# Multi-Objective Optimization Method for Hybrid Ship Power System Capacity

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## Abstract

**Due to the intensification of environmental problems, the world has paid more attention to the environmental protection of ships. The use of renewable energy and energy storage system (ESS) can effectively reduce ship's fuel consumption and greenhouse gas emissions. The optimal sizing of new energy systems and ESS is crucial in a hybrid ship power system where the reduction of operating costs and $CO_2$ emission is important. This paper takes annual operating costs and emissions as goals, and proposes a multi-objective optimization method for the capacity configuration of hybrid ship power system, considering the influence of ship swing and ESS cycle life. Case studies on an electric propulsion ship that include photovoltaic (PV), wind turbine generation system and ESS are shown to prove the effectiveness of the proposed method.**

## Keywords

**Hybrid Ship Power System; Renewable Energy; $CO_2$ Emission; Multi-objective Optimization.**

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## 1. Introduction

The increasing attention to environmental protection issues has led to stricter regulations on ship greenhouse gas emissions, improving ship energy efficiency and reducing emissions have become crucial research directions [1]. At the same time, the fierce competition in the global ship market also puts forward higher requirements on ship operating costs. Therefore, it's necessary to consider both economy and environmental protection when studying this problem [2].

Some methods have been proposed including route optimization, power management, the use of renewable energy and ESS, to solve this problem. An energy management optimization method which uses differential evolution (DE) algorithm to optimize the power distribution of ship generator sets for classic ships is proposed in [3], significantly reduced ship operating costs and $CO_2$ emissions. An optimized and control method for the ESS capacity in an electric propulsion ship is proposed to prove that the optimal capacity of the ESS can reduce the operating cost during the ship's entire lifetime in [4]. It has been proved that ESS containing supercapacitors and lithium batteries can significantly improve the ship power system with short operating cycle and severe load fluctuation in [5]. A novel multi-clustering algorithm is proposed to optimize ESS capacity for an all-electric ship considering uncertain power load and meteorological data along the navigation route in [6]. However, only single optimization objective is considered in [3] and [4]. The influence of ESS life on operating costs is ignored in [4]-[6]. Literature [6] did not consider the influence of ship swing on photovoltaic power generation.

In view of the shortcomings of the above literatures, this paper takes an electric propulsion ship with PV arrays, wind turbine generation system, ESS and diesel generator sets as an example, optimizes two targets of ship annual operating costs and $CO_2$ emissions with real meteorological data along the navigation route, considering the above two effects. In order to calculate the optimal capacity of each components, the multi-objective differential evolution algorithm based on decomposition and multi-strategy mutation (MODE-DMSM) is utilized in this work, and the ship power load data is known.

The rest of this paper is organized as follows: Section 2 describes models of ship power system components. Section 3 formulates the problem. Section 4 shows the simulation results. Section 5 draws conclusions.

## 2. Hybrid Ship Power System Components

### 2.1 Hybrid System Structure

The ship power system includes diesel generator sets, PV system, wind turbine generation system and ESS. The electrical loads are mainly divided into propulsion load and other load. The structure of the ship power system is shown in Fig 1.

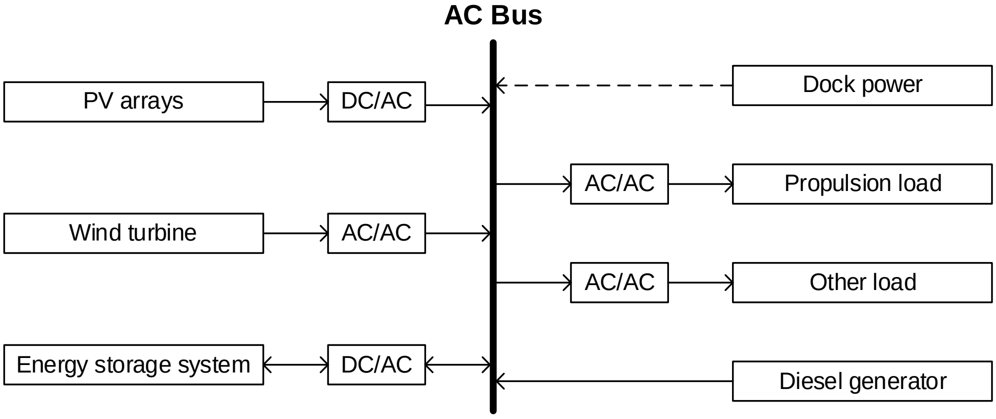

Fig. 1 Structure of ship power system

This ship takes 10 days to sail from Dalian in China to Singapore, four times a year for a total of 1920 hours. When the ship is anchored, all the power load is supplied by the dock power. In the end, the optimization involved 1608 hours a year, and the wind speed, solar irradiation, temperature and load curves were sampled hourly.

### 2.2 Models of System Components

#### 2.2.1 PV Arrays

The output power of a photovoltaic (Photovoltaic, PV) arrays is mainly related to the solar irradiation, area of PV panels, photoelectric conversion efficiency, and the ambient temperature. The PV output $P_{\mathrm{pv}}(t)$ at time $t$ is as follows:

$$P_{\mathrm{pv}}(t)=N_{\mathrm{pv}}\cdot A\cdot G(t)\cdot\eta_{\mathrm{pv}} \tag{1}$$

Where $N_{\mathrm{pv}}$,$A$,$G(t)$ and $\eta_{\mathrm{pv}}$ denote the number of PV panels, PV area (m$^2$), solar irradiation at time $t$, and photoelectric conversion efficiency. The value of $\eta_{\mathrm{pv}}$ is not only related to the maximum conversion efficiency of photovoltaic panels, but also depends on parameters such as power tracking system efficiency, operating temperature and solar irradiation, as shown in equations (2) and (3).

$$\eta_{\mathrm{pv}}=\eta_{\max}\cdot\eta_M\cdot\left(1-\beta\cdot\left(T_c-T_{\mathrm{ref}}\right)\right) \tag{2}$$

$$T_c=T_a+\left[\frac{T_{\mathrm{normal}}-20}{800}\right]\cdot G(t) \tag{3}$$

where $\eta_{\max}$ is the max conversion efficiency of PV; $\eta_M$,$\beta$ and $T_{\mathrm{ref}}$ denote the max conversion efficiency of power tracking device, temperature coefficient, and reference temperature of PV, which are taken to be 1, 0.05, and 25°C in this paper. The temperature of PV panels $T_c$ is related to environment temperature $T_a$, normal operating temperature $T_{\mathrm{normal}}$ (45°C) and solar irradiation $G(t)$.

The PV panels are installed horizontally on the deck, so the ship irregular swing will affect the output of PV system. The influence caused by the position change in the vertical direction can be neglected, and the influence caused by the rolling of the ship is mainly considered [7]. The rolling of the ship will cause the equivalent light-receiving area of the photovoltaic panel to change, which is approximately equivalent to the change of the solar irradiation [8], and the solar irradiation is corrected according to equation (4):

$$G^{'}(t) = \frac{G(t)(1+\cos\theta)}{2} + \frac{G(t)(1-\cos\theta)}{2}\cdot \cos(2\pi f t) \tag{4}$$

where $G^{'}(t)$, $\theta$ and $f$ denote modified irradiation, maximum swing angle (±16°) and swing frequency (0.05 Hz). Since the sampling period of all data is 1 hour, the average value o f the hourly irradiation is taken here. The data of single PV panel is shown in Table 1. The data of solar irradiation and ambient temperature along the navigation route in 2019 is shown in Fig 2. Meteorological data comes from NASA’s Terra satellite[9].

Table 1. Data of a PV panel

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Life time | 30 years | Efficiency | 18% |
| Rated power | 160 w | Length | 1.16 m |
| Cost | 60 $ | Width | 0.83 m |

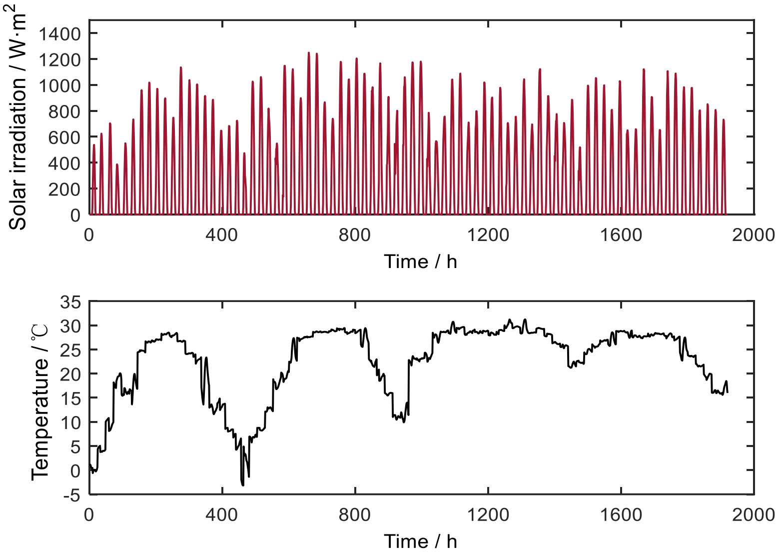

Fig. 2 Data of solar irradiation and temperature

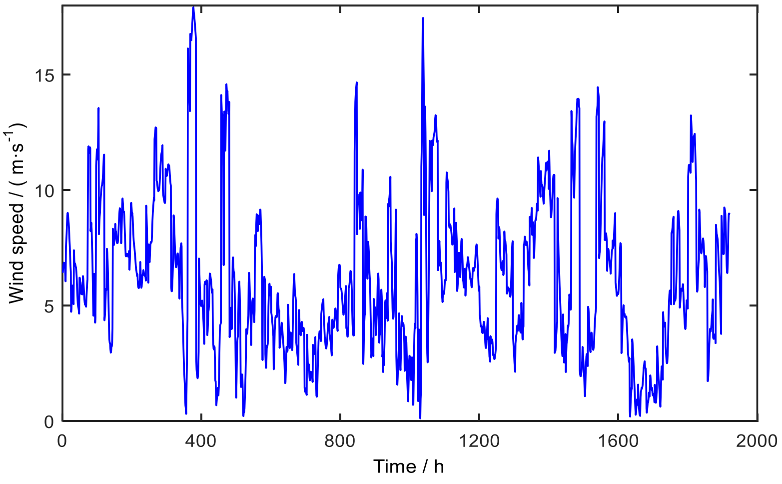

Fig. 3 Wind speed data

### 2.2.2 Wind Turbine Generation

The power generated by the wind turbine $P_{\mathrm{wt}}(t)$ at the time $t$ can be obtained as follows:

$$P_{\mathrm{wt}}(t)=\begin{cases}0 & 0\le v_t\le v_{\mathrm{ci}}\\ N_{\mathrm{wt}}\cdot P_{\mathrm{wt\_r}}\dfrac{v_t-v_{\mathrm{ci}}}{v_{\mathrm{r}}-v_{\mathrm{ci}}} & v_{\mathrm{ci}}\le v_t\le v_{\mathrm{r}}\\ N_{\mathrm{wt}}\cdot P_{\mathrm{wt\_r}} & v_{\mathrm{r}}\le v_t\le v_{\mathrm{co}}\\ 0 & v_t\ge v_{\mathrm{co}}\end{cases} \tag{5}$$

$$0\le P_{\mathrm{wt}}(t)\le N_{\mathrm{wt}}\cdot P_{\mathrm{wt\_r}} \tag{6}$$

where $N_{\mathrm{wt}}$, $P_{\mathrm{wt\_r}}$ and $v_t$ denote the number of wind turbine, rated power of single wind turbine and wind speed. The parameter $v_{\mathrm{ci}}$, $v_r$ and $v_{\mathrm{co}}$ denote cut-in speed, rated speed and cut-out speed. The data of single wind turbine is shown in Table 2. Data of wind speed along the navigation route is shown in Fig 3.

Table 2. Data of wind turbine generator

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Life time | 30 years | Rated speed | 8 m/s |
| Rated power | 30 kW | Cut-in speed | 3 m/s |
| Cost | 1000 $/kW | Cut-out speed | 15 m/s |

### 2.2.3 Energy Storage System

The energy storage system can suppress grid fluctuations caused by the intermittency and sudden changes of wind and solar power in the ship power grid. When the power that is generated by PV, wind turbine and diesel generators exceeds the power load, ESS is charged:

$$E(t)=\begin{cases}E(t-1)+P_{\mathrm{ess}}(t)\cdot\eta_c\cdot\Delta t & t>1\\ E(0)+P_{\mathrm{ess}}(t)\cdot\eta_c\cdot\Delta t & t=1\end{cases} \tag{7}$$

where $E(t)$, $P_{\mathrm{ess}}(t)$ and $\eta_c$ denote the energy stored in ESS, output of ESS and charging efficiency. The time period $\Delta t$ is taken as 1 hour in this paper. $E(0)$ is the initial energy in ESS.

If the power generated by PV, wind turbine and diesel generators can't meet the load, ESS is discharged:

$$E(t)=\begin{cases}E(t-1)+P_{\mathrm{ess}}(t)/\eta_d\cdot\Delta t & t>1\\ E(0)+P_{\mathrm{ess}}(t)/\eta_d\cdot\Delta t & t=1\end{cases} \tag{8}$$

where $\eta_d$ is discharging efficiency.

The service life of LiFePO4 batteries is related to factors such as depth of discharge (DOD), temperature, charge and discharge power, etc. Under the conditions of 20°C operating environment, 0.8 DOD and 1C charge and discharge, the battery has a cycle life of about 5000 times [10]. Then the life time of the ESS $y_{\mathrm{ess}}$ (year) can be obtained by equation (9):

$$y_{\mathrm{ess}}=\frac{\sum(P_{\mathrm{dis}}(t)/\eta_d)\cdot\Delta t}{5000\cdot S} \tag{9}$$

where $P_{\mathrm{dis}}(t)$ and $S$ denote the discharging power of ESS (kW) and the capacity of ESS (kW·h). The data of single LiFePO4 battery is shown in Table 3.

Table 3. Data of battery

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Capacity | 1 kW·h | Max charge power | 1 C |
| Max SOC | 0.1 | Max discharge power | 1 C |
| Min SOC | 0.9 | Charge efficiency | 85% |
| Cost | 200 $ | Discharge efficiency | 100% |

### 2.2.4 Diesel Generator

Different from power system on land, ship diesel generator must meet the total power load, regardless of the use of renewable energy. The ship diesel generator installed total capacity of 4.6 MW, sufficient to ensure 100% reliability. The relationship between the fuel consumption ($FC$) per hour and the output power of diesel generators $P_d$ can be obtained as follows:

$$FC(P_d) = a_0 + a_1 \cdot P_d + a_2 \cdot P_d^2 + a_3 \cdot P_d^3 \tag{10}$$

$$SFC(P_d) = F_C(P_d)/P_d \tag{11}$$

where $a_0$, $a_1$, $a_2$ and $a_3$ are parameters to calculate $CO_2$ emission. The specific fuel consumption ($SFC$) is used to find the best operating conditions of diesel generator. In this paper, $SFC$ is taken to be $336.8 - 66.5 \cdot P_d + 8.2 \cdot P_d^2$ ($\mathrm{kg} \cdot \mathrm{MW}^{-1} \cdot h^{-1}$).

### 2.2.5 Load

The electric propulsion ship has four operating conditions which are regular cruising, docking, loading/unloading and anchoring. Diesel generators always provide most of the electric energy. When the ship is on the condition of loading/unloading and anchoring, dock power will be used to supply all of the ship load.

The load is mainly divided into propulsion load and other load. The energy from PV and wind turbine does not supply the constant propulsion load here. The maximum and minimum of load in four conditions is shown in Table 4. Total load is shown in Fig. 4.

Table 4. Loads under four conditions

| Conditions | Max of propulsion/kW | Max of total/kW | Time proportion |
|---|---|---|---|
| Cruising | 3900 | 4500 | 0.84 |
| Docking | 2700 | 3800 | 0.02 |
| Loading/unloading | 3600 | 4300 | 0.11 |
| Anchoring | 0 | 750 | 0.03 |

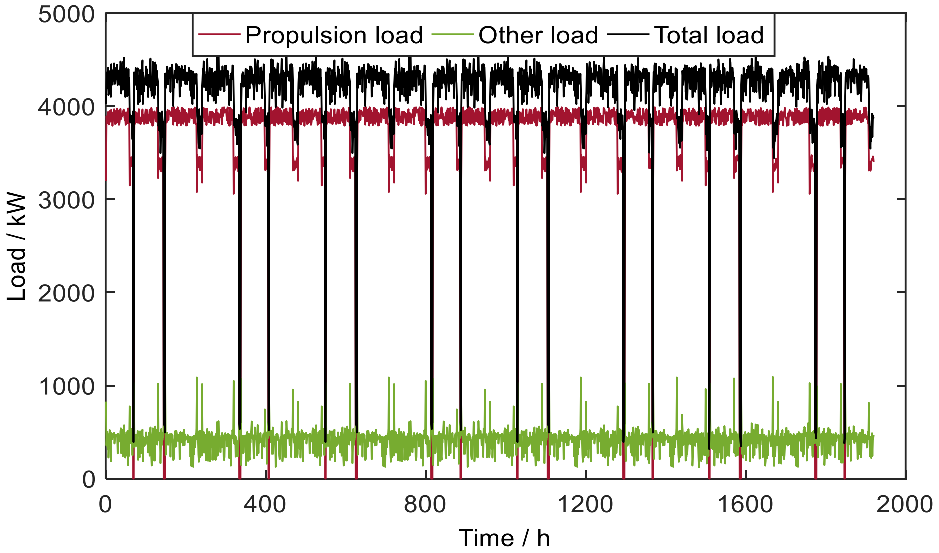

Fig. 4 Ship load for one year

## 3. Problem Formulation

### 3.1 Objective function

The optimization problem of ship power system capacity takes annual operating cost $f_1$ and $CO_2$ emission $f_2$ as the optimization goals, and configures the capacity of each power supply part and the output power of diesel generators under the condition of satisfying system operation constraints.

$$\begin{cases} min \quad f_1 = C_f + C_{\text{in}} + C_{\text{re}} + C_{\text{mt}} \\ min \quad f_2 = AEEOI = \sum_{j=1}^{T} \omega_j \cdot EEOI_j / T \end{cases} \tag{12}$$

More specifically,

$$\begin{cases} C_{\text{f}} = \sum_{j=1}^{T} c_{\text{f}} \cdot P_j \cdot SFC(P_j) \cdot \Delta t_j \\ C_{\text{in}} = \sum_{i=1}^{3} N_i \cdot c_i \cdot \dfrac{r(1+r)^{y_i}}{(1+r)^{y_i} - 1} \\ C_{\text{re}} = \sum_{i=1}^{3} N_i \cdot c_i \cdot ceiling(\dfrac{y_{\text{ship}}}{y_i} - 1) \cdot \dfrac{r(1+r)^{y_i}}{(1+r)^{y_i} - 1} \\ C_{\text{mt}} = \sum_{i=1}^{4} \sum_{j=1}^{T} c_{\text{mt}i} \cdot P_{ij} \cdot \Delta t_j \end{cases} \tag{13}$$

where $C_f$, $C_{\text{in}}$, $C_{\text{re}}$ and $C_{\text{mt}}$ denote fuel cost, install cost, replecement cost and maintenance cost, $c_{\text{f}}$, $c_i$ and $c_{\text{mt}_i}$ denote fuel price, ennergy system price and maintenance price, $y_i$ is the life time of energy system. The fucntion $ceiling$ is used to rounding of a real number nearest integer.

$$\begin{cases} EEOI_j = \frac{mCO_{2,j}}{LF_j \cdot V_j \cdot \Delta t_j} \\ mCO_{2,j} = c \cdot P_j \cdot SFC(P_j) \\ \omega_j = \frac{V_j \cdot \Delta t_j}{dis_{max}} \end{cases} \tag{14}$$

The objective $f_2$ (average energy efficiency operation indicator, AEEOI) is modified from energy efficiency operation indicator (EEOI) [6]. The $EEOI_j$ in each time period along the route is calculated using (14) where $mCO_{2,j}$ is the $CO_2$ emission. The weighting factor $\omega_j$ of $EEOI_j$ can be obtained in (14) where $LF$, $V$ and $dis_{max}$ denote ship's load factor, ship speed and the longest passage which the ship sials during $\Delta t$.

### 3.2 Constrains

1) Output power limit of each power system.

$$P_{min,i} \le P_i \le P_{max,i} \quad \forall i \tag{15}$$

where $P_{min,i}$ and $P_{max,i}$ denote the minimum and maximum of $i^{\text{th}}$ power system.

2) Balance between power generation and electric load.

$$P_d + P_{\text{pv}} + P_{\text{wt}} + P_{\text{ess}} = P_{\text{load}} \tag{16}$$

where $P_{\text{load}}$ is the ship power load.

3) The limit of diesel generator.

$$|P_{d,j} - P_{d,j-1}| / \Delta t_j \le R_C \quad \forall j \tag{17}$$

where $R_C$ denotes the maximum climbing rate of diesel generator.

4) Renewable power system and ESS installable size limit.

$$N_{min,i} \le N_i \le N_{max,i} \quad \forall i \tag{18}$$

where $N_{min,i}$ and $N_{max,i}$ denote the minimum and maximun amount of $i^{\text{th}}$ power system.

### 3.3 Solution method

According to the optimization model established above, the capacity of each power system is solved with the annual operating cost and $CO_2$ emissions as the optimization goals. This paper uses multi-objective differential evolution algorithm based on decomposition and multi-strategy mutation (MODE-DMSM) to solve this problem.

## 4. Simulation Result and Discussion

Three cases are obtained by simulation. Case 1 shows the initial condition (diesel only), case 3, case 4 and case 5 are optimal results with different weight distributions of the sub-objective functions. Case 2 shows the optimal result without the use of ESS. The number or size of PV panels, wind turbine and ESS in all cases have reached the maximum installable size (1000 $m^2$ and 6 wind turbine generators, respectively), because the combine cost of the renewable energy system is lower than the cost of fuel generation.

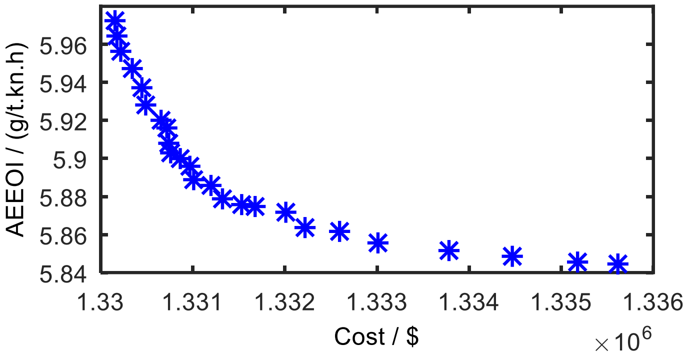

Fig. 5 Pareto frontier

Table 5. Cases obtained by simulation

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| PV ($m^2$) | 0 | 1000 | 1000 | 1000 | 1000 |
| Wind (kW) | 0 | 180 | 180 | 180 | 180 |
| ESS (kW·h) | 0 | 0 | 778 | 832 | 813 |
| Fuel cost ($) | 1359286 | 1306773 | 1279407 | 1287383 | 1286274 |
| Total cost ($) | 1359286 | 1334054 | 1334006 | 1332213 | 1331195 |
| AEEOI (g/tn.kn.h) | 6.41 | 6.15 | 5.86 | 5.89 | 5.92 |

The cost and the emission of case 2 comparison of case 1 are both reduced, which proves that the application of new energy reduces the power generation of diesel generators and reduces greenhouse gas emissions. The randomness and intermittency of new energy will lead to fluctuations in the ship power grid, which can be eliminated by the ESS in case 3-5. Compared with case 2, case 3-5 have further improvement in two indicators.

## 5. Conclusion

Aiming at two goals of reducing ship operating cost and reducing ship greenhouse gas emissions, this paper establishes a multi-objective optimization model for the capacity of renewable energy system, and uses MODE-DMSM algorithm to solve the model. The simulation results prove the use of renewable energy and ESS can reduce ship operating costs and $CO_2$ emissions. The use of renewable energy and ESS can significantly reduce fuel consumption and emissions.

Future study will consider the influence of wind and ship speed on the output of wind turbines, the output control strategy of each power supply system.

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