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Technical requirements and economic benefit evaluation of interaction between vessel charging and battery swapping stations and power Grid

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Abstract. Electric vessels have developed rapidly with the advancement of transportation electrification in recent years. The power battery capacity of large vessels usually reaches several MWhs, in which case battery change technology is more applicable. A vessel charging and battery swapping station has the dual attributes of power utilization and energy storage and can realize Vessel to Grid through charging and discharging facilities. Aiming at the scenarios of interaction between vessel charging and battery swapping stations and the power grid, this paper studied technical requirements of several participants, established an input-output analysis model and analyzed multiple influencing factors. The results show that revenues cannot be increased effectively with the increase of the number of spare batteries alone; the interactive service can achieve a balance of payments when the battery cost is higher than 1.4 ¥/ Wh, and; benefits may not be gained when the battery life is less than 5 years.

1 Introduction

There are many inland rivers and lakes in China. A large number of traditional vessels have caused serious pollution. The impact on urban areas is more prominent when they call at ports. The promotion of electric vessels is an important part of transportation electrification [1] and the transformation of port shore power facilities is also a future trend [2]. It is difficult for cargo ships to call at ports for charging due to their large carrying capacity and MWh-level power batteries in combination with the carrying rule and the impact of port work. Therefore, the construction of vessel charging and battery swapping stations is a necessary approach to responding to the development of electric vessels.

Large-capacity spare batteries in charging and battery swapping stations can be used as an energy storage system to provide auxiliary services for the power grid and thus obtain additional revenues. In addition, Vessel to Grid (V2G) can also be realized through two-way charging and discharging equipment during berthing [3]. The research on the participation of electric vehicle charging and battery swapping stations in the interaction with the power grid has been relatively mature [4], but there is less research on the scenarios of vessel charging and battery swapping stations.

To this end, this paper first established an interactive framework of "vessel - shore power - grid", proposed technical requirements for multiple key roles, further put forward an input-output evaluation method of vessel charging and battery swapping stations in response to shore power system and grid load fluctuations, and finally conducted a sensitivity analysis of multiple influencing factors.

2 Interactive frameworks of "vessel - shore power - grid"

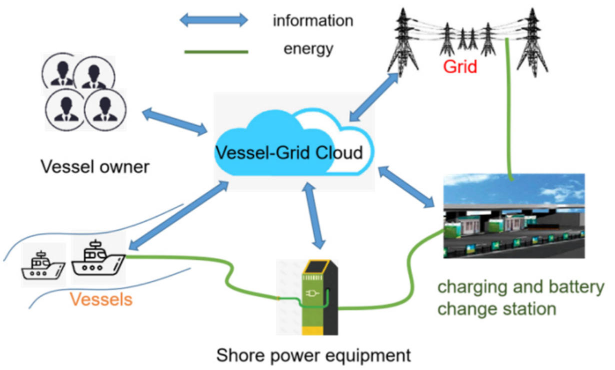

Figure 1. Interactive framework

As shown in Figure 1, the Vessel-Grid Cloud platform requires the ability of mass data storage and high-speed parallel computing in order to open up information congestion points of the grid and charging and battery swapping stations, analyze the response plan of spare batteries and V2G in battery change stations based on requirements of grid operation optimization and issue

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control commands. Shore power facilities shall provide standardized charging and discharging interfaces and be able to realize two-way meter measurement. Electric vessel users provide charging behavior data and vessel data by registering on the mobile terminal. Batteries for change are reserved according to user behavior or sufficient power is left at the end of V2G to avoid users' anxiety for mileage. For distribution network dispatching, reasonable predictions shall be made on the load of electric vessels in the next period, and requests for peak regulation, alleviation of transmission congestion and improvement of power energy shall be made according to the power consumption curve.

3 Input-output evaluation model

3.1Operation mode of vessel charging and battery swapping stations

There are 4 main operation modes for charging and changing battery stations that have relevant services and respond to grid interaction demands according to their energy flow [5]:

(1) Instation battery charging mode: the charging time and power of the charger are reasonably controlled according to the charging demand of batteries stored on the battery rack, the load of the grid and the electricity price. Battery change is carried out when required by electric vessels.

(2) Instation battery discharging mode: auxiliary services of the power market are attended according to dispatching needs of the grid so as to meet the requirements of grid peak regulation and alleviation of transmission congestion and gain auxiliary service costs.

(3) Electricity mode for ships calling at ports: ships connect to the distribution network through shore power equipment, which provides auxiliary power for lighting and unloading, etc. or charges ships.

(4) Discharging mode for ships calling at ports: ships calling at ports supply power to the grid in reverse through two-way charging guns to gain auxiliary service costs.

3.2Energy conservation model

Charging and battery swapping stations comply with energy conservation when operating in a steady state:

$$E_{ch} = E_{dis} + E_V \quad (1)$$

Where E_{ch} is the total charging power; E_{dis} is the power released to the grid during interaction; E_V is the power consumption during traveling.

3.3Analysis of revenues and expenditures

The economic model consists of revenues and expenditures:

$$R_y = (I_y - O_y) \bullet (1 - \varepsilon) \quad (2)$$

Where R_y is the total profit in year y; I_y is the total income in year y; O_y is the cost in year y; ε is the tax rate.

(I) Revenue analysis

Revenues include the income from charging and battery swapping, auxiliary service costs and the residual value income of charging and battery swapping stations after a certain number of years.

(1) Income from charging and battery swapping.

$$I_{1,y} = (P_c + S_c) \cdot E_c + (P_e + S_e) \cdot E_e \quad (3)$$

Where P_c and P_e are charging and battery swapping prices respectively; S_c and S_e are charging and battery swapping service fees respectively; E_c and E_e are charging and battery swapping capacities respectively.

(2) Auxiliary service costs, gained by feed to the grid:

$$I_{2,y} = P_a E_{dis} \quad (4)$$

Where P_a is the electricity price for participation in auxiliary services; E_{dis} is the electricity released to the grid.

(3) Residual value income. The residual value $I_{3,y}$ in year y is:

$$I_{3,y} = \sum P_k \cdot (1 - R_0 - y \cdot R) \quad (5)$$

Where P_k is the original value of equipment k in the battery change station; R_0 is the initial depreciation rate; R is the annual depreciation rate. The residual value of the battery system is mainly considered.

(II) Expenditure analysis

Expenditures mainly include construction costs, electricity purchase costs and operation and maintenance costs.

(1) Construction costs O_1, mainly including initial investment costs O_c for the construction of charging and battery swapping stations, their special distribution stations and low-voltage lines in the initial stage. Cloud platform establishment costs O_p and renovation costs O_v of two-way charging piles, etc. shall also be considered if interactive services are applied. Variable costs mainly include spare battery purchase costs O_b:

$$O_b = P_b \cdot C \quad (6)$$

Where P_b is the purchase cost of battery power per kilowatt hour and C is the total capacity of the battery purchased.

(2) Electricity purchase costs $O_{2,y}$ is:

$$O_{2,y} = D\left(\frac{E_V}{\eta_c \eta} + \frac{E_{dis}}{\eta_c^2 \eta}\right) \cdot P_g \quad (7)$$

Where η_c is the efficiency of the charger; η is the efficiency of the battery change station; η is the price of electricity purchase from the grid for the charging station; D is annual operation days of the battery change station.

(3) Operation and maintenance costs. $O_{3,y}$ can be calculated based on the proportion of fixed assets, i.e.

$$O_{3,y} = \sum \sigma_k \cdot P_k \quad (8)$$

Where σ_k is the proportion of operation and maintenance costs of equipment k in equipment costs. The operation and maintenance cost C_V of interactive services shall also be considered if interactive services are applied.

3.4Economic benefit evaluation method

Economic benefits were evaluated with Net Present Value (NPV) [6]:

$$npv_y = \sum_{i=1}^{n} \frac{V_i}{(1+r)^i} \quad (9)$$

Where r is the discount rate, 8%; V_i is the i th cash value in year y. That is, $V_i = [V_1, V_2, \ldots, V_n]$.

4Case analysis

4.1Parameter descriptions

Related parameters of expenditures are shown in Table 1:

Table 1. Expenditure parameters (¥)

O_c	O_p	O_v	P_b	P_g	C_V
620000	500000	120000	1.2/Wh	0.38/kWh	20000

Related parameters of revenues are shown in Table 2:

Table 2. Revenue parameters (¥)

P_c	S_c	P_e	S_e	P_a	R_0	R
0.88/kWh	0.1/kWh	0.98/kWh	0.2/kWh	0.88/kWh	30%	5%/year

Relevant parameters of vessels and batteries are shown in Table 3:

Table 3. Relevant parameters of vessels and batteries

Number of large vessels	Battery capacity of large vessels	Number of small vessels	Battery capacity of small vessels	Number of spare batteries for large vessels	Number of spare batteries for small vessels	Charging and discharging efficiency	Battery aging rate
5	2000kWh	20	200kWh	3	5	0.95	3%/year

In addition, the annual average number of equivalent cycles of batteries is 150 for each vessel. 80% of large vessels and 50% of small vessels choose battery change. The battery aging rate increases by 50% after participation in the interaction. The battery system cannot be used for vessels but only provides instation interactive services when it is attenuated to 70% of the initial capacity and must enter the recycling system when it is attenuated to 50%.

Economic calculation was made for the 10-year investment period. Economic benefits with (A) and without (B) participation in the interaction were compared. As shown in Figure 2, revenues can be achieved soon and operational risks are reduced in scenario B though the initial investment is large.

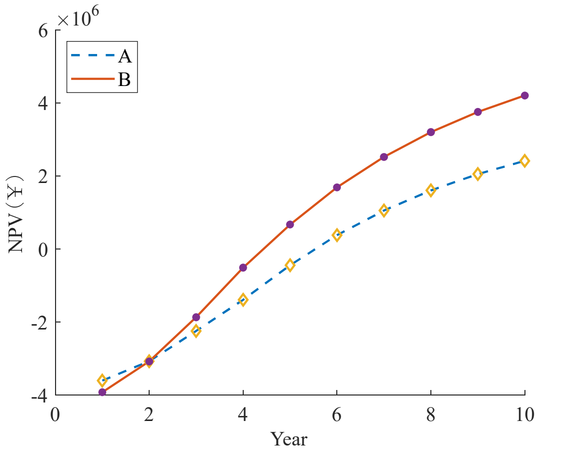

Figure 2. NPV comparison for different investment periods

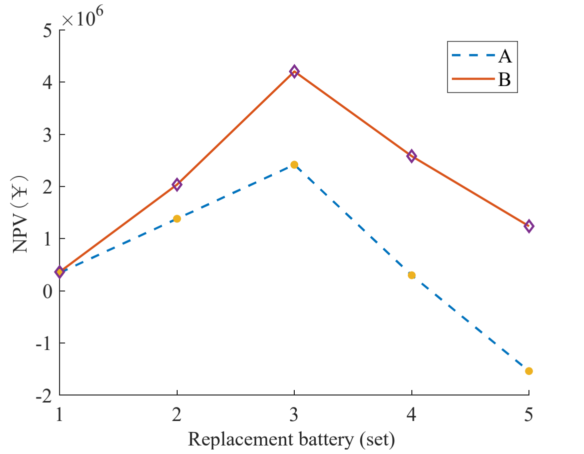

Figure 3. Analysis on the impact of the number of batteries

4.2Sensitivity analysis

(1) Number of spare batteries

The number of spare batteries for large vessels was changed and NPVs at the end of the 10-year investment period were compared, as shown in Figure 3.

A reasonable increase in the number of spare batteries can provide battery change services effectively and bring benefits from grid interaction. However, it is not always better to have more spare batteries. When the number of spare batteries exceeds the resources required for battery change services and grid interaction, on the one hand, the operation and maintenance costs of fixed assets will increase; on the other hand, the depreciation of excess batteries will cause cash loss, thereby resulting in low final revenues after 10 years.

(2) Power battery cost

As shown in Figure 4, the higher the cost, the lower the final revenue. Additional profits of interactive services are required to ensure the balance of payments when the battery cost is higher than 1.4 ¥/ Wh.

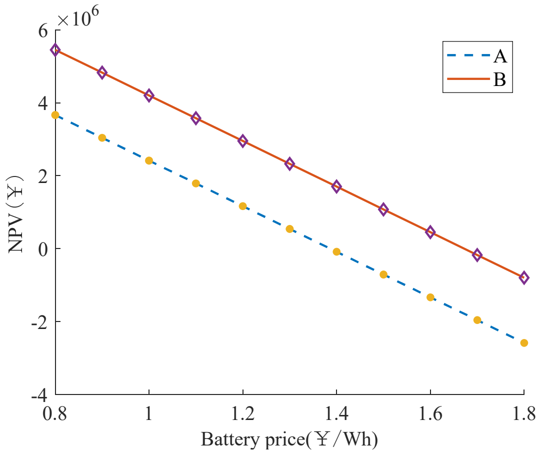

Figure 4. Battery cost impact analysis

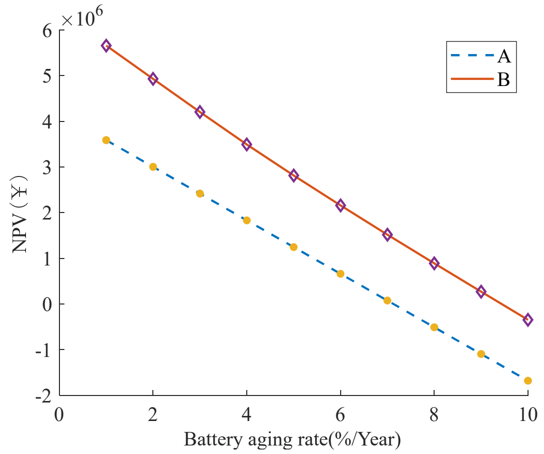

Figure 5. Analysis on the impact of battery aging rate.

(3) Battery aging rate

As shown in Figure 5, the faster the aging, the lower the final revenue. Existing power batteries generally have an aging rate of about 3% per year, which can guarantee the revenue of vessel battery change stations. However, the final revenue can increase by over 30% in scenario A and 50% in scenario B for every 1% reduction in the attenuation rate if the battery health is properly managed.

5Appendices

Electric vessels are developing rapidly, but the operation mode and investment analysis of vessel charging and battery swapping stations are still unclear. To this end, this paper put forward a technical framework for the interaction between vessel charging and battery swapping stations and the power grid, established an input-output analysis model and analyzed multiple influencing factors. The results show that (1) The number of spare batteries shall be determined based on the demand for battery change services and auxiliary services of the grid; (2) interactive services are required to achieve the balance of payments if the cost of battery is higher than 1.4 ¥/ Wh; (3) it will be difficult to make revenue if the battery life is too short. The revenue can be increased by more than 30% for every 1% reduction in the attenuation rate.

In the future, we can further optimize the V2G control process according to users' charging and battery swapping habits, considering interactive scenarios such as standby application and demand response, and meanwhile increase economic benefits for users of charging and battery swapping stations and electric vessels.

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