

Energy Transmission Mode Based on All-electric Vessels for Pelagic Islands and Its Coordinated Scheduling Strategy

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Abstract. There is a lack of effective liaison between pelagic island microgrids, leading to inflexible transmission of energy between islands. However, the interconnection mode by submarine cables is not economical due to the long distances between islands. Therefore, an energy supply mode based on all-electric vessels is proposed in this paper. The framework and working principle of the mode are first introduced. A two-stage optimization model is established considering the coordinated operation of island microgrid and the swapping plan of all-electric vessels. The simulation results show that the proposed transmission mode can reduce overall costs and the proposed scheduling strategy can promote renewable energy consumption and reduce operation costs.

1 Introduction

Pelagic islands and the surrounding affiliated islands are rich in wind/solar energy resources. However, since pelagic islands are generally distributed in the form of island groups, the land area of a single island is very limited, and only small part islands are liveable and developable. These islands are usually densely populated. If renewable energy (RE) equipment is fully placed on these islands too, it is difficult to separate the generation units from residential areas and other equipment to be separated from the residential area of the island. The noise and light pollution are hard to avoid and the life quality of island residents will be greatly affected.

To cope with the above problem, the islands are divided into resident islands (RIs) and energy supply islands (ESIs) according to the population distribution and resource reserves. ESIs are generally uninhabited, large-capacity renewable energy units and energy storage systems are arranged on the island to undertake the task of supplying energy to RIs. ESIs are equipped with conventional units (gas turbines, diesel turbines). They rely on RE provided by ESIs and conventional units to maintain energy autonomy.

The energy transmission requires an appropriate medium. Submarine cables are certainly feasible. However, interconnection projects usually have extremely high investments and are difficult to repair. In addition, not all islands are available for cable interconnection due to route restrictions.

An alternative scheme using all-electric vessels to transmit RE is proposed in this paper: Multiple sets of integrated battery energy storage modules are configured both on ESIs and RIs. Each battery module can independently manage energy according to the current

state of charge (SOC). The energy management system (EMS) of pelagic islands will optimize the working state of each battery according to the RE and load data. All-electric vessels with sufficient loading space which can load/unload energy storage battery module are configured between islands. They can timely transport and replace battery modules between islands according to the instructions issued by the EMS. Thus, an energy supply link to RIs is formulated. Although this model has a certain increase in the investment cost of power stations and energy storage systems, its battery swapping mode can decouple the charging and discharging operation of the energy storage system from the vessel's space-time behaviour. In addition, the overall management of the battery energy storage module can optimize the charge and discharge process, extend battery service life and reduce long-term operating costs.

In-depth studies have been carried out on the battery swapping model for conventional urban public traffic systems, including the battery swapping challenge [1], the operation mode of electric vehicle charging stations [2] and the battery management of smart charging/swapping services [3]. An optimal planning method for charging/swap stations is proposed in Ref.[4] considering life cycle costs. Ref.[5] proposes a transient model of the battery storage system to study its impact on power system transient stability. Ref.[6] proposes a centralized charging strategy of electric vehicles under the battery swapping scenario by considering optimal charging priority and charging location based on spot electric price. A dynamic operation model of battery storage system in the electricity market is proposed in Ref.[7], the proposed strategy is able to acquire additional revenue by responding actively to the price fluctuation in the electricity market.

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The above researches provide rich technical experiences for the planning, operation, and optimization of power swap stations in urban power grids. However, different from the traditional power station charging mode, the main function of the power station in pelagic islands is to store fluctuating and unstable RE sources and distribute them to RIs in time, which will help to maximize the consumption of RE and reduce the island fuel consumption. In this process, the coordination of the charge and discharge strategy with the scheduling of all-electric vessels is particularly important.

However, the energy transmission route based on all-electric vessels is firstly proposed in this paper, the scheduling strategy for vessel route and energy storage systems has not been studied either. Therefore, a two-stage optimization model is established considering the coordinated operation of island microgrid and the swapping plan of all-electric vessels. The simulation results verify the effectiveness of the proposed model.

2 Energy Transmission Mode Based on All-electric Vessels

A typical energy supply framework for pelagic islands is shown in **Fig.1**. There are several ESIs around the RI, which are equipped with large capacity renewable energy units, a charging & swapping station (CSS) and a vessel storage module. The power produced by them is stored in the energy storage module. Considering that the series and parallel operation of energy storage units with different SOC will reduce the effective capacity and safety performance of the equipment, and shorten the cycle life, the battery energy supply system of the power plant is composed of one or multiple groups of packaged large-capacity battery energy storage modules. Each module has a separate port, so it can independently control its charge and discharge power.

The vessel station, CSSs and island EMS achieve communication, information sharing and operation scheduling in a common framework protocol. Based on the wind/solar forecasting data, the EMS of ESI calculates the expected charging time of the battery module, the EMS of RI controls the battery module, gas turbines, and flexible load according to the SOC of the battery module, so as to realize the optimal operation of RI. At the same time, EMS optimizes the battery swapping priority of each island, and send the battery swapping plan to all-electric vessels in advance so that the vessel can complete the replacement and recovery of the battery module according to the plan.

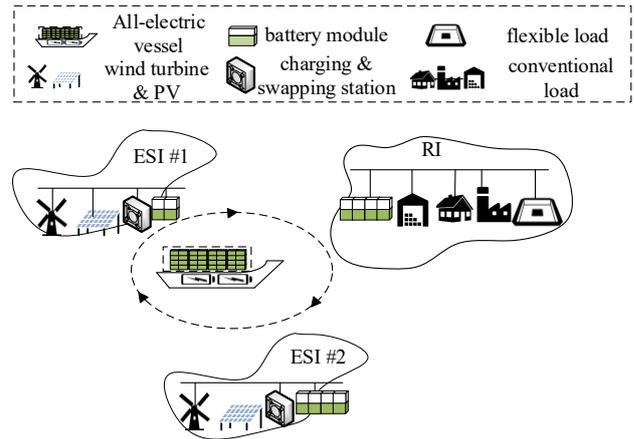


Fig. 1. Energy supply framework for pelagic islands

3 Two-stage scheduling model for Pelagic Islands and Energy Transmission Routes Based on All-electric Vessels

Because the forecast error of wind power and PV output is related to the forecast time scale, the shorter the forecast time scale is, the lower the forecast error is. For pelagic islands, the capacity of each unit is small, diesel units and gas turbines can be started quickly and their output can be adjusted in time, it is unnecessary to make a day-ahead plan. For exclusive all-electric vessels, they are usually parked in the island port for standby when there are no swapping demands. Therefore, they can meet the demand for real-time scheduling. Based on the above assumptions, this paper uses an intraday rolling optimization scheduling model to develop a 0-24h optimization scheduling plan. According to the current states of RI and ESI, the plan is developed every hour, which is shown in **Fig.2**. The optimization variables include the decision-making variables of swapping states, the charging/discharging power of battery modules, the on/off state and power of the flexible load.

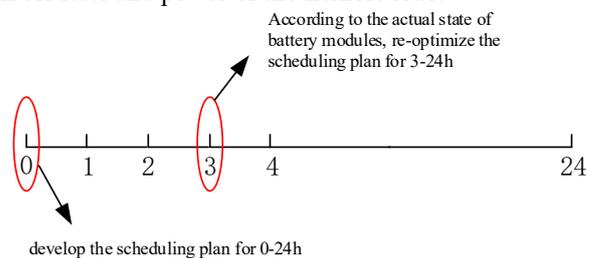


Fig.2 Rolling optimization model for daily scheduling

3.1. Model of flexible load

RI is equipped with desalination units and water tanks. Desalination units need to produce adequate fresh water in advance to meet the users' water demand in the next day. It should be noted that the reservoir capacity is large enough to accommodate the total amount of fresh water prepared in one day.

Since the desalination units is controlled by the EMS of RI, its on-off state and operating power can be adjusted actively during its operation period. Assuming that the daily fresh water demand is W_d , the operation period of desalination unit is $[T_{st}, T_{end}]$:

$$\sum_{t=T_{st}}^{t=T_{end}} \frac{s_{dh}^t P_{dh}^t}{\lambda_{dh}} \geq W_d \quad (1)$$

$$s_{dh}^t = 0 \quad \forall t \notin [T_{st}, T_{end}] \quad (2)$$

$$P_{dh\min} < P_{dh}^t < P_{dh\max} \quad (3)$$

Where s_{dh} is the 0-1 decision variable of desalination unit. P_{dh}^t is the power of the desalination unit, $P_{dh\max}$, $P_{dh\min}$ is the upper and lower bound of the desalination unit. λ_{dh} is the unit power consumption of freshwater production.

3.2. Objective function

The coordinated scheduling model aims to minimize the overall operation costs of RI, including the generation costs of conventional units, the pollutant emission costs, the onshore RE costs, the battery storage costs and the costs of wind/solar curtailment:

$$\begin{aligned} \min F = & \sum_{i=1}^I C_{DT} (\beta P_{Di}^t + \gamma) + \sum \alpha_j W_j P_{Di}^t + C_{re} E_{tr} (1 - \eta_{ch}) \\ & + C_{re} (E_{retol} - E_{tr}) + \sum_{j=1}^J C_{tr}^j (e_{tr}^j - e_{trq}^j) (1 - \eta_{dch}) \end{aligned} \quad (4)$$

Where P_{Di}^t is the power of conventional unit at time t , T is the time interval; β and γ are fuel consumption coefficients, C_{DT} is the fuel price; α_j and W_j are the cost conversion coefficient and unit emission of pollutant j , respectively, the value refers to Ref. [8]; η_{ch} is the charging efficiency of storage battery, $E_{retol} - E_{tr}$ is the RE curtailment of RI, J is the transmission time during the scheduling period.

3.3. Constraints

1) Due to the limitation of the island area, the scale of ocean island grid is very small, and the length of cable is usually only hundreds of meters or several kilometres. Therefore, the network loss can be ignored. The power balance of RI is:

$$P_{dch}^t + P_{Di}^t = P_{load}^t \quad \forall t \in T \quad (5)$$

Where P_{dch}^t is the discharging power of battery at time t , P_{load}^t is the sum of load demand at time t .

2) Energy balance constraint of the storage battery:

$$W_{bat}^t = W_{bat}^{t-1} + \tau \left(P_{ch}^t \eta_{ch} \lambda_{er}^t - \frac{P_{dch}^t}{\eta_{dch}} \lambda_{lc}^t \right) \quad (6)$$

Where W_{bat}^t is the energy of the storage battery at time t , τ is the time interval. λ_{er}^t , λ_{lc}^t are the state variable of the storage battery, which is determined by the swapping time and sequence. When the storage battery is connected to ESI, the value of λ_{er}^t is 1. When the storage battery is connected to RI, the value of λ_{lc}^t is 1.

3) Constraint of the SOC of storage battery:

$$W_{bat}^{end} \geq W_{bat}^{st} \quad (7)$$

$$0.1 < SOC < 0.9 \quad (8)$$

Where W_{bat}^{end} is the SOC of the storage battery at the end of the scheduling period and W_{bat}^{st} is the SOC of the storage battery at the start of the scheduling period.

4) Constraint of the output of conventional units:

$$P_{Di,\min} < P_{Di}^t < P_{Di,\max} \quad (9)$$

$$\left| P_{Di}^{t+1} - P_{Di}^t \right| \leq \Delta P_{Di,\max} \quad (10)$$

Where $P_{Di,\min}$, $P_{Di,\max}$ are the upper and lower bound of conventional units, respectively. $\Delta P_{Di,\max}$ is the maximum ramp rate.

5) Constraint of the swapping mode:

$$S_{bat1}^t + S_{bat2}^t \leq 1 \quad (11)$$

$$S_{bat1}^t + S_{bat1}^{t+1} \leq 1 \quad (12)$$

$$S_{bat2}^t + S_{bat2}^{t+1} \leq 1 \quad (13)$$

Where S_{bat1}^t , S_{bat2}^t are two types of swapping mode.

3.4. Optimization method

Since the constraints in Section 3.3 are linear, the above model is a mixed-integer linear programming model. This paper uses CPLEX solver to solve the above problem.

4 Case study

A case including one RI and one ESI is studied in this paper. Assuming that the ESI is equipped with 200kW wind turbines, 100kW PV. RI is equipped with two conventional units. One is a conventional gas turbine with a rated power of 250KW to meet the power demand of all loads during normal operation (the peak value of the conventional load is 223.5kw), and the other is an emergency standby diesel unit with a rated power of 80kW (the peak value of non-interruptible load is 60kW). The daily freshwater demand of RI is 50t. There are two storage battery modules, each of which is composed of 500 batteries of 2V/1000Ah. The maximum charging/discharging current is 0.2C. The distance between the RI and the ESI is 37km. The voyage time for all-electric vessels is 1 hour. The other parameters are shown in Table.1 (The annual operation and maintenance costs of all kinds of units is taken as 5% of its investment).

Table 1. Parameters of different unit in pelagic islands

ESI	
Unit investment of wind turbines ^[9]	1450 \$/kW
Unit investment of PV	1700 \$/kW
All-electric vessel & storage battery ^[10]	
Investment of all-electric vessel	10,000 \$
Transportation cost for round trip	30 \$
Charging/discharging efficiency	90%
Investment of storage battery	650 \$/kWh
The maximum depth of discharge	80%
The maximum recycle times	4000
RI	
Gas price	0.68 \$/m ³
Pollutant cost	0.07 \$/kW
β	0.55m ³ /kW
γ	0.2m ³
Ramp rate of gas turbine	150kW/h
The minimum power of gas turbine	30kW
The minimum power of diesel unit	10kW
Ramp rate of diesel unit	80kW/h
The rated power of desalination unit	60kW
Operation time of desalination unit	0: 00-12: 00
The minimum power of desalination unit	8kW
Unit power consumption of freshwater production	7kW/t

The average liquefied natural gas (LNG) price is about 772 \$/t, considering the shipping cost of LNG fuel is about 0.03 \$/m³, the vaporization cost and management cost is about 0.06 \$/m³, the price of natural gas in this paper is 0.68 \$/m³. ESI and RI are both equipped with all-electric vessels.

The operation cost is mainly affected by the power characteristics of RE and load demand. Due to the stochastic characteristics of RE, two typical scenarios are considered in this paper:

Scenario 1: The RE output is high and wind power fluctuations are relatively gentle.

Scenario 2: The RE output is low and wind power is with strong anti-peaking characteristics.

The initial SOC of the two energy storage modules is set to 0.5. To verify the effectiveness of the strategy, the following schemes are compared.

Scheme 1: ESI does not construct any RE power generation unit, the load demand of RI is only met by gas turbines.

Scheme 2: ESI and RI are connected by submarine cables and energy storage system is not constructed.

Scheme 3: ESI and RI are connected by all-electric vessels. All-electric vessels are scheduled in real-time based on the SOC of battery modules. The principle of battery swapping strategy is designed as when the SOC of the battery module in RI is below a certain limit and the SOC differences between the two islands reach a threshold, the priority of the RI energy storage replacement is higher. When the SOC of the battery module in ESI is higher than a certain limit and the SOC differences between the two islands reach a threshold, the priority of the ESI energy storage replacement is higher. The specific principle is shown as:

$$\begin{cases} |SOC_{ESI} - SOC_{RI}| \geq 0.6 \\ SOC_{ESI} \leq 0.15 \end{cases} \quad (14)$$

$$\begin{cases} |SOC_{ESI} - SOC_{RI}| \geq 0.6 \\ SOC_{ESI} \geq 0.85 \end{cases} \quad (15)$$

Where SOC_{ESI} , SOC_{RI} are the SOC state of the battery module in ESI and RI respectively.

Scheme 4: ESI and RI are connected by all-electric vessels, the scheduling scheme is formed through the proposed model.

1) Scenario 1

The wind/solar output and the typical day-ahead forecast load curve and the actual load curve of RI are shown in Fig.3. The forecast load curve is generated by adding a 20% deviation to the original actual load curve.

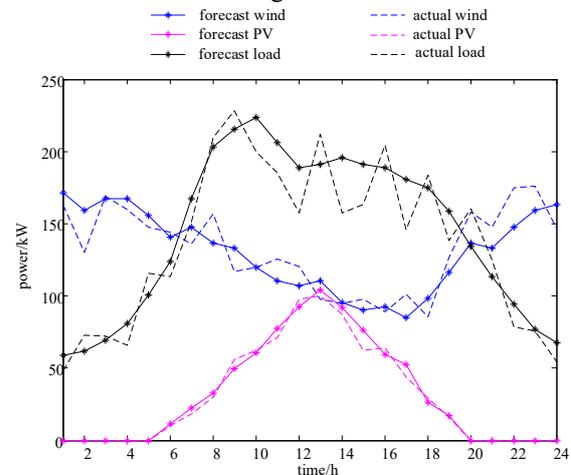


Fig.3 Renewable energy and load demand under Scenario 1

Since the operation cost of the gas turbine is a linear function and the RI net is small in scale, the network loss is negligible. Therefore, the power of the desalination unit does not affect the daily operating cost of the RI for Scheme 1.

The total energy consumption of the conventional load in RI is 3466.8 kWh, and the energy consumption of the desalination unit is 350 kWh. Since the gas turbine is normally open, its fuel consumption in 24 hours is only related to the total power generation. Therefore, the total daily operation cost of Scheme 1 is 1799.5 \$.

The investment of 35kV submarine cable is about 140 k\$/km, the service life is 30 years. Regardless of the transmission loss of the cable, when the ESI does not build an energy storage system, the total daily cost (the investment is converted to equivalent annual cost) of Scheme 2 is 2536.8 \$.

For Scheme 3, the SOC states, swapping states and power curves in ESI, RI are shown in Fig.4. It should be noted that when the value of SOC is 0, the battery energy storage is vacant on the corresponding island (in transit). If the value of swapping state is 1, it indicates that the corresponding swapping mode is adopted at that time.

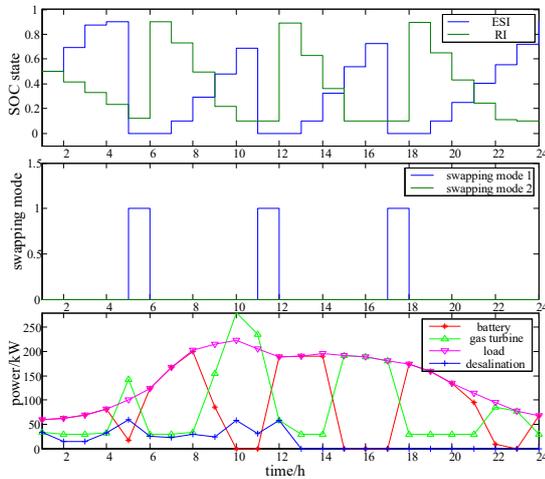


Fig.4 Optimization result of scheme 3 under Scenario 1

For Scheme 4, the SOC states, swapping states and power curves in ESI, RI are shown in Fig.5.

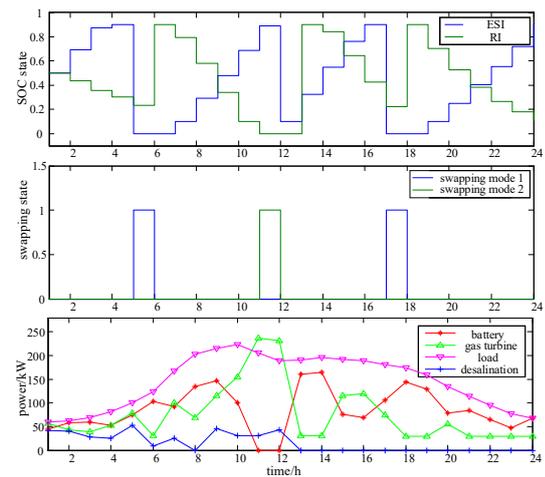


Fig.5 Optimization result of scheme 4 under Scenario 2

Table.2 Operation results of different schemes under Scenario 1

Scheme	Wind/solar curtailment/ %	Cost of gas turbine /\$	Total daily cost /\$
Scheme 1	0	1799.5	1799.5
Scheme 2	1.5	399.3	2536.8
Scheme 3	3.8	956.3	1685.7
Scheme 4	2.9	845.1	1537.3

Table 2 gives the operation results of the 4 schemes. Although Scheme 2 (cable connections) has the least wind/solar curtailment, the total daily cost is the highest because of the investment of submarine cables. This is also the main reason why pelagic islands still rely heavily on conventional units. In fact, for Scheme 2, even if it is equipped with energy storage systems and the wind/solar energy can be fully consumed, (the total RE output is 3920.3 kWh, which is greater than the total load demand, that is, the most ideal situation is that the gas turbine is

not needed and the load is fully satisfied by the RE). By converting the cable investment into daily cost, the total daily cost of Scheme 2 is 2203.3 \$, which is still much higher than other schemes. The cost-effectiveness of Schemes 3 and Scheme 4 (energy supply route by all-electric vessels) are better than those of Scheme 1 and Scheme 2. The total cost of scheme 4 is reduced by 14.6% and 40.3% respectively, compared with Schemes 1 and Scheme 2.

For Scheme 3, because the energy production and consumption rate of ESI and RI are not always balanced, the total daily RE consumption under the same number of energy swapping times is not as good as that of Scheme 4, and it leads to higher fuel consumption in RI. Scheme 4 can improve the RE consumption rate and reduce the operation cost by optimizing the swapping plan, the power of energy storage and flexible load.

The RE output and load demand under Scenario 2 are shown in Fig.6.

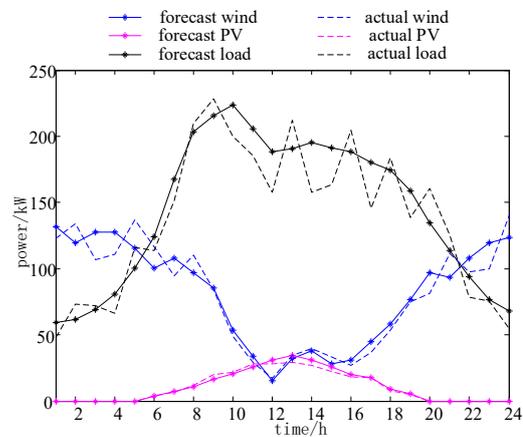


Fig.6 Renewable energy and load demand under Scenario 2

Table.3 Operation results of different schemes under Scenario 2

Scheme	Wind/solar curtailment/ %	Cost of gas turbine /\$	Total daily cost /\$
Scheme 1	0	1799.5	1799.5
Scheme 2	1.2	882.9	3081.0
Scheme 3	2.5	1206.8	1782.5
Scheme 4	1.9	1079.2	1684.2

From Table.3, as the output of RE sources decreases, except for Scheme 1, the cost of each scheme has increased. Scheme 2 is still the least economical solution. Compared with Scheme 3, Scheme 4 still reduces the operating costs by 5.8% based on more efficient energy swapping plans.

Besides, under normal scenarios, the cost-effectiveness of energy transmission routes based on all-electric vessels is superior to those of conventional schemes using gas turbines or cable connections. Compared with Scheme 3, the overall cost and the amount of wind/solar curtailment are both reduced in Scheme 4.

5 Conclusion

This paper proposes an energy supply mode based on all-electric vessels. A two-stage optimization model is

established considering the coordinated operation of island microgrid and the swapping plan of all-electric vessels. The major conclusions are as follows:

- 1) Compared with conventional isolated supply mode (gas turbine) and cable-connected supply mode, the overall costs of the proposed supply mode based on the transmission routes of all-electric vessels are lower, with an average drop of 10.5% and 42.6% respectively.
- 2) The cable-connected mode can maximize the transmission of electric energy and reduce the curtailment of wind/solar resources, but the high investment cost of submarine cables results in the highest overall cost of island microgrid. In practical projects, it is advisable to consider the actual needs comprehensively and adopt the most appropriate technical solution.

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