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Logistic optimization of the mobilized and distributed battery for improving the renewable energy penetration in urban energy systems

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ABSTRACT

High penetration rate of renewable energy and the real-time charging of large-scale electric vehicles pose technical and economic challenges to the traditional urban power system. This urgently calls for accelerating the development of smart energy solutions to improve the resilience of urban power system, and mobilized and distributed battery is believed to have the potential to provide the solution due to the advantages of high energy density, fast response, and convenient installation. Aiming at effectively satisfying the enormous urban power demand and realizing the cost-effectiveness and environmental-sustainability of power supply, this paper develops a novel method to achieve logistics and scheduling optimization of batteries at various temporal and spatial scales between renewable energy power plants (REPs) and cities. The objective function is to minimize the total cost of battery purchase and transportation considering the railway transport capacity, battery balance and other technical constraints. Based on the forecast results of available supply and demand of fully charged batteries in each REP and city, the detail battery transportation route and volume can be obtained. Finally, the proposed approach is applied to six cities in China, and the results demonstrate that the battery logistics and scheduling model can effectively improve the penetration of renewable energy, thereby realizing the low-carbon development of urban energy system.

Keywords: Logistic optimization, mobilized and distributed battery, low-carbon development, urban energy systems

NONMENCLATURE

Abbreviations	
REP	Renewable energy power plant
Sets	
$\mathrm{I}/\mathrm{i}, \mathrm{i}'$	The set of supply and demand nodes
$\mathrm{I_D}$	Demand node
$\mathrm{I_S}$	Supply node
N/n	The set of trains
Parameters	
b_1	The base price related to weight
b_2	The base price related to weight and transportation distance
cap_i	The maximum supply volume of batteries at node i
d_i	The demand volume of batteries at node i
$l_{i,i'}$	The distance between node i and node i'
M	A maximum value
$mass$	The weight of a battery
v_{max}	The maximum battery load of a train
Variables	
R_i	The deviation between demand and actual supply of batteries at node i
$V_{i,n,i'}$	The battery transportation volume of train n from node i to node i'
$B_{i,n,i'}$	If the battery is transported from node i to node i' by train n, $B_{i,n,i'} = 1$. Otherwise, $B_{i,n,i'} = 0$.

1. INTRODUCTION

Increasing environmental awareness, global goals related to the greenhouse effect and renewable energy, and the desire to reduce our dependence on fossil fuels are changing the patterns of power system generation, consumption and storage [1-3]. On the generation side, low carbon development trends are accelerating the replacement of traditional fossil fuel power plants by various intermittent and non-schedulable renewable energy sources such as solar and wind power plants. On the demand-side, the increasing penetration rate of electric vehicles will cause the grid load to increase or decrease suddenly and brings great uncertainty to the resource demand, and it will incur huge costs to upgrade the current grid infrastructure and operation strategies. In addition, it's costly to build high-voltage, long-distance, large-capacity transmission lines to provide users with large amount of intermittent and volatile renewable energy, especially when power plants are far away from users. Many studies have explored the technical economy and applicability of relevant equipment in the system, and found that large-scale energy storage system could help to maintain reliable and flexible power supply, including thermal energy storage (M-TES) system [4, 5], electrical energy storage [6], and thermoelectric energy storage [7, 8]. However, the results indicate that the economy of the energy storage system still needs to be further improved.

Towards the above-mentioned problems, technologies that help overcome daily variability of the power system without affecting the grid's efficiency and cost-effectiveness are absolutely critical to achieving low-carbon development. Mobilized and distributed battery is believed to have the potential to provide the solution due to the advantages of high energy density, fast response, convenient installation and the possibility to build anywhere in the distribution networks. A part of discussion has been conducted on the utilization of the mobile batteries to improve reliability and resilience of power system in emergencies. Sun et al., [9] proposed a time-space network model to optimize the charging and discharging positions of batteries, and the operation strategy of mobile batteries in transmission networks could be obtained to enhance the power system resilience, alleviate transmission congestion, and reduce operation costs in disaster areas. Afterwards, the authors in [10] established a security-constrained unit commitment model to optimize the use of existing space on freight trains. By adopting the Lagrangian decomposition-based technology, the convergence rate of the algorithm is accelerated, verifying the adaptability and superiority of the model and algorithm.

The above studies have proved the various values of battery transportation and logistics. However, in the large area, the performance of specific battery logistics optimization considering spatial scales is rarely investigated yet, and the economy and feasibility of battery transportation and logistics at various temporal and spatial scales need to be further demonstrated when supporting the logistics flow and energy flow in different regions.

In this paper, we propose a general methodology for the logistic optimization of the mobilized and distributed battery, as shown in Fig.1. It can be noted that the electricity generated from REPS are collected and transmitted to charging station for battery charging

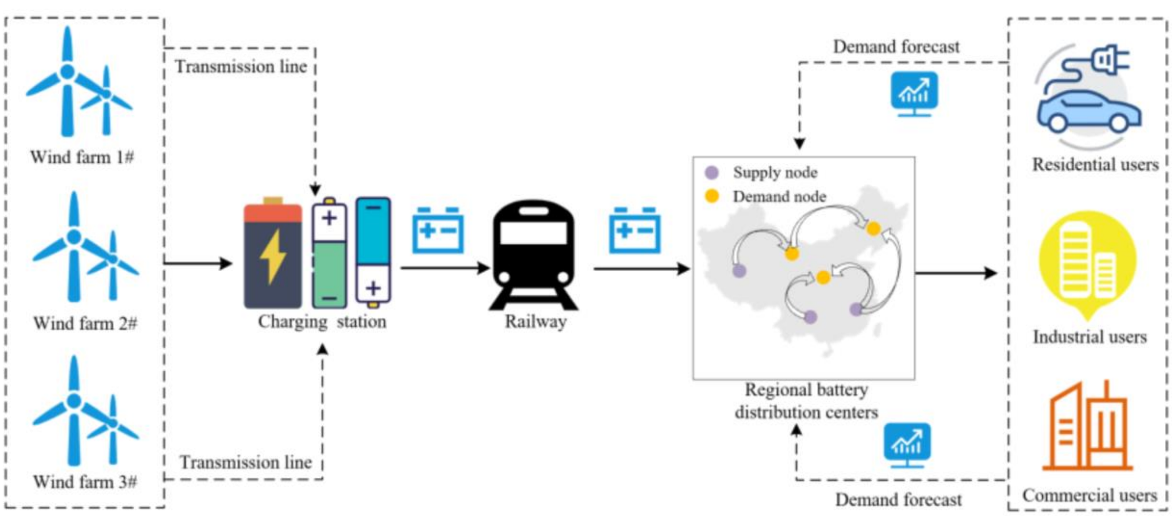

Fig 1 The logistics framework of the mobilized and distributed battery.

through high-voltage transmission lines, and then the fully charged batteries are delivered from REPs to cities through railway. On the demand side, the main users include electric vehicle owners from residential users, industrial users, and commercial users. Based on the forecast results of available supply and demand of fully charged batteries in each REP and city, the detail the detail battery transportation route and volume can be obtained by conducting the logistics optimization method. It should be noted that the fully charged batteries can be transported not only from REPs, but also from cities to cities, which means that cities can serve as an intermediate transfer node to facilitate the supply of batteries to other cities.

2. MATHEMATICAL MODEL

In this section, a general methodology is proposed to determine the transportation scheme for fully charged batteries from REPs to cities. The objective function is to minimize the total cost that includes the fixed cost of containers and the transportation cost of batteries, consider the container packing capacity, battery demand and supply constraints.

2.1 Objective function

The battery transportation and logistics optimization problem aim at finding the optimal allocation scheme of batteries to satisfy the demand at least costs. As mentioned above, the objective function of stage one is to minimize the total cost, which is composed of the fixed cost of containers, freight charges of batteries, and penalty costs for unsatisfied demands and underloaded containers as shown in Eq. (1).

$$\min F = f_1 + f_2 + f_3 \tag{1}$$

Specially, the fixed cost of containers is related to the base price related to weight, the weight per battery, and the transportation volume of batteries. The freight charges of batteries are determined by the base price per unit transportation distance and weight, transportation distance and transportation volume of batteries.

$$\begin{aligned} f_1 = \mathrm{b}_1 \times mass \times \sum_i \sum_n \sum_{i' \in I_i} V_{i,n,i'} \\ + \mathrm{b}_2 \times mass \times \sum_i \sum_n \sum_{i' \in I_i} \left(V_{i,n,i'} \times l_{i,i'} \right) \end{aligned} \tag{2}$$

where, b_1 is the base price related to weight, [$/t]; b_2 is the base price related to weight and transportation distance, [$/t·km]; $mass$ represents the weight of a battery, [t]; $V_{i,n,i'}$ represents the battery transportation volume of n train from node i to node i', [-]; $l_{i,i'}$ is the distance between node i and node i', [km].

The penalty cost for unsatisfied demands is considered following Eq. (3), where m is a maximum value, R_i represent the deviation between demand and actual supply of batteries, and the specific mathematical expression of R_i is shown in Eq. (6).

$$f_2 = m \times \sum_i R_i \tag{3}$$

It should be noted that the transportation volume of fully charged batteries for a train is limited by the maximum load capacity. In order to meet the battery demand of each city with the minimum number of trains, $\mathrm{f}_3$is considered to limit all trains departing from REP to be fully loaded except for the last train.

$$f_3 = \sum_{i,i' \in I_i} \left(\sum_{n \in N} n \times V_{i,n,i'} \right) \tag{4}$$

2.2 Constraints

At any supply node, i.e. REP, the total number of batteries for all trains sent from supply node i to other demand nodes i' shall be less than or equal to the maximum supply volume cap_i.

$$\sum_{i' \in I_i} \sum_n V_{i,n,i'} \le cap_i \quad \forall i \in I_S \tag{5}$$

For any node, it must satisfy the supply and demand balance constraints. Specifically, the total number of batteries transported to node i from other nodes i' minus the total number of batteries transported from node i to other nodes i' should match the demand of node i as much as possible. Here, d_i represents the volume of batteries required by the demand node.

$$\sum_{i' \in I_i} \sum_n V_{i',n,i} - \sum_{i' \in I_i} \sum_n V_{i,n,i'} + R_i = d_i \quad \forall i \in I_D \tag{6}$$

Taking into account the loading capacity of train, each train has an upper loading capacity limit v_{max} to prevent overloading. Eq. (7) requires the binary variable $B_{i,n,i'}$ is equal to 1 once the train n is selected to transport the battery from node i to node i'.

$$V_{i,n,i'} \le B_{i,n,i'} v_{max} \quad \forall i, i' \in I_i, n \in N \tag{7}$$

As described before, cities can serve as an intermediate transfer node to facilitate the supply of batteries to other cities. Therefore, whether the train departs from a renewable energy plant or a city, there is only one destination for the same starting node.

$$\sum_{i' \in I_i} B_{i,n,i'} \leq 1 \quad \forall i \in I_i, n \in N \tag{8}$$

In order to avoid the situation of no-load train and maximize train utilization, Eq. (9) is required to make the preceding trains as full as possible.

$$\sum_{i' \in I_i} V_{i,n,i'} \leq \sum_{i' \in I_i} V_{i,n-1,i'} \quad \forall i, i' \in I_i, n > 1 \tag{9}$$

2.3 Optimization Method

The model was implemented in GAMS 28.2.0 and solved by CPLEX 12.9.0 running in parallel deterministic mode using up to eight threads. The termination criteria were a relative optimality tolerance of 10−4. The hardware consisted of a Windows 10, 64-bit desktop with an Intel i7-9750H (2.6 GHz) processor and 16 GB of RAM.

3. RESULTS AND DISCUSSIONS

3.1 Input data

In this paper, six cities, i.e. Heilongjiang, Gansu, Fujian, Shanghai, Jilin, and Liaoning are selected to verify the effectiveness of the general method, and it should be noted that all six cities have REPs, which means that these cities are both supply nodes and demand nodes. For cities such as Gansu and Fujian, they are fully able to deliver batteries to other regions while meeting their own electricity demands. Regarding to cities such as Shanghai, the electricity demand is completely met by the supply from other regions. According to the weather forecast data of local wind farms, the wind power output in the next 24 hours is predicted and converted into the corresponding number of fully charged batteries, as shown in Fig.2. Similarly, the battery demand is predicted based on the electric vehicle ownership and typical local load characteristics, as shown in Fig.3. It should be noted that the electricity generated from REPs are far from being able to meet the electricity demand of the city, so the demand curve has been processed so that renewable energy can meet part of the city's electricity demand.

According to the previous study [11], b_1 and b_2 are set as 2.14 and 0.011, respectively. The weight of a battery is 250 kg, and the energy density of a battery is 200Wh/kg [12]. The upper loading capacity limit of a train is 50000. After knowing about the forecast results of available supply and demand of fully charged batteries in each node, the dispatch scheme of batteries could be optimized ahead.

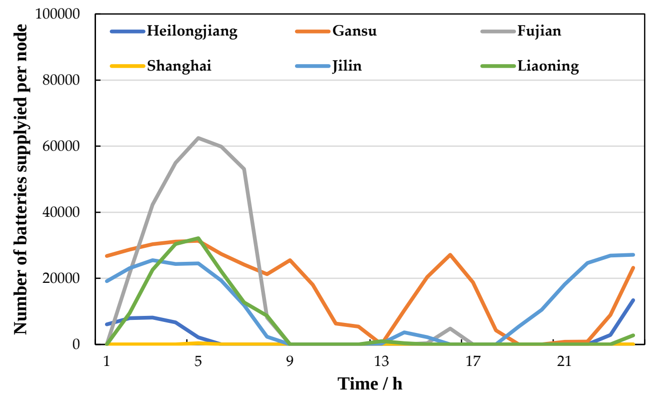

Fig 2 Number of batteries supplied per node.

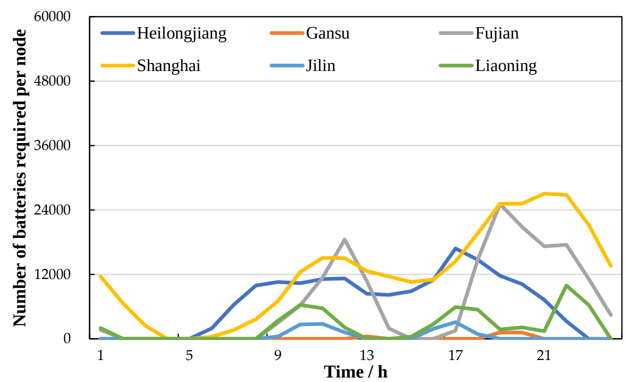

Fig 3 Number of batteries required per node.

3.2 Results and discussions

The detail transportation and logistics optimization schemes of the mobilized and distributed battery are presented in Fig.4 and Fig.5. In Fig.4, the orange ring represents that local electricity demand are met by the batteries charged by the local wind farms, and the dotted line represents the logistics flow of batteries between regions. Results show that the deviation between demand and actual supply of batteries at each node is equal to 0, which means that the battery demand of each city is completely satisfied, thereby improving the renewable energy penetration in urban energy systems. From these figures, it can be found that due to insufficient wind resources and high electricity demand in Shanghai and Heilongjiang, more trains are dispatched to transport fully charged batteries to these cities to meet their electricity demands. On the contrary, the cities such as Jilin, Liaoning, Fujian, and Gansu have abundant wind resources and are completely self-sufficient. Therefore, the model considers the available volume of batteries and transportation distance and makes the train as full as possible to achieve the goal of minimum total cost. For instance, wind farm in Fujian provides more batteries to Shanghai due to its closer distance than Jilin. The sum of the fixed cost of

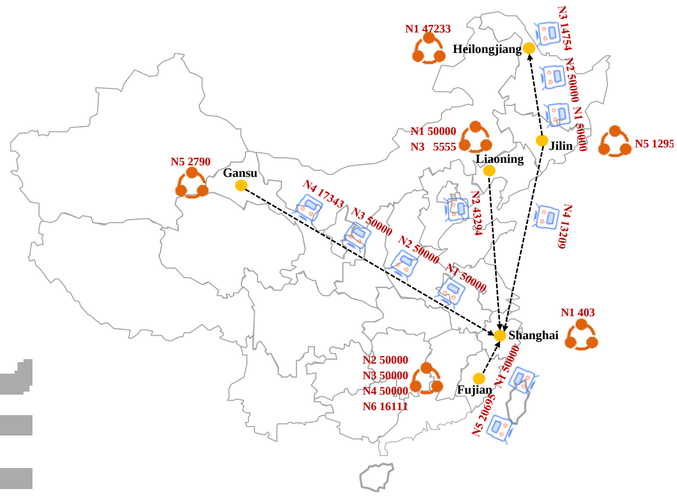

Fig 4 The optimization result of battery logistics scheme.

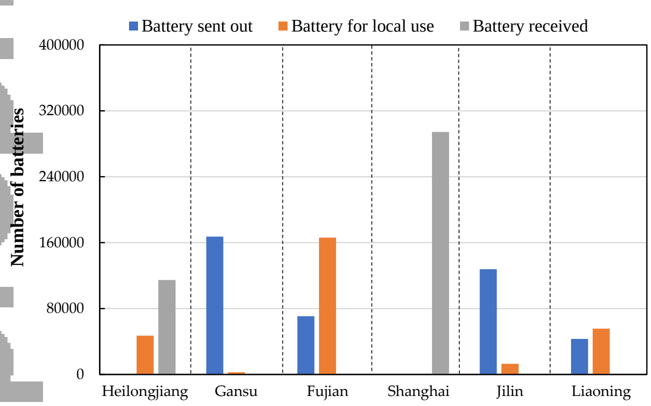

Fig 5 The detail logistics scheme of batteries at each node.

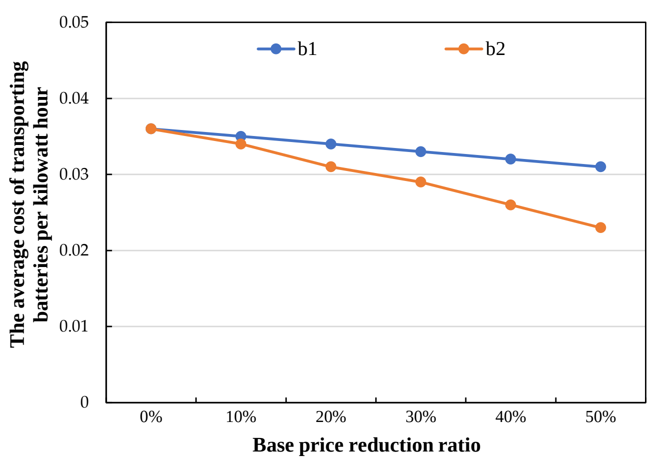

Fig 6 The average cost of transporting batteries per kilowatt hour under different reduction radio of base prices.

containers and the freight charges of batteries is equal to 200.07 million \$. Also, the cost of transporting a battery is calculated as 1.8 \$, and the average cost of transporting batteries per kilowatt hour is 0.036 \$/kWh, verifying the economic feasibility of the model.

The base prices b_1 and b_2 are two important factors that influence the economic feasibility of the mobilized and distributed battery. Fig.6 presents the change of the average cost of transporting batteries per kilowatt hour along with the reduction of base prices. It can be found that the average cost of transporting batteries per kilowatt hour decreases with the decrease of base prices. In particular, the base price b_2 that related to weight and distance has greater effect on the average cost than b_1, highlighting the importance of freight charges of batteries in urban energy systems. In detail, when base prices b_1 and b_2 are decreased by 10–50%, the average cost of transporting batteries per kilowatt hour can be reduced by 2.8%-13.9% and 5.6%-36.1%, respectively.

4. CONCLUSIONS

In this paper, a general method was proposed to determine the optimal transportation and logistics scheme of the mobilized and distributed battery. As an illustrative example, the method was applied to six cities in China to verify the effectiveness of the method. According to the results, the following conclusions can be deduced:

(1) The battery logistics optimization method can optimize the battery transportation and logistics scheme between regions, and improve the renewable energy penetration in urban energy systems.

(2) The economic performance of the battery logistics optimization method considering the spatial scale is verified by an example.

(3) Sensitivity analyzes of base prices are conducted to provide further insights into the battery logistics optimization, and results show that the freight charges of batteries have a great impact on the economic performance of the battery logistics scheme.

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