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Abstract

This study introduces a fast distributed economic dispatch approach for hybrid ship microgrids. Initially, an economic dispatch model is formulated for a hybrid ship microgrid integrating both fossil fuel-based generators and renewable energy sources, with the primary objective of minimizing the total operational cost of all power generation units. An environmental cost component is incorporated into the model to mitigate emissions of pollutants and to promote higher utilization of renewable energy generators. Subsequently, a fast distributed algorithm is developed to solve the optimization problem efficiently. Simulation results demonstrate that the proposed method achieves rapid convergence to a new equilibrium, particularly under variations in photovoltaic power output, confirming its effectiveness and suitability for the hybrid ship microgrid considered in this study.

Keywords: Efficient hybrid ship microgrid operation, distributed economic dispatch, renewable energy utilization, photovoltaic power integration, maritime emission control, energy storage management, optimal shipboard power distribution

1 Introduction

As governments around the world increasingly prioritize reducing pollution from maritime transport and boosting the integration of advanced clean-energy technologies within the shipping industry, the strategic value of hybrid ships, those that combine

traditional fuel-based propulsion with renewable energy sources, is becoming ever more pronounced [1]. These hybrid vessels hold the promise of significantly reducing both fuel consumption and greenhouse-gas emissions, while aligning with nations' climate targets and sustainable development goals.

In a typical hybrid ship architecture, onboard electrical power is delivered via a multi-source generation system: conventional internal-combustion or turbine generators operate alongside renewable-energy generators, such as solar photovoltaic (PV) arrays or wind turbines [2]. However, the challenging environment at sea, including rapid changes in weather conditions, high salinity, and mechanical motion, imposes operational constraints. Such variability can undermine the consistent performance of renewable generators, making them unreliable as a sole or primary power source in a microgrid context [3].

Studies highlighted in Reference [4] emphasize the inherent intermittency and fluctuations of renewable energy generation, underscoring the critical role of energy storage devices, such as super-capacitors or flywheels, in hybrid ship microgrids to maintain sufficient electrical energy throughout the voyage. These storage solutions not only mitigate the variability of renewable sources but also enhance the overall stability and responsiveness of the microgrid under dynamic load conditions.

To maximize efficiency and minimize operating costs in such hybrid microgrids, the economic dispatch problem has become a focal point of study. This problem can be formulated as a constrained optimization task, where the objective is to minimize total operational cost subject to power balance constraints, generation capacity limits, and perhaps additional system constraints, such as ramp rates, state-of-charge limits, or reserve requirements [5–7]. Solutions to this problem for ship-based microgrids must account for the highly dynamic nature of both load, due to propulsion demands, hoteling loads, and auxiliary systems, and generation, due to variability in renewable output and conventional generator performance.

A variety of algorithmic strategies have been proposed in the literature to tackle the economic dispatch problem in hybrid ship microgrids. Traditional optimization approaches, including linear programming, quadratic programming, and mixed-integer programming, have been employed where the system model can be reasonably approximated as convex. For more complex and nonconvex formulations, researchers have explored metaheuristic techniques such as genetic algorithms, particle swarm optimization, and differential evolution. Hybrid methods combining heuristic search with classical optimization, such as particle swarm optimization plus interior-point methods, have also shown promise, especially when real-time or near-real-time dispatch decisions are required.

Moreover, advanced control frameworks that fuse energy dispatch with supervisory control and data acquisition or distributed energy management systems are emerging. These frameworks enable real-time monitoring of generation, storage, and load, predictive forecasting of renewable output, and adaptive control of dispatch decisions. By incorporating short-term weather forecasts, wave or wind predictions, and ship navigational planning, the microgrid controller can proactively adjust generation and storage setpoints to improve cost efficiency and reliability.

Nonetheless, several challenges remain. First, the design of a robust dispatch algorithm must balance economic objectives against technical constraints such as energy-storage degradation, system losses, and dynamic stability. Second, the stochastic nature of maritime renewable resources demands that dispatch strategies be resilient and adaptive to real-time conditions. Third, the physical constraints of a ship, including limited space, weight, safety requirements, and maintenance needs, impose practical limits on the capacity and type of energy storage and generation systems that can be deployed.

In this work, we propose a comprehensive framework for economic dispatch in a hybrid ship microgrid equipped with photovoltaic panels and energy storage systems, including super-capacitors and flywheels. Our approach incorporates a predictive model for PV generation based on sea-state and irradiance forecasts, a dynamic dispatch algorithm that optimizes generation and storage flows under realistic constraints, real-time supervisory control to manage charging and discharging of storage devices, and fault-tolerant strategies to handle unexpected renewable dropouts or load surges. Through detailed simulation studies under different sea and weather scenarios, our results demonstrate that the proposed method can reduce operational cost, improve renewable utilization, and ensure system stability over long voyages.

Overall, this research lays groundwork for deploying economically optimized hybrid microgrids in maritime vessels, supporting cleaner, more efficient, and sustainable sea transport.

Several studies have addressed the economic dispatch problem in shipboard microgrids. Reference [8] formulated a model for all-electric ship microgrids equipped with diesel generators and energy storage systems, taking greenhouse gas emissions into account, and applied a particle swarm optimization algorithm to solve the dispatch problem. In Reference [9], an economic dispatch model for a shipboard microgrid with hybrid energy storage was developed, and a decentralized optimization method was proposed to optimize dispatch while considering the extended service life of storage devices. Reference [10] focused on reducing emissions and generation costs and improving battery utilization by establishing an economic dispatch model for hybrid ship microgrids with diesel generators and batteries, and employed a distributed algorithm to address the optimization problem. Considering the reliability and safety issues in shipboard microgrids powered by gas fuel and renewable energy generators, Reference [10] introduced a distributed optimization algorithm based on the alternating direction method of multipliers to minimize generation costs. Reference [10] proposed an economic dispatch model that incorporates diesel generator emission constraints for all-electric ship microgrids and designed a distributed optimization algorithm based on deep reinforcement learning, enhancing flexibility for both the load and supply sides of the system.

These previous works have made substantial contributions to the study of economic dispatch in shipboard microgrids. Nevertheless, achieving fast convergence remains a key challenge, particularly because ship microgrids require rapid response times under real maritime conditions.

Beyond the studies above, hybrid and electrified ship power systems have been examined from several complementary angles. A technical and environmental assessment of microgrid models for electrified maritime transport shows that generators, batteries, renewable units and an energy management system can be integrated so that the loading of diesel generators is reduced and redundancy of supply is increased [11]. For the PV part of such systems, the application of solar panels in the ship power supply system, including the charge controllers, inverters and batteries needed for continuous supply at night and in poor weather, is described in [12], where it is also noted that fuel savings from solar energy are smaller on large ships than on small ferries. A review of innovative methods and technologies for improving the energy efficiency of ships groups the measures into design and operational categories and lists hybrid systems and wind assistance among the emerging solutions, whose main drawback is high initial investment [13].

Reliability and practical experience are equally important. Methods for the quantitative assessment of the reliability and operational safety of the ship power supply system, based on technical diagnostics and a complex quality criterion, allow the condition of its elements to be compared and unplanned outages to be prevented [14]; this becomes more relevant as PV, wind and storage units add further elements to the microgrid. Practical experience with alternative energy on ships is so far limited to modest PV capacities, for example about 40 kW on a 60,213 GT car carrier and 93 kW on a solar-powered ferry, while hybrid solar-wind-battery ferries and shore-side power supply are reported to reduce fuel use and emissions [15]. At the control level, a fuzzy-logic-based energy storage management system for the MVDC power system of an all-electric ship [16] and a stand-alone hybrid PV, fuel cell and diesel generator system with battery or supercapacitor storage [17] illustrate how storage and mixed sources are coordinated. To the best of our knowledge, however, these works do not combine weather-limited PV output, emission penalties and renewable subsidies in a fast distributed dispatch, which is the gap addressed in this paper.

In this paper, the main contributions are summarized as follows. To overcome the intermittent power generation from photovoltaic panels caused by extreme sea weather, an economic dispatch model is developed for hybrid ship microgrids, considering both emission penalties and electricity generation subsidies. Furthermore, a distributed optimization algorithm with a fast convergence rate is proposed to efficiently solve the economic dispatch problem, thereby minimizing economic losses caused by abnormal equipment operation in hybrid ship microgrids.

The structure of the remainder of the paper is organized as follows. Section 2 presents the hybrid ship microgrid model and the associated objective function. Section 3 introduces relevant concepts from graph theory and details the distributed optimization algorithm employed. Section 4 demonstrates the advantages of the proposed distributed optimization method through simulation-based comparisons. Finally, the study's conclusions are summarized.

2 Methodology

The methodology of this study addresses the fast and efficient organization of maritime transportation using a hybrid ship microgrid equipped with photovoltaic (PV) panels. The hybrid ship microgrid integrates multiple energy sources, including PV panels, conventional diesel generators, wind turbines, and energy storage systems such as batteries and supercapacitors. The ship's loads comprise propulsion systems, auxiliary electrical equipment, and onboard devices, all of which require continuous and reliable power during navigation.

The core of the methodology is the formulation of an economic dispatch model for the hybrid ship microgrid. This model considers generation costs, emission penalties, operational limits of generators, and the intermittent nature of PV power. A distributed optimization algorithm is employed to solve the economic dispatch problem efficiently, enabling real-time coordination of generators and storage devices to meet dynamic load requirements while minimizing operating costs. The microgrid model incorporates multiple types of flows: electrical flow (E-flow) from generators to loads, pollutant flow (G-flow) representing emissions, communication information flow (I-flow), and local control flow (L-flow). These flows facilitate energy management, emission control, and communication across the microgrid, ensuring optimal system performance under varying maritime conditions.

Simulation studies are carried out under different operational and weather scenarios to validate the performance of the proposed methodology. Key metrics include renewable energy utilization, system stability, operational cost, and convergence speed of the distributed optimization algorithm. The results confirm that the proposed approach provides a reliable, fast, and efficient solution for maritime transport management using hybrid ship microgrids with PV panels.

3 Discussion of the results

This section presents the configuration of the hybrid ship microgrid analyzed in this study. The components installed on the hybrid ship are illustrated in Fig. 1 and include both power generation and consumption equipment. The generation system consists of fuel-based generators, wind turbines, photovoltaic panels, and battery storage units. The load side encompasses the ship's propulsion system as well as various electrical appliances and auxiliary equipment. Throughout the voyage, all electrical demand from the ship's loads is met by the integrated power generation system.

In Fig. 1, different flows are represented to describe system interactions: E-flow refers to the transmission of electrical energy from generators to loads; G-flow indicates the movement of atmospheric pollutants; I-flow represents communication and information exchange; and L-flow denotes the flow of local control information within the microgrid.

3.1 Objective Function

The main objective of this study is to minimize the operating costs of power generators while simultaneously reducing emissions of air pollutants. The total cost function

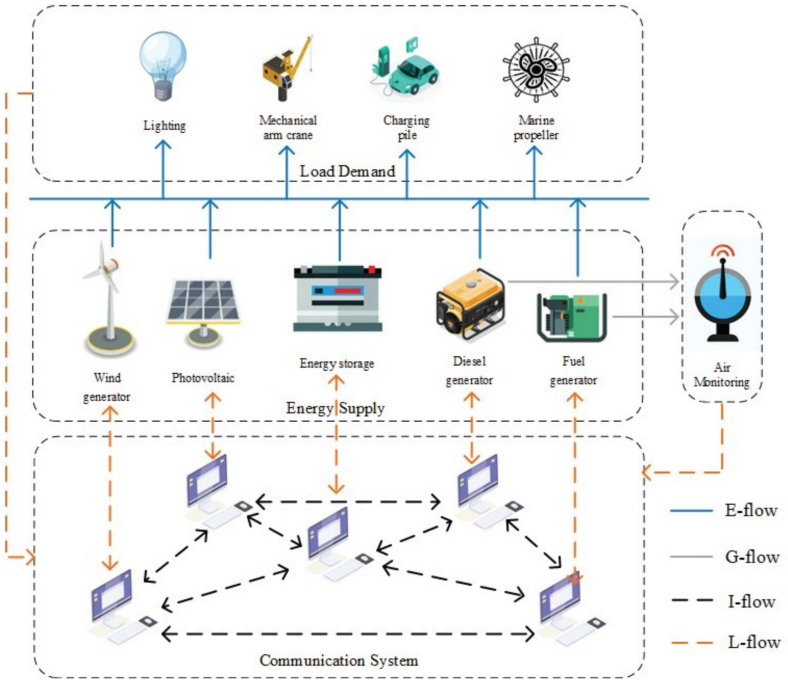


Fig. 1 Structure for hybrid ship microgrid

is composed of three key components: the cost associated with power generation, the environmental cost due to pollutant emissions, and the cost related to battery maintenance. The corresponding mathematical formulation is expressed as follows:

$$\min C_{\text{total}} = \min \{C_{\text{gc}} + C_{\text{ec}} + C_{\text{bc}}\} \tag{1}$$

Here, C_{total} represents the total cost function, C_{gc} denotes the generation cost component, C_{ec} corresponds to the environmental cost, and C_{bc} represents the battery maintenance cost. The generation cost function includes the expenses associated with producing electricity from photovoltaic panels, wind turbines, diesel generators, and fuel-based generators, and it is expressed mathematically as equation (2).

$$C_{\text{gc}} = C_{\text{PV}} + C_{\text{W}} + C_{\text{DG}} + C_{\text{F}} \tag{2}$$

$$C_{\text{PV}} = \sum_{i=1}^{n_1} \left(\alpha_{\text{PV},i} + \beta_{\text{PV},i} P_{\text{PV},i} + \gamma_{\text{PV},i} P_{\text{PV},i}^2\right) \tag{3}$$

$$C_{\text{W}} = \sum_{i=1}^{n_2} \left(\alpha_{\text{W},i} + \beta_{\text{W},i} P_{\text{W},i} + \gamma_{\text{W},i} P_{\text{W},i}^2\right) \tag{4}$$

$$C_{\text{DG}} = \sum_{i=1}^{n_3} \left(\alpha_{\text{DG},i} + \beta_{\text{DG},i} P_{\text{DG},i} + \gamma_{\text{DG},i} P_{\text{DG},i}^2\right) \tag{5}$$

$$C_{\mathrm{F}} = \sum_{i=1}^{n_4} \left(\alpha_{\mathrm{F},i} + \beta_{\mathrm{F},i} P_{\mathrm{F},i} + \gamma_{\mathrm{F},i} P_{\mathrm{F},i}^2\right) \tag{6}$$

In this formulation, C_{PV}, C_{W}, C_{DG}, and C_{F} represent the costs associated with photovoltaic panels, wind turbines, diesel generators, and fuel generators, respectively. The positive cost coefficients are denoted by $\alpha_{\mathrm{PV},i}$, $\beta_{\mathrm{PV},i}$, $\gamma_{\mathrm{PV},i}$, $\alpha_{\mathrm{W},i}$, $\beta_{\mathrm{W},i}$, $\gamma_{\mathrm{W},i}$, $\alpha_{\mathrm{DG},i}$, $\beta_{\mathrm{DG},i}$, $\gamma_{\mathrm{DG},i}$, $\alpha_{\mathrm{F},i}$, $\beta_{\mathrm{F},i}$, and $\gamma_{\mathrm{F},i}$. The corresponding output powers of the generators are denoted as $P_{\mathrm{PV},i}$, $P_{\mathrm{W},i}$, $P_{\mathrm{DG},i}$, and $P_{\mathrm{F},i}$, while n_1, n_2, n_3, and n_4 represent the number of devices for each type of generator.

The environmental cost function is composed of two parts: a penalty for pollutant emissions and a subsidy for renewable energy generation. Diesel and fuel generators are subject to emission penalties based on the number of pollutants they produce, while renewable energy sources receive subsidies proportional to their power output. The detailed mathematical formulation of the environmental cost function is presented as follows:

$$C_{\mathrm{ec}} = C_{\mathrm{pun}} - C_{\mathrm{sub}} \tag{7}$$

$$C_{\mathrm{pun}} = 10^{-2} C_{\mathrm{DG}} + \sum_j \lambda_j \sum P_{\mathrm{DG},j}^2 + 10^{-2} C_{\mathrm{F}} + \lambda_1 P_{\mathrm{F},i}^2 \tag{8}$$

$$C_{\mathrm{sub}} = \sum \zeta_{\mathrm{PV},i} P_{\mathrm{PV},i} + \sum \zeta_{\mathrm{W},i} P_{\mathrm{W},i} \tag{9}$$

In this formulation, C_{pun} represents the penalty imposed for pollution emissions, while C_{sub} denotes the subsidy provided for environmental protection. The parameters λ_j ($j = 1, 2, 3$) are positive coefficients corresponding to penalties for CO_2, SO_2, and NO_x emissions, respectively. Additionally, $\zeta_{\mathrm{PV},i}$ and $\zeta_{\mathrm{W},i}$ indicate the subsidies awarded for electricity generated by photovoltaic panels and wind turbines.

The cost associated with battery maintenance can be represented by a quadratic function that depends on both the charging and discharging power of the battery.

$$C_{\mathrm{bc}} = \pi + \xi P_{\mathrm{B}}^2 \tag{10}$$

Here, π and ξ represent positive cost coefficients associated with the battery, and P_{B} denotes the battery's charge or discharge power.

3.2 Constraints

1. Supply-Demand Balance. To guarantee the proper operation of the ship, the total power generated by all sources must satisfy the load demand. The mathematical representation of this supply-demand balance is given in equation (11).

$$\sum_{i=1}^{n_1} P_{\mathrm{PV},i} + \sum_{i=1}^{n_2} P_{\mathrm{W},i} + \sum_{i=1}^{n_3} P_{\mathrm{DG},i} + \sum_{i=1}^{n_4} P_{\mathrm{F},i} = \sum_{i=1}^{m} L_i \tag{11}$$

Here, L_i represents the power demand of the ship's load, and m denotes the total number of electrical facilities onboard.

2. Output Power Constraints. During the voyage, the output of each generator is restricted within specified minimum and maximum limits. In the hybrid ship microgrid model, the generation capacity limits and optimal power constraints for photovoltaic and wind generators are expressed in equations (12) and (13). Similarly, the power capability and ramp rate constraints for diesel and fuel generators are represented in equations (14) and (15). These constraints ensure safe and reliable operation of all power sources under varying load and environmental conditions.

$$0 \leq P_{\mathrm{PV},i} \leq P_{\mathrm{PV,max}}^{\mathrm{nor}} \tag{12}$$

$$0 \leq P_{\mathrm{W},i} \leq P_{\mathrm{W,max}} \tag{13}$$

$$P_{\mathrm{DG,min}} \leq P_{\mathrm{DG},i} \leq P_{\mathrm{DG,max}} \tag{14}$$

$$P_{\mathrm{F,min}} \leq P_{\mathrm{F},i} \leq P_{\mathrm{F,max}} \tag{15}$$

Here, $P_{\mathrm{PV,max}}$ and $P_{\mathrm{W,max}}$ are the inequality constraint coefficients determined by the feasible operating ranges of photovoltaic and wind generators, respectively. The parameters $P_{\mathrm{DG,min}}$, $P_{\mathrm{DG,max}}$, $P_{\mathrm{F,min}}$, and $P_{\mathrm{F,max}}$ are positive coefficients that define the ramp rate limits for diesel and fuel generators, ensuring safe and stable operation during power transitions.

Batteries serve as the primary energy storage system in the hybrid ship microgrid, supplying sufficient power to maintain ship operation when photovoltaic panels or wind turbines are unable to generate electricity effectively. The corresponding inequality constraint for the battery's output power is expressed in equation (16).

$$\mathrm{SoC}_{\min} \leq 1 - \tau P_{\mathrm{B}} \leq \mathrm{SoC}_{\max} \tag{16}$$

Here, $\mathrm{SoC}_{\min}$ and $\mathrm{SoC}_{\max}$ denote the minimum and maximum allowable states of charge of the battery, respectively, while τ represents the efficiency factor for the conversion of electrical energy during battery operation.

Two primary weather conditions can reduce the power output of photovoltaic panels below their normal levels. The first occurs when sea visibility falls below 50 meters, resulting in a generation output of approximately 5% of the nominal capacity. The second occurs during cloudy and rainy conditions, which limit solar irradiance and reduce generation output to between 7% and 15% of normal operation. The corresponding output power limits for photovoltaic panels under these extreme weather conditions are represented in equation (17).

$$0 \leq P_{\mathrm{PV},i} \leq \kappa_m \cdot P_{\mathrm{PV,max}}^{\mathrm{nor}} \quad (m = 1, 2) \tag{17}$$

Here, κ_1 represents the efficiency ratio relative to the normal power output when sea visibility is below 50 meters, while κ_2 denotes the efficiency ratio under cloudy and rainy conditions.

3. Gas Emission Constraints. The release of harmful gases resulting from fossil fuel combustion is restricted in accordance with applicable environmental protection regulations. The corresponding emission limit constraints for each pollutant are

expressed as follows:

$$0 \leq M_{\mathrm{CO_2}} \leq M_{\mathrm{CO_2}}^{\max} \tag{18}$$
$$0 \leq M_{\mathrm{SO_2}} \leq M_{\mathrm{SO_2}}^{\max} \tag{19}$$
$$0 \leq M_{\mathrm{NO_x}} \leq M_{\mathrm{NO_x}}^{\max} \tag{20}$$

In this context, $M_{\mathrm{CO_2}}^{\max}$, $M_{\mathrm{SO_2}}^{\max}$, and $M_{\mathrm{NO_x}}^{\max}$ define the upper limits for CO_2, SO_2, and NO_x emissions, respectively, whereas $M_{\mathrm{CO_2}}$, $M_{\mathrm{SO_2}}$, and $M_{\mathrm{NO_x}}$ indicate the actual emissions produced. The operational output of diesel and fuel generators is regulated by a combination of their ramping capabilities and the maximum allowed pollutant emissions, ensuring that environmental standards are met while maintaining adequate power supply for the hybrid ship microgrid.

To evaluate the performance of the proposed method, a hybrid ship microgrid comprising 11 power generation units is established. As illustrated in Fig. 2, the microgrid includes two photovoltaic panels (agents 1 and 2), two diesel generators (agents 3 and 4), one energy storage system (agent 5), three wind turbines (agents 6, 7, and 8), and three fuel generators (agents 9, 10, and 11). The relevant technical parameters, as introduced in Section 2, are summarized in Tables 1 and 2.

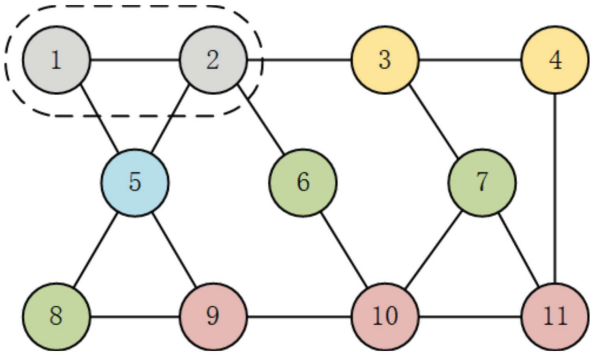


Fig. 2 Communication topology of the hybrid ship microgrid.

The economic dispatch model of the hybrid ship microgrid is formulated as equation (20) to achieve minimum total operational cost. The proposed fast distributed algorithm is employed to solve this problem efficiently. When the photovoltaic panels fail to operate under normal conditions, the economic dispatch is recalculated. Adjusting the upper output limit of the photovoltaic generators at 45 seconds results in reconvergence of the incremental cost at 70 seconds. The new optimal output power values under these conditions are

$$[8.00,\ 8.00,\ 20.93,\ 24.81,\ 25.00,\ 42.09,\ 48.70,\ 37.01,\ 21.44,\ 26.69,\ 37.33],$$

demonstrating the adaptability of the proposed method to sudden variations in renewable power availability.

Table 1 Parameters of the generators

Generators	α_i	β_i	γ_i	P_{min}	P_{max}
PV1	0.025	−0.5	0.6	0	85
PV2	0.031	−0.48	0.51	0	85
DG1	0.027	−0.36	0.47	0	290
DG2	0.019	−0.25	0.43	0	290
STO	0.031	–	0.19	25	80
W1	0.031	−0.43	0.59	0	175
W2	0.027	−0.39	0.46	0	175
W3	0.033	−0.61	0.34	0	175
F1	0.041	−0.41	0.65	20	250
F2	0.034	−0.12	0.15	20	250
F3	0.015	−0.12	0.29	20	250

Table 2 Parameters of the environment cost function

Generators	Subsidize or punish	P_{min}	P_{max}
PV	−0.02	–	–
W	−0.019	–	–
DG	0.037	0	90
F	0.021	0	200

The new dispatch can be examined further. The eleven output powers add up to 300.00 MW, which equals the total load demand in the supply-demand balance (11) when the energy storage output (agent 5, 25.00 MW) is included. The PV units (agents 1 and 2) supply 16.00 MW (5.3% of the load), the three wind turbines 127.80 MW (42.6%), the two diesel generators 45.74 MW (15.2%), the three fuel generators 85.46 MW (28.5%) and the storage 8.3%; hence PV and wind together cover 143.80 MW, or 47.9% of the load. Each PV unit operates at 8.00 MW, i.e. 9.4% of its 85 MW rating, which lies within the 7–15% range (5.95–12.75 MW) assigned to cloudy and rainy conditions in equation (17). The storage unit operates at 25.00 MW, equal to its lower limit in Table 1, and the fuel generators remain above their 20 MW minimum, so the constraints of the model are satisfied. The wind turbines operate at only 24.3% of their combined 525 MW limit, which shows that in an incremental-cost dispatch the renewable share is governed by the cost coefficients and subsidies rather than by capacity limits; larger subsidies would increase renewable utilization at the expense of fuel-based generation.

The observed behaviour, reconvergence of the incremental cost about 25 s after the change of the PV limit, is consistent with distributed economic dispatch methods that take communication delays into account [5]. The ship-oriented studies [8–10] address voyage scheduling, decentralized storage management and battery degradation, while the present model adds weather-limited PV output and combined penalty and subsidy terms. It should be noted that the case study uses a 300 MW load and 85 MW PV

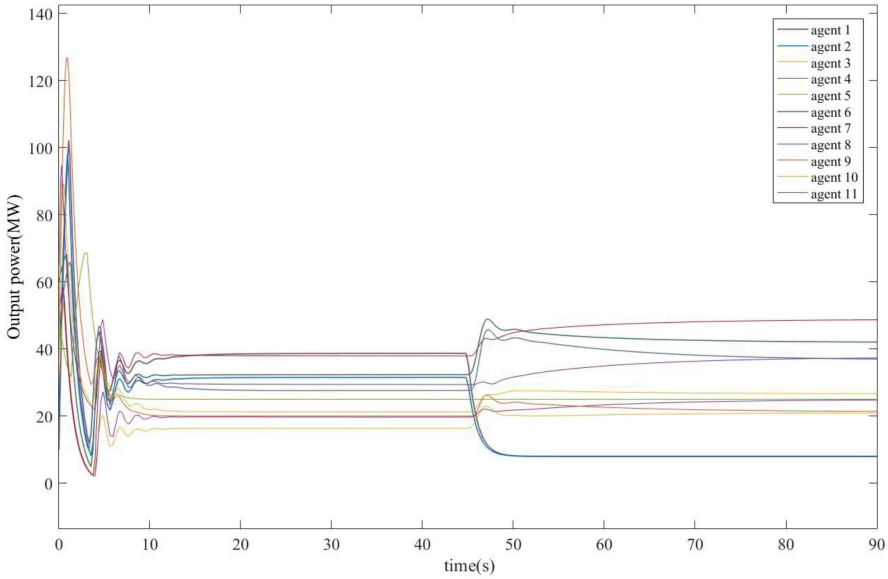


Fig. 3 Output power curves of fast distributed economic dispatch

units, whereas commercial shipboard PV installations are of the order of tens of kilowatts [15]; the parameters are therefore best interpreted as a normalized benchmark that must be scaled to the load profile and the available deck area of a specific vessel. Under such scaling PV would cover only a small share of the load, which is consistent with the finding in [12] that fuel savings from solar energy are smaller on large ships; the generators and storage would then carry most of the load, so that the reliability of the microgrid elements [14] and the energy management of the microgrid [11] become decisive.

Further work will include a quantitative comparison of the convergence speed with other distributed algorithms on the same case, reporting of the total operating cost and emissions before and after the PV limit change, and simulations with time-varying load and PV and wind profiles for a real route, including Caspian Sea conditions, together with ramp-rate constraints of the generators.

4 Results

1. The proposed fast distributed economic dispatch method provides effective management of hybrid ship microgrids, maintaining stable and reliable operation even under changing maritime conditions and varying load demands.
2. The algorithm demonstrates rapid adaptation to fluctuations in photovoltaic and wind power generation, ensuring that power supply meets load requirements while simultaneously minimizing total operational costs.

By enhancing the utilization of renewable energy sources and incorporating environmental cost considerations, the approach reduces pollutant emissions, offering an efficient, eco-friendly, and practical solution for modern hybrid ship power systems.

In the case study, the incremental cost reconverged within about 25 s after the PV upper limit was reduced at 45 s, and PV and wind units supplied 47.9% of the 300 MW load in the new dispatch.

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