance. One of the necessary steps is to have advanced information about all system units' generation and consumption profiles. Thus, day-ahead optimization is performed by gathering load and generation information in advance to optimize operations over a 24-hour time horizon. Port energy operations such as generation scheduling, exchange energy with the utility, and battery SoC condition status are handled at this level. However, the problem formulation for energy management is controlled by several operational constraints due to capacity limitations, the flexibility of power resources, and power balances. The following are the assumptions for the optimization used in this study:

- All incoming ferry at the terminal utilize cold ironing shore power system.
- The port terminals do not impose any constraints on the length of ships, allowing them to accommodate vessels of maximum size visiting the port.

The objective function of stage 2 is formulated in (8) to minimize the operating cost at the port.

$$Min\left\{Cost_d^{op}=\sum_{t=1}^{24}RTP_tP_t^{grid}\right\} \tag{8}$$

RTP_t stands for the real-time price of the local grid at time t, meanwhile P_t^{grid} is the power grid purchased at time t. P_t^{grid} defined as a free variable thus the positive value indicates the amount of electricity drawn from the grid, while the negative value indicates the selling surplus energy generated by the port to the grid. The constraints of the operation optimization are defined in (9)-(16). Considering the transfer limit of a PCC, the energy interaction boundaries are as shown in (9).

$$P_t^{grid}\leq load^{max} \tag{9}$$

Constraint (10) is to ensure all the loads are included in the formulation.

$$load_t^{total}=l_t^{terminal}+l_t^{CI}\forall t \tag{10}$$

$load_t^{total}$ indicates the active power consumption of port terminal at time t. The load combines the load from the port terminal (including the buildings and lighting system) as well as the load from the ship, which consumes cold ironing. Constraint (11) is to ensure the power dispatched from solar is within upper and lower bound power at time t.

$$P_t^{PVmin}\leq P_t^{PV}\leq P_t^{PVmax}\forall t \tag{11}$$

Constraints (12)-(15) are the mathematical formulation for energy storage in this case study. Energy storage is a foundational component that stores excess energy produced by renewable sources and supplies energy during times of severe demand. To maintain the battery life, the state of energy (SOE) must be regulated within certain limitations. The ESS limitation for SOE was formulated in constraint (12).

$$SOE_t^{ESSmin}\leq SOE_t^{ESS}\leq SOE_t^{ESSmax}\forall t \tag{12}$$

Similarly, charging and discharging power from the battery must be within the lower and upper bound value indicated in constraints (13) and (14).

$$P_t^{dismin}\leq P_t^{dis,ESS}\leq P_t^{dismax}\forall t \tag{13}$$

$$P_t^{chargmin}\leq P_t^{char,ESS}\leq P_t^{charmax}\forall t \tag{14}$$

Meanwhile, the SOE value at time t is calculated by using the equation in (15).

$$\forall tSOE_t=SOE_{t-1}+\left(P_t^c\eta_c-\frac{P_t^d}{\eta_d}\right)\Delta t\forall t \tag{15}$$

The most important constraint in the energy network is the power balance between generation and consumption. It is to avoid oversupply and undersupply during operation. The power from the utility, PV, and ESS during discharging should be equal to the total load and ESS during charging. Constraint (16) expresses the power balance requirement. The values of parameters for the system are summarized in Table 3.

$$P_t^{grid\_buy}+P_t^{PV}+P_t^{dis,ESS}=load_t^{total}+P_t^{char,ESS}+P_t^{grid\_sell}\forall t \tag{16}$$

The operation optimization for the implementation of cold ironing and clean energy in the ferry port is developed as a mixed-integer linear programming (MILP) optimization problem. It is processed in a general algebraic modeling system (GAMS) using the CPLEX solver with 0.063 s of computational time.

4. Results and discussion

The results of the proposed system's simulation are presented in this section, together with an in-depth discussion of the optimal sizing, operation optimization, and environment assessment.

4.1. Optimal sizing

In this case study, current operational terminals at Elkihisar and Tavşanli are mainly powered by the national grid. The berthed ferries at the port did not employ cold ironing and relied only on onboard fuel-powered auxiliary generators. As a result, it emits hazardous gasses into the port area during the staying period. However, the proposed approach considers renewable energy generation from solar panels at the port terminal and cold ironing services to power the incoming ferries. The EMS framework strategy involves two stages which are sizing and operational optimization.

In the sizing stage, the main objective is to minimize expenditures on investments while providing optimal capacity for each component in the network. The proposed system is compared with the utility grid as the base system. Table 4 summarizes the financial comparison result from the sizing stage for 25 years lifetime. The sizing results suggest that the proposed structure with optimally sized grid/PV/ESS/CI configuration has the best architecture for a prospective ferry port, with the lowest NPC in its categories of $9.04 M. The significant difference between the

Table 3
Parameters used for the system simulation.

Parameters	Value	Unit	Parameters	Value	Unit
P_t^{PV}	0–536.2	kW	$SOE_t^{initial}$	8	kWh
Δt	1	hour	η_c/η_d	95	%
$P_t^{dismin}/P_t^{charmin}$	0.2SOE	kWh	T	24	hour
$P_t^{dismax}/P_t^{charmax}$	0.2SOE	kWh	Δt	1	hour
$SOE_t^{ESSmin}/SOE_t^{ESSmax}$	5/200	kWh	RTP	1–5.75	TL

Table 4
Economical comparison between the proposed system and base system.

System	Configuration	Cost				Ren Frac (%)	Grid	
		Initial capital ($)	O&M ($/year)	LCOE ($/kWh)	NPC ($/kWh)		Energy purchase(kWh/year)	Energy sold(kWh/year)
Proposed	Utility/PV/ESS/CI	5.47 M	282,209	1.02	9.04 M	32.7	1,952,650	63,469
Base	Utility/CI	3.7 M	379,418	1.40	8.50 M	0	2,710,125	0

Table 5
Sizing outcome for each component.

Component	Parameter	Value	Unit
PV	Rated capacity	680	kW
	Production	887,326	kWh/year
	Max output	703	kW
	Mean output	101	kW
	Hours of operation	4377	hrs/year
	PV penetration	32.7	%
	Levelized cost	0.155	$/kWh
ESS	Nominal capacity	200	kWh
	Bus voltage	600	V
System converter	Capacity	452	kW
	Mean output	93.7	kW
	Hours of operation	4377	Hrs/year
Grid	Energy purchase	1,952,650	kWh/year
	Energy sold	63,469	kWh/year

proposed system and the base system is in its components, whereas the base system is solely powered by the national grid. Thus, this explained the reason the initial capital for the proposed system is higher than the base system with $5.47 M and $3.7 M respectively. The cost differs significantly in the proposed energy network due to the additional investment in the PV, ESS, and converter system components. Meanwhile, the base system doesn't need those components and only requires the investment cost for the cold ironing facilities at the berth and the cost of retrofitting the ferries.

The sizing capacity for each component is mainly affected by the load profile at the port and space constraints for the installation location. The load profile is evaluated for the one-year period in which the main consumption comes from the port (buildings/lighting) and cold ironing. The load profile helps to comprehend the fluctuation in active power over time and to ensure that production can meet the demand from the electrical load. Fig. 6 shows a year load profile for the port consumption and cold ironing consumption. The average consumption for the port load and cold ironing is 1124 kWh/day and 6863 kWh/day respectively. Meanwhile, the peak load for the port load and cold ironing load is 96 kW and 628.85 kW respectively. The annual requirement for electricity is 2,710,125 kWh.

Table 5 shows the optimal size for the proposed structure. According to the simulation results, the system with 680 kW-PV, 200 kWh-ESS, and 452 kW-converter connected to the grid is the optimal sizing after considering the demand profile and installation space. The installation size of the solar panel is mainly restricted by the available area in the location to prevent disrupting the port's existing running business. Due to this constraint, the renewable fraction generation in the port's energy network contributes 32.7 % approximately. It can generate 887,326 kWh of electricity on an annual basis. Meanwhile, the system converter is designed to extract the maximum power from the solar panels. The uncontrollable PV output that relies heavily on geographical location, necessitates using an energy storage system to store excess energy and deploy it later. In certain scenarios, a large capacity bank is desired in the power system. The great challenge is that energy storage would be way too expensive to be economically viable. As the objective function in this stage is to minimize the investment cost, the ESS with 200 kWh capacity is compatible with the system. Furthermore, the main purpose of the ESS in this case is to deal with the intermittent nature of PV output.

The flexibility of scheduling the energy distribution to the port load with the PV and ESS reduces the levelized cost of electricity (LCOE) of the proposed system to $0.102 per kWh, which is lower than the base system. Meanwhile, the LCOE of the base system is $0.14 per kWh because it acquires 100 % of its energy from the utility. Consequently, this led to the highest annual operating cost of purchasing energy with $379418. In contrast, the cost of purchasing energy for the proposed

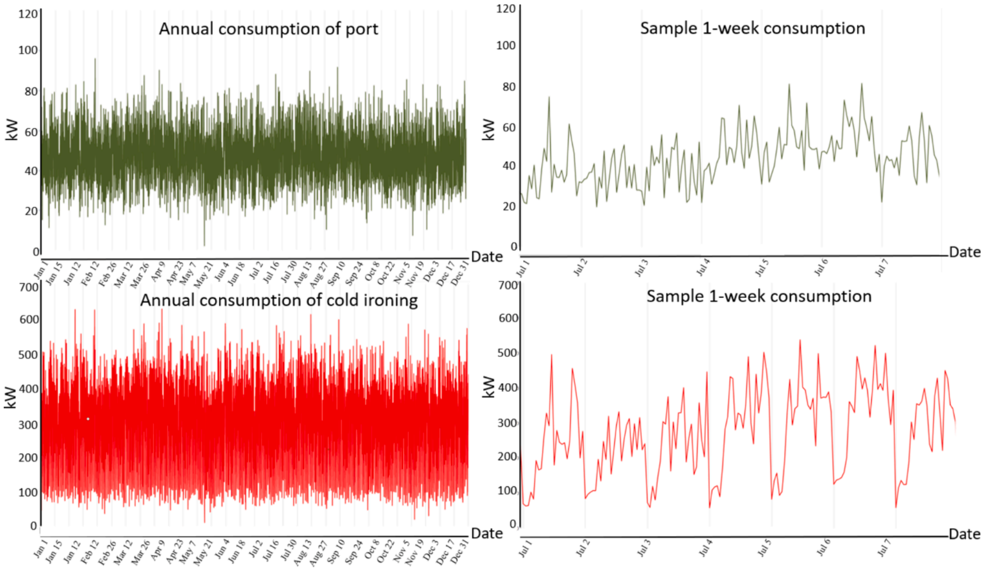


Fig. 6. Load profile for port load and cold ironing.

system is $282209/year which is 25.62 % lower than base system.

The flexibility of energy distribution from the proposed configuration is illustrated in Fig. 7. The black line shows the purchase of electricity executed during the PV-producing deficit when the sun goes down at night until dawn. The red line indicates the energy surplus during 100 % renewable penetration is sold back to the grid. However, the output from PV generation strongly depends on the solar radiation, clearness index, and temperature which make it fluctuate over time. Based on a one-year analysis, the proposed system can purchase the energy from the grid at approximately 1,952,650 kWh and sell the surplus energy to the grid approximately at 63,469 kWh. In comparison, the base system purchases 2,710,125 kWh per year that resulting higher LCOE of $0.14 kWh. Thus, the deployment of PV in the port's energy network provides an avenue of profiting extra money by selling back energy to the main grid while also reducing emissions compared to the base model.

According to the findings of this study, the sizing strategy allows the port operator to enjoy energy and environmental benefits at the lowest possible cost. In comparison to the existing research studies that apply sizing strategy at ferry ports such as in [13], where the simulation is performed by considering different solar plant capacities ranging from 1000 kW to 10000 kW. It demonstrates that raising the PV size increases the cost while offering more electricity surplus that can be sold back to the national grid. However, it is appropriate as a decision-making guideline for organizations that are not tied to the budget constraint for the investment. Furthermore, another limitation, such as space constraint, is an important aspect to consider in a specific case, especially for the feasibility analysis with the restricted area for installation. This limitation is considered in this proposed approach in stage one to ensure that its installation is feasible at the site location. In real practice, the available installation area is limited, which affects the capacity of the components that may be installed. Generally, port operators do not permit the use of certain restricted areas to avoid disrupting their present operations, which explains the necessity of space constraints for the installation at the location.

4.2. *Operation optimization*

The discussion in stage one demonstrates that the installed capacity of the component influences output generation and capital expenditure. Despite the numerous constraints, implementing the proposed energy coordination using the EMS strategy is feasible. However, several aspects are capable of stimulating changes in the cold ironing power consumption, which is the new load in the proposed system, resulting in dynamic load behavior. Among them is the pattern of ship arrival that varies with the season, the varying frequency of ships per hour, the period of ships' berthing, and the energy demand per ship [19]. To a certain extent, the varying generation and demand profile has an impact on the daily port operation. Highlighting the issue, the day-ahead operation optimization in stage two of the proposed EMS framework is performed allowing the port energy network to operate reliably and cost-effectively. The energy management algorithm of the EMS that is formulated with operational constraints, the electricity demand, and real-time prices will schedule the optimum coordination of generation-consumption.

The objective function in this stage is minimizing the operational cost over a 24-hour time horizon. It allows the system to schedule all the port resources economically while maintaining the balance between energy production and electricity demand from the port and cold ironing. The simulation results from the proposed energy configuration give the cost of operation of $403.67 kWh/day approximately. In contrast to the base system that is primarily powered by the national grid, the optimization output yields $1102.99 kWh/day. The comparison outcomes between the two systems demonstrate that the proposed system's operational cost is 63.402 % lower than the base system, resulting in significant cost savings daily. The promising results prove that the scheduling strategy from the EMS framework can enhance reductions in costs.

Fig. 8 (a) and (b) illustrate the energy scheduling outcome of the optimization operation from both of base system and proposed system perspectives. The high percentage of cost savings from the proposed system is because it incorporates green energy with an integrated energy storage system, yielding a lower energy cost. Aside from being environmentally friendly, the local generation of solar electricity at the port also reduces the pressure for energy needs on the grid. It can be observed in Fig. 8 (a), the port continues importing electricity from the power grid during high demand between 9.00 am – 2.00 pm and 6.00 pm – 8.00 pm despite the high price. It is because the base system is entirely reliant on the utility to serve its load requirement from the shoreside and shipside (cold ironing).

In contrast, the proposed system, allows the energy distribution in a flexible manner. Fig. 8 (b) shows the scheduling energy for the proposed system when the energy price is high during a peak time interval (9.00 am – 2.00 pm), the port imports the energy from the PV and discharges the energy storage. At the same time, the port also gains economic benefit by selling back surplus energy to the grid between 10.00 am – 2.00 pm. Surplus energy takes place when the amount of energy produced exceeds the amount of energy required. Meanwhile, during zero solar generation at the time interval 6.00 pm – 8.00 pm, port operators minimize their grid's energy purchase by discharging the energy from ESS, assisting in lowering expenses during high-price hours. The integrated energy storage attempted to increase its SOE by charging the ESS at times 1.00 am – 6.00 am and 3.00 pm – 4.00 pm using an optimization algorithm that can recognize between cheap and expensive periods. A day ahead RTP approach in the EMS enables a feasible charging strategy by charging the ESS when the rate is low and discharging the

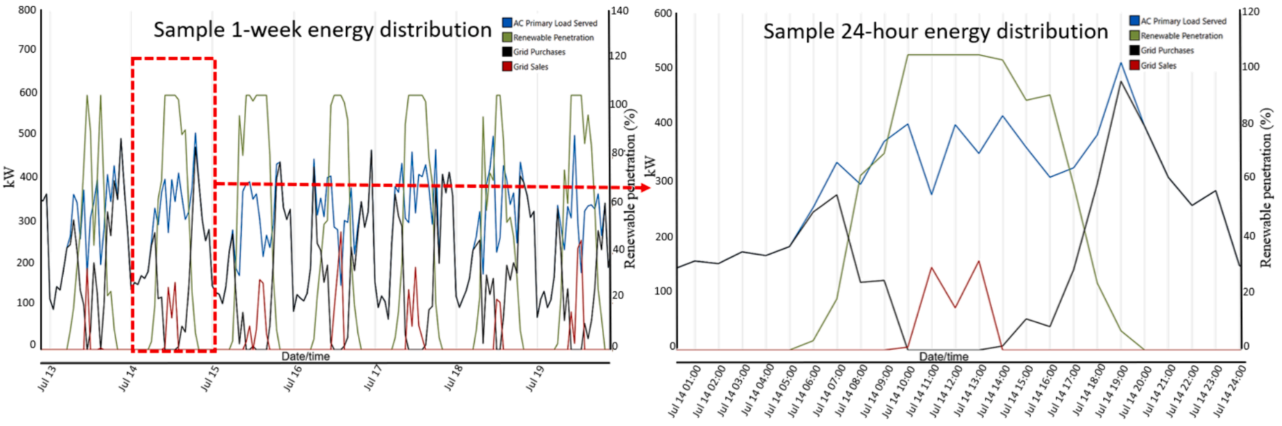
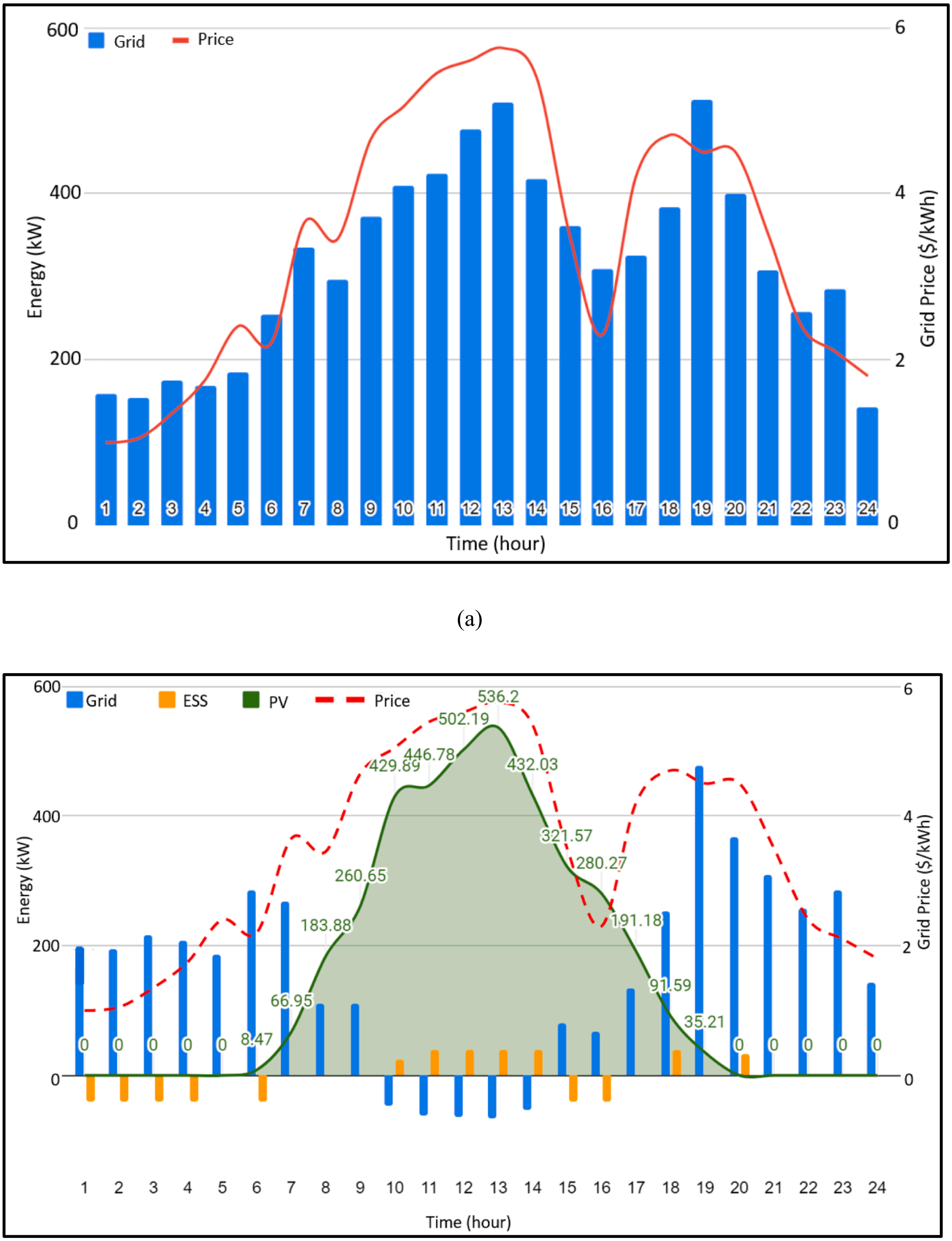


Fig. 7. Energy distribution from the proposed system.



(a)

(b)

Fig. 8. (a) Energy scheduling for base system (b) Energy scheduling profile for the proposed system.

ESS when the rate is high. The implementation of ESS improves the port's energy distribution with the accessibility of additional power during peak hours by supporting active power during that time interval while lowering power purchases. The analysis from the simulation concludes that the operation optimization step with a practical problem formulation in the EMS framework is capable to reduce overall energy consumption at the port. The findings of the optimization technique are consistent with prior research literature [20].

4.3. Environment assessment

The purpose of the environmental assessment is to evaluate the emission benefit gained from the proposed system implementation. The emission analysis is discussed considering two perspectives which are shoreside and shipside. This is due to cold ironing being the pioneer technology for eliminating the emission from the ship activities at port meanwhile the local generation of renewable sources on the shoreside is to enhance emission neutrality. The most common gases of emission CO_2, NO_X, SO_2, and PM are considered in the analysis. The amount of the generated emission is calculated by using the following equation.

$$EM_\sigma = \varepsilon_\sigma .E\forall\sigma \tag{17}$$

Where the amount of emission, EM (kg) for each type of particle σ that belong to CO_2, NO_X, SO_2, PM can be calculated by multiplying the coefficient factor of ε_σ (g/kWh) with the amount of energy used, E (kWh). The coefficient value in this analysis is based on the data in [21] and listed in Table 6.

The emission results for each perspective are shown in Table 7. From the ship-side perspective, the emission analysis is compared between the ship that uses cold ironing systems and those that use auxiliary engines. The result shows significant improvement in emission reduction where the CO_2, NO_X, SO_2, and PM have been reduced to 38.44 %, 97.7 %, 96.69 %, and 92.1 % respectively. This is due to the energy transfer from the shoreside electricity allowing the ship to switch off the diesel fuel generator and stop emitting the emission from it. Thus, replacing the auxiliary engines with the cold ironing power system for electricity supply during berthing activities at the port is a promising solution to mitigate the substantial percentage of emissions. In addition, it also eliminates the noise and vibration problem which brings comfort to the people at the closed radius. Some study suggests that cold ironing eliminate total emission due to the far distance between the port location and the power plant [22]. Due to this, it appears that the emission from the power plant as the end source for the cold ironing doesn't give impact the port. However, major study prefers a fair judgment in term of emission benefit that can be gained from this system by considering the possible emission related. Therefore, the emitted pollution from the power grid is considered in numerous cold ironing emission evaluation studies. To correlate the standard evaluation with every other study, cold ironing emission in this case study is evaluated by using the emission coefficient from the grid.

In terms of the emission generated from the shoreside perspective, the analysis is compared between the base system and the proposed system, where both systems have a different structure of energy generation. The proposed approach results in a 28 % reduction in all types of emissions. This outcome is strongly dependent on the variety and share of the energy mix in the system configuration. The higher the proportion of energy mixed with renewable sources, the greater the emissions reduction can be realized. In this case study, the generation configuration of the base system is mainly supplied by the national grid while the proposed system consists of mixed sources generation (grid/PV/ESS). The purpose of solar power implementation is not only to provide ports with an alternative source for a reliable system but also to enhance emission neutrality for cold ironing applications. This fact is consistent with the findings in this case study, which demonstrated that solar power increased the proposed system's ability to reduce emissions. It is worth pointing out that if the electricity from the shore does not derive from clean sources, the outcome of the cold ironing is simply a transfer of the polluting source from the ships to the shore site.

Table 6
The coefficient value for emission analysis.

Sources	Coefficients for emission (g/kWh)			
	CO_2	NO_X	SO_2	PM
Marine diesel oil (0.5 % sulfur)	692	13.9	2.12	0.38
Grid	426	0.32	0.07	0.03

Table 7
Emission result between the proposed system and based system.

Side analysis	System	CO_2 (kg/yr)	NO_X (kg/yr)	SO_2 (kg/yr)	PM (kg/yr)
Shipside	Diesel fuel	1709.71 k	34342.45	5237.84	938.86
	Cold ironing	1052.51 k	790.62	172.95	74.12
Shoreside	Base system	1154.51 k	867.24	189.71	81.304
	Proposed system	830.78 k	624.06	136.51	58.51

4.4. Study limitation

This study provides methodological contributions including novel frameworks for feasibility assessment, system configuration, and energy management, while the class of problems addressed focuses on enabling economically viable and environmentally sustainable cold ironing solutions for short-berthing ferry operations through clean energy integration. While the specific context of this study is ferry operations at medium-sized port terminals, the underlying system integration concepts learned from this study could potentially be adapted and applied to other fields with appropriate modifications and validation. The proposed two-stage optimization framework, which involves system sizing and operational optimization, can potentially integrated into other applications where optimal system design and operational scheduling are required such as supply chain management, production planning, and resource allocation problems in various industries.

However, there are some limitations identified where cold ironing application to the ferry type of ship faces a challenge with the length of time it stays at the port. It is because the time gap for the next departure is short due to the frequent trips per hour, with an average of 15 min before the following trip. Ferry is maritime transport that conducts a short distance trip from one location to another location. Unlike cargo and cruise ships that have long berthing hours ranging from a few hours to a few days, offering plenty of time for charging. In contrast, a ferry ship typically transits for 15 to 20 min for loading and discharging its client. Highlighting the issue, future studies can extend this research by considering several possible solutions such as a cable management system (CMS), fast charging solution, and battery swap technology. As the connection time is critical for a ferry, a fast cable connection is necessary to reduce the cable connection time during plugging and unplugging while ensuring safety, which requires further research in CMS. Ultra-fast charging technology is also vital to improve the charging time performance of the ferry charger. As an alternative, battery swap technology for the ferry ship should also be investigated.

From a commercial point of view, while the study manages to minimize the system cost, implementing the proposed energy system configuration still require substantial upfront capital investments. These high initial costs could be a significant barrier for port operators and ferry companies, especially for medium-sized or smaller entities with limited financial resources. Besides, implementing the proposed solutions would likely require coordination and acceptance from various stakeholders, including port authorities, ferry operators, energy providers, and potentially local communities. Failure to effectively engage and align these stakeholders could pose significant challenges to commercial deployment.

5. Conclusion

The electrified solution of cold ironing for the ferry ship together with renewable local generation at the port terminal has been proposed. It aims to deliver competitive and green energy transfer solutions to both port operators and ship owners. A strategic EMS framework paired with the sizing stage and optimization technique has also been applied for optimal system operation. The proposed methodology considers a variety of technical and economic constraints in the problem formulation. The key findings of this study and their implications for the perspectives of environment, energy, and finance are summarized as follows:

- Environment: The implementation of cold ironing technology that providing shore power to ferries during passenger loading and unloading operations, has resulted in substantial reductions in emissions of CO_2, NO_X, SO_2, and PM. Coupling this technology solution with locally generated clean energy sources further amplifies the emission mitigation potential. Nevertheless, the extent of emission reduction achieved on the shore side depends greatly on the size and capacity of the deployed renewable energy infrastructure.
- Energy: The proposed system presents significant energy implications by promoting the use of electrification technology and renewable sources, eliminates the need for fossil fuel consumption, supporting dynamic energy demands, and enabling energy trading with the grid. The PV and ESS systems support the load requirements of cold ironing and port operations during peak hours, alleviating grid burden. Additionally, the surplus energy generated from solar panels, can be sold back to the grid, generating revenue. It represents a sustainable and environmentally friendly approach to meeting the energy needs of ferry operations and port activities.
- Financial: From a financial perspective, the proposed EMS demonstrating the economic benefits for the maritime sector. The sizing strategy facilitated in the proposed system having the lowest net present cost, while operation optimization technique applied led to a substantial operational cost reduction. This substantial decrease in operational expenditures holds significant appeal for ferry lines, as it provides an attractive solution for ship owners to adopt sustainable practices while benefiting from lower operational costs.

CRediT authorship contribution statement

Nur Najihah Abu Bakar: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tayfun Uyanik:** Conceptualization, Writing – original draft. **Yasin Arslanoglu:** Supervision. **Juan C. Vasquez:** Supervision. **Josep M. Guerrero:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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