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Battery Swap Mode Popularization Path of the Electrification of Motor Vehicles in Beijing

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Abstract: The popularization of battery swapping technology of the electrification of motor vehicles is an orientation for Beijing to achieve China's strategy of carbon neutrality. By analyzing the operational characteristics of road traffic in Beijing, the average hourly electric vehicle replacement demand in the city with battery swapping strategy is predicted. Based on the existing battery swap station technology, this paper proposes a centralized battery swap station infrastructure for large-scale battery swap service, and calculates the new power consumption and power load of the battery swap station in the city. Under the carbon neutralization goal, the new power consumption in Beijing should come from wind power and photovoltaic new energy power with zero carbon emissions. According to the fluctuation and randomness characteristics of wind power and photovoltaic power generation in North China, the paper presents a load-following power supply solution for 500 kV flexible DC transmission system at both ends with battery energy storage of battery swap station. With that the minimum installed scale of wind power and photovoltaic and the number of electric vehicle power cells that should be reserved every day in the city are calculated.
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Keywords: carbon neutrality; electrification of motor vehicles; battery swapping; zero carbon power supply; battery storage; Beijing

1 Beijing electric vehicles and charging mode choice

To address the global climate change crisis, China has proposed a strategic goal of striving to reach the peak of CO_2 emissions by 2030 and achieve carbon neutrality by 2060. Beijing is one of the first group of cities in China to set the goal of reaching peak carbon emissions. As early as 2015, Beijing planned to achieve peak carbon emissions around 2020. Currently, Beijing's carbon emissions have appeared to reach peak and suggested a stable downward trend[1]. Achieving carbon neutralization by 2060 becomes an important goal for the future development of Beijing.

Since 2014, the transportation sector in Beijing has surpassed industry and become the second largest source of carbon emissions. Road traffic dominated by fossil fuel vehicles is the direct source of carbon emissions. Beijing's statistics [2] showed that the CO_2 emissions from gasoline and diesel consumption in 2019 were 2.04×10^7 t (see Tab. 1) and accounted for approximately 12% of the total CO_2 emissions.

The electric revolution of motor vehicles continues to progress. In 2019, the number of electric vehicles in Beijing reached 325,000 and the annual new electric vehicles exceed that of fossil fuel vehicles[4]. Under the carbon neutrality target, electric vehicles are expected to completely replace fossil fuel vehicles in Beijing, achieving electric revolution and zero carbon emissions for roadway traffic.

Tab. 1 CO_2 emissions of vehicles with gasoline and diesel oil

Energy type	Consumption in 2019/t	Low calorific value/(J/t)	Carbon content per unit calorific value/t/J	Carbon oxidation rate/%	Activity data /J	CO_2emission factor/(t/J)	CO_2emission/t
Gasoline	5.01×10^6	4.48×10^{10}	1.89×10^7	98	2.24×10^{17}	6.80×10^7	1.53×10^7
Diesel oil	1.62×10^6	4.33×10^{10}	2.02×10^7	98	7.014×10^{16}	7.30×10^7	5.12×10^6

Data sources: Reference [2–3]

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The charging mode of electric vehicles involves two options: onboard charging and battery swap. In the on-board charging mode, electric vehicles are connected to an external charging pile to charge the battery pack in the vehicle. The battery swap mode involves disassembling the power battery of electric vehicles and replacing it with a new battery[5-6]. The on-board charging mode takes a long time and is not as convenient as conventional car refueling. In the battery swap mode, electric vehicle charging and battery charging are separated, with a fully charged battery quickly installed like car refueling when the old battery charging is completed in an external dedicated charging facility; in this mode the use of electric vehicles is similar to typical car users' habits. Therefore, the popularization of battery swap mode is expected to become a new development direction of motor vehicle electrification in Beijing.

2 Prediction of vehicle use characteristics

2.1 Current mode dominated by fossil fuel vehicles

According to the 2019 statistics [4], the number of on-road motor vehicles in Beijing is 6.365 million. These motor vehicles are classified into 11 categories, including passenger motor vehicles, cargo motor vehicles, semi-trailer tractors, special operation vehicles, and military vehicles, etc. Based on ownership, motor vehicles are also categorized as private cars and corporate fleet cars. The number of private cars (private light-duty passenger vehicles and private micro passenger vehicles) is 4.67 million, accounting for 73.4% of the overall vehicle fleet. In 2019, the average rate of private car use in Beijing was 74.4%. The average annual mileage is 14,300 km. The average daily travel distance is 40.8 km/vehicle.

A survey on cars in Beijing's market shows that the average full load fuel capacity of private cars is approximately 62 L. The actual on-road fuel consumption is approximately 0.1 L/km. The average full load mileage is 620 km. The estimated average refueling time for private cars in Beijing is 15 days. The average daily refueling times are approximately 232,000. In 2019, Beijing had about 1,000 operational gas stations per day[7]. Each gas station served 232 private cars per day. Assuming a refuel of 62 L of gasoline each time, daily refuel amount per gas station for private cars is 14,400 L or 11 tons.

The Beijing statistics[2] have suggested that 2019 average daily gasoline and diesel consumption in Beijing are approximately 13,700 tons and 4,434 tons, respectively. The average daily gasoline and diesel sales at each gas station are 14 tons and 4.5 tons, respectively. It can be estimated that, excluding private cars, other vehicles in Beijing add 3 tons of gasoline and 4.5 tons of diesel per day. Given the lack of statistical data on other vehicles use, this paper presents estimates based on average daily refueling times and volume for private cars; each gas station in Beijing serves other vehicles 158 times a day, which is 68.1% of services for private cars.

2.2 Complete electric vehicles fleet with battery swap mode

Assuming that Beijing has completed the motor vehicle electrification with the existing vehicle ownership level, Beijing will have 6.365 million electric vehicles in the city. In terms of motor vehicle types and ownership, the proportion of private light-duty electric vehicles remains unchanged 73.4%. It is further assumed that private light-duty electric vehicles have the same use pattern as that of fossil fuel cars, with an average annual mileage of 14,300 km and an average daily travel distance of 40.8 km.

The survey of electric vehicles on sale in Beijing shows that the battery capacity of private light-duty electric vehicles is generally 70 kWh and the actual driving power consumption is approximately 0.2 kWh/km; the fully charged driving distance is 350 km (considering that the power cannot be completely exhausted during actual use, it is calculated as 315 km with the assumption of 90% capacity), which is less than the average driving distance of 620 km for fossil fuel vehicles. Electric vehicle battery technology is developing rapidly and the battery capacity is increasing[8-10]. Under the condition of constant actual driving power consumption, when the battery capacity is increased to 150 kWh, the travel distance with full power of private light-duty electric vehicles will reach 750 km (assuming 90% capacity or 675 km) and exceed the level of existing fossil fuel vehicles. In order to reduce the cost of battery production and operation, the battery specifications and models should be unified under a universal battery swap mode. In this paper, 150 kWh is set as the unified battery capacity of electric vehicles under the universal battery swap mode.

Under the condition of 150 kWh battery power and 0.2 kWh/km power consumption, the average battery swap interval, battery swap frequency, and the daily number of electric vehicles with battery replacement are estimated according to traffic characteristics of private light-duty electric vehicles in Beijing (see Tab.2). Assuming a simplified scenario with the daily battery swap demand of electric vehicles occurring during the time window of 7:00–18:00, the average hourly number of private light-duty electric vehicles is calculated during the battery swap working period. According to Section 2.1, the refueling times of other fossil fuel vehicles in Beijing are 68.1% of that of private cars; based on this ratio, the hourly battery swap quantity of other types of electric vehicles in Beijing can be estimated. Using data presented in Tab.2, the hourly average number of electric vehicles in Beijing that need to change electricity under the universal battery swap mode is approximately 29,400, accounting for 0.46% of the total number of electric vehicles.

Tab. 2 Battery swapping features for electric vehicles in Beijing

Vehicle type	Indicator/unit	Numerical value
Private light-duty electric vehicle (battery level at 150 kWh and power consumption of 0.2 kWh/km)	Average driving distance of each vehicle for power change/km	675
	Average time between power changes of each vehicle/d	16.54
	Average power exchange frequency per vehicle/(times/d)	0.06
	Daily power change quantity/10^4 vehicles	21.01
	Quantity of electricity to be changed per hour/10^4 vehicles	1.75
Other types of electric vehicles	Quantity of electricity to be changed per hour/10^4 vehicles	1.19

3 Facility demand and energy consumption characteristics of universal battery swap mode

3.1 Current situation of battery swap mode

The implementation of battery swap mode requires special facilities for replacing electric vehicle batteries, which is called battery swap station[11-13]. By 2020, there are more than 400 battery swap stations in China, which can be classified into taxi battery swap stations and private light-duty electric vehicles battery swap stations. Beijing has approximately 140 taxi replacement power stations serving 20,000 taxis with power replacement in the city, accounting for 20% of the total number of taxis; there are 10 private light-duty electric vehicle exchange stations serving approximately 5,000 private electric vehicles.

Taking the existing operational stations for private electric vehicles power replacement as example, the station typically includes three parts: replacement warehouse, charging warehouse, and operation warehouse. A light-duty electric vehicle drives into the battery swap room to automatically replace battery, which takes about 5 minutes. The replaced battery is charged in the charging bin, and staff operate and monitor various types of equipment in the monitoring bin. The size of the exchange station is about 7.6 m×5.6 m×3.2 m, covering an area of approximately 43 m^2. Only one vehicle can have battery replacement at a time and five batteries can be charged at the same time. The maximum daily battery swap capacity is 72 vehicles[14].

3.2 Conceptual design of centralized battery swap station

Under the universal battery swap mode, there will be a large daily demand for battery swap of electric vehicles in Beijing and, similar to the existing gas stations, the battery swap stations will be distributed all over the city. The swap and charging capacity of the battery swap station needs to be substantially improved for developing a battery swap facility that can provide battery swap services for multiple electric vehicles at the same time; a centralized battery swap station[15-16] is the solution (see Fig. 1). The centralized battery swap station is equipped with multiple electric vehicle battery swap workstations, battery charging and distribution stations, monitoring room, and other auxiliary facilities.

1) Battery swap place

The battery swap station shall be operated automatically to complete the replacement of batteries for electric vehicles, including dismantling old batteries and installing new batteries. With the existing battery swap technology, it takes five minutes for an electric vehicle to complete the battery swap operation. The reserved interval for battery swap between two vehicles is considered as 1 min and the battery swap capacity with one electrician position is 10 vehicles per hour. Based on the above assumptions, the total demand for power replacement stations is 2,940 to replace batteries for 29,400 electric vehicles every hour in Beijing and are distributed in different centralized power replacement stations.

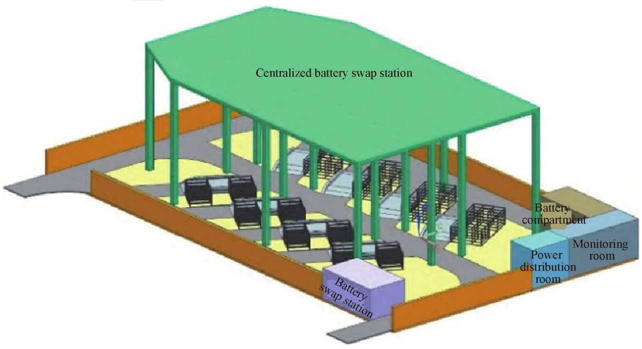

Fig. 1 Conceptual design of centralized battery swap stations

2) Charging place

Under the popular battery swap mode, the battery swap of electric vehicles is separated from battery charging and the replaced battery is charged at the charging place of the battery swap station. In order to shorten the battery transmission distance and time, the charging place should be configured 1-to-1 close to the battery swap place (see Fig. 2). The charging station consists of a battery rack and charging facilities that allow for multiple batteries charging at the same time.

3.3 Energy consumption characteristics

One electrician exchange position can complete the battery swap for 10 vehicles per hour. With the 150 kWh battery capacity, the hourly power demand of each electrician exchange position is 1,500 kWh. The average total demand of electric energy per hour for all 2,940 electrician changing positions in Beijing is 4.41×10^6 kWh. The battery swap station works for 12 hours every day and the daily demand for battery swap is 5.29×10^7 kWh; the annual demand for electricity exchange is 1.93×10^{10} kWh, which is 16.6% of the total social electricity consumption in Beijing in 2019 (1.17×10^{11} kWh). The average power consumption of all battery swap stations in Beijing is 4,410 MW, which is 18.7% of the historical maximum power load of 23,700 MW in Beijing.

4 Zero-carbon power supply

4.1 Zero-carbon power supply target

Although the end use of electricity produces no carbon emissions as downstream energy consumption, upstream power production still produces a large amount of CO_2 emissions due to the large proportion of thermal power in China's power generation and supply. The CO_2 emissions from power supply in Beijing reached 8.09×10^7 t in 2019[2-3], accounting for 47.6% of the peak carbon emissions. Therefore, under the goal of carbon neutralization, the new power demand for popularizing the battery swap mode in Beijing needs to rely on zero-carbon power. Based on the resources in and around Beijing, zero-carbon power for Beijing can be provided by wind power generation and photovoltaic power generation from the Zhangjiakou new energy base.

4.2 Wind power supply characteristics

Compared with conventional thermal power generation, wind power generation and photovoltaic power generation depend on weather conditions. Under a fixed installed capacity, wind and photovoltaic power generation will change with weather conditions and is not controllable. Such weather-based variation reflects uncertainty and randomness of the wind and photovoltaic power generation.

The fluctuation of wind and photovoltaic power generation is reflected from their changing average power generation rates in different seasons and periods, as shown in Fig. 3[17]. The average wind power generation rate in northern China is the largest in winter and the smallest in summer, and the most significant fluctuation occurs on a spring day. The average photoelectric generation power is the largest in summer and the smallest in winter, but similar during spring and autumn; the largest fluctuation occurs on a Summer day.

Although average wind and photoelectric power generation can be estimated for each period using statistical average, their actual power generation at any time is unknown and uncontrollable, which determines the randomness of wind and photoelectric power generation. According to the measured data of annual power generation of a wind farm in China (see Fig. 4)[18], wind power generation has random and discrete characteristics.

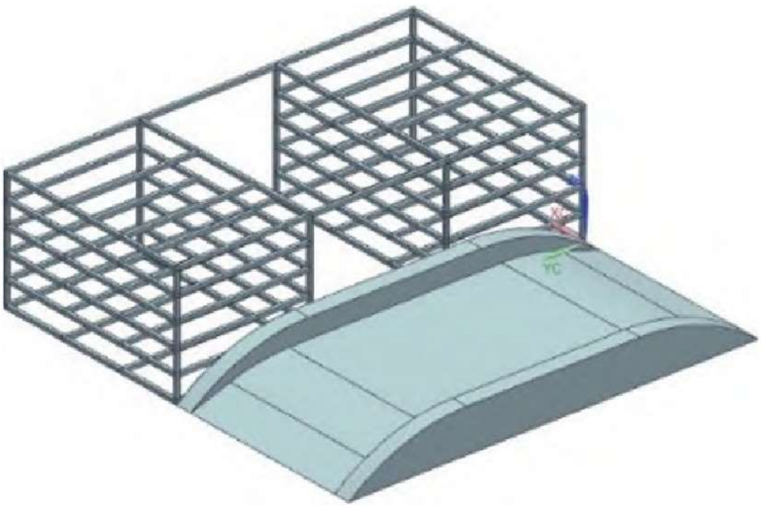

Fig. 2 Layout of battery charge facilities

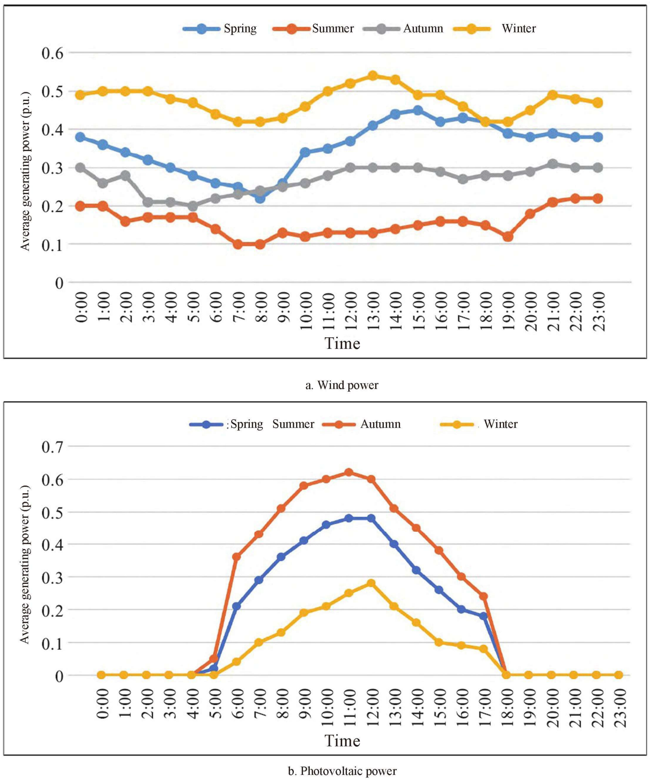

Fig. 3 Hourly output of wind and photovoltaic power generation by season in North China

Data source: Reference [17]

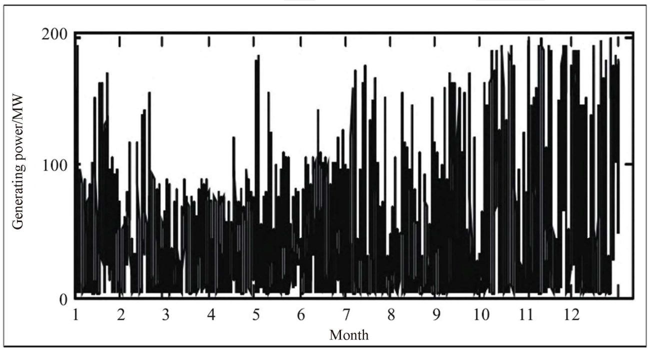

Fig. 4 Daily wind power generation of a wind farm

Data source: Reference [18]

Because of the fluctuation and randomness, wind power generation fails to supply power based on the demand from the load side. This is also the main reason why wind power generation can not be completely accepted by the power grid for a long time[19]. In order to achieve the goal of zero-carbon power supply under the universal battery swap mode, the variability and randomness of wind power generation supply have to be addressed.

4.3 Wind power supply solutions

To address the fluctuation and randomness of wind power generation supply, it is necessary to change the traditional principle of providing power supply according to the demand of power load or keeping the source to follow the load; instead, the power load can be adjusted according to the scale of power generation or keeping the load to follow the source[20-21].

4.3.1 Solve the problem of variability

For large-scale wind and photoelectric power generation bases, the average power generation during each period of a day has a statistical pattern[22]. At battery swap stations, the battery swap demand within a day also has a pattern. Therefore, the two patterns can be matched.

Under the universal battery swap mode, the daily battery swap characteristics of electric vehicles in Beijing can be estimated based on hourly power consumption. The characteristics of seasonal daily average wind and photoelectric power generation are also assessed according to the hourly average power generation. In theory, the matching of electric vehicle replacement power and the wind or photoelectric average power generation should be balanced by hour, and the power battery required for power replacement in the next hour should be charged during the previous hour. Given the fluctuation of wind and photoelectric power generation, it is impossible to ensure that the average power generation per hour is greater than the battery swap power. Therefore, the power balance needs to be expanded to meet the total battery swap demand at the battery swap station within one day. Based on this principle, a minimum scale of wind and photoelectric power generation can be planned. At the same time, it is necessary to plan the amount of battery stored in the replacement power station, and achieve the balance between electricity supply and demand in a day through battery energy storage from the demand side.

4.3.2 Solve the problem of randomness

In the case of regular fluctuation of average power generation, the randomness of wind and photoelectric power generation is reflected in the irregular change of actual power generation per hour. It is necessary to consider both the supply side and the demand side to solve the problem of random output and input of power generation.

1) Power transmission problem

The problem of randomness in wind and photoelectric power generation is essentially the power transmission problem of isolated wind and solar power plants without synchronous power supply. Current research usually applies flexible DC transmission technology to solve the problem[23-24]. Flexible DC transmission is a new technology that introduces turn-off power electronic devices and pulse width modulation technology into the field of DC transmission. It can flexibly rectify the input AC into DC without being affected by the random change of AC voltage and frequency. It is suitable for the power transmission of isolated wind and photoelectric power plants without synchronous power supply.

Under the universal battery swap mode, the new power demand in Beijing is met by the wind and photoelectric power provided by the Zhangjiakou new energy base and transmitted to the Beijing power grid through flexible DC with a flexible and direct system at both ends. The system structure is shown in Fig. 5. Converter station 1 is connected to the wind power plant of Zhangjiakou new energy base and all power output is processed through converter station 1, which is not connected to the AC synchronous power grid of Zhangjiakou City. Converter station 2 is connected to Beijing AC synchronous power grid. The power grid of Beijing, as a pure receiving power grid, accepts the AC inverter formed in converter station 2. Under the universal battery swap mode, the battery swap stations used by road traffic in Beijing perform similarly as the existing gas stations, are distributed in different locations in Beijing, and get connected to the Beijing power grid.

Converter station 1 is arranged near Zhangbei new energy base and converter station 2 is arranged near Beijing power grid, with a distance of about 200 km. 500 kV or higher voltage transmission lines are used for long-distance power transmission. At present, the same type of demonstration project—Zhangbei renewable energy flexible DC power grid demonstration project (±500 kV, 3,000 MW) has been completed and in operation.

The index of power balance for a flexible direct system at both ends is DC voltage. When the input power of the DC system is greater than the output power of the DC system, the DC voltage will increase; otherwise, the DC voltage will decrease. The random change of wind and photoelectric power generation can be monitored using the voltage controller of the flexible direct system. When the change exceeds the limit set by the system, the voltage controller is triggered to issue a charging power adjustment command to the battery swap station in Beijing power grid, with a required response speed in milliseconds[23].

2) Power reception problem

The problem of stochastic generation reception of wind and photoelectric power is essentially an issue of dynamic adjustment of battery charging power. The charging process of power battery is an electrochemical reaction process. Taking lithium iron phosphate power battery as an example[25], the battery is composed of positive electrode (lithium iron phosphate and aluminum foil), negative electrode (graphite and copper foil), diaphragm, and electrolyte (see Fig. 6). The diaphragm allows lithium ions instead of electrons to pass through and therefore separates the positive and negative electrodes. In the battery charging process, lithium ions are separated from the positive lithium iron phosphate to enter the electrolyte, pass through the diaphragm, and then arrive at the negative electrode. At the same time, the released electrons move in the external circuit from the positive electrode to the negative electrode; on the negative electrode, lithium ions are embedded in graphite carbon and combined with electrons.

Fig. 5 Two terminal flexible DC transmission system

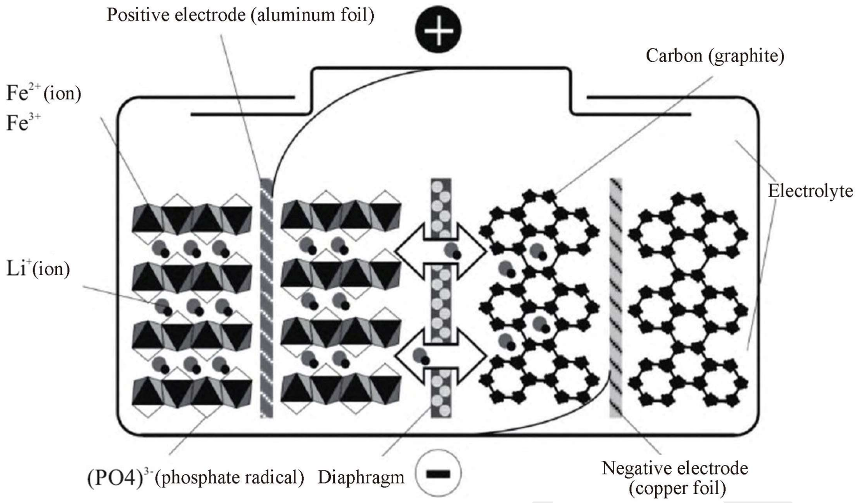

Fig. 6 Internal structure of LiFePO4 battery

Data source: Reference [25]

The speed of lithium ion insertion and detachment directly affects the battery charging speed and further determines the battery charging power. If the charging current is too high and exceeds the embedding and stripping speed of lithium ions, lithium ions will have insufficient time to embed into the negative graphite carbon and will combine with electrons externally to form lithium atom crystals, which will accumulate on the electrode surface, reduce the battery capacity and service life, and increase the battery safety risk. The magnitude of charging current is represented by the charging rate C, with 1 C representing the charging current required for the power battery to complete charging in one hour. Currently the charging rate of lithium battery can reach 1.5–2.0 C; in the future, with the maturity of solid-state battery related technology, the charging rate is expected to reach 5 C[26]. Therefore, to solve the problem of wind and photoelectric random power generation reception, the power battery needs to have a high charging rate ability and the charging current can be quickly adjusted in the charging process.

In summary, with the randomness of wind and photoelectric power generation, the DC voltage of the flexible direct system at both ends fluctuates, which triggers the voltage controller to perform and calculate the power to be adjusted. By sending the charging current adjustment command to the power battery, the charging power can be quickly increased or reduced to achieve the power balance.

4.4 Minimum installed capacity and transmission planning

There are abundant wind power and photoelectric resources around Beijing, especially in Zhangjiakou. By 2030, the total installed capacity of wind and photovoltaic power in Zhangjiakou will reach 20,000 MW and 30,000 MW, respectively. According to the seasonal daily average power generation characteristic curve of wind power generation in north China, different daily average power generation can be obtained with different installed capacity. Under the condition of 150 kWh battery capacity, the daily demand for electricity exchange in Beijing is 5.29×10^7 kWh.

Under the universal battery swap mode, the road traffic power consumption in Beijing is large during the daytime. This paper assumes the working period from 7:00 to 9:00 for a total of 12 hours. During the battery swap working period, the battery swap station shall charge and change power at the same time; during other periods, the only activity is charging. The demand for electricity exchange has daily characteristics, while the wind and solar power generation is carried out at all times and charging is not periodic. Therefore, the power balance between charging and battery swap should be calculated based on the battery swap cycle with a day as the temporal unit.

With the daily power generation greater than the demand for a battery swap, the installed capacity of wind and photoelectric power is determined as the minimum scale for planning purposes (see Tab. 3). In summer, wind power generation is the smallest, and photoelectric power generation is the largest; wind power generation occurs all day, but photoelectric power generation only occurs during the daytime. Therefore, the summer daily average power generation is the smallest. When the installed capacity of wind power is 5,600 MW and the installed capacity of photoelectric power is 5,700 MW, the total is 11,300 MW. The annual average daily power generation exceeds the power consumption with the minimum difference of 2.27×10^5 kWh in summer. When the total installed capacity remains unchanged, but the installed capacity of wind power is 5,700 MW and the installed capacity of photoelectric power is 5,600 MW, the minimum difference is reduced to 4×10^4 kWh in summer. Since the construction land area of wind power under the same capacity is much smaller than that of photoelectric power, this paper concludes 5,700 MW for wind power and 5,600 MW for photoelectric power, with a sum of 11,300 MW as the minimum total installed scale to meet the battery swap demand.

Tab. 3 Gap between daily power generation and consumption of different installed capacity by season

Installed capacity/MW			Difference between average daily power generation and power consumption/kWh			
Wind power	Solar power	Total	Spring	Summer	Autumn	Winter
5 600	5 600	11 200	1.76×10^{7}	-3.36×10^{5}	6.05×10^{6}	2.11×10^{7}
5 600	5 700	11 300	1.80×10^{7}	2.27×10^{5}	6.46×10^{6}	2.12×10^{7}
5 700	5 600	11 300	1.84×10^{7}	4×10^{4}	6.69×10^{6}	2.22×10^{7}
5 500	5 700	11 200	1.71×10^{7}	-1.49×10^{5}	5.81×10^{6}	2.01×10^{7}
5 700	5 500	11 200	1.80×10^{7}	-5.23×10^{5}	6.29×10^{6}	2.20×10^{7}

The operational transmission capacity of 2020 Zhangbei renewable energy flexible DC power grid demonstration project is 3,000 MW. With improved current capacity and withstand voltage level of converter valve in the future, the rated voltage of flexible DC transmission technology will reach 800 kV, the rated current will reach 4,000 A, and the transmission capacity will reach 6,000 MW[27]. With the existing 3,000 MW technology, it is necessary to build four flexible direct transmission lines for Beijing's road traffic energy consumption under the universal battery swap mode; with the technology of 6,000 MW in the future, two flexible direct transmission lines can be developed.

5 Quantity of reserved power batteries

With the 150 kWh battery power and 0.2 kWh/km power consumption, the hourly number of electric vehicle batteries to be replaced in Beijing is 29,400 during the battery swap working period as assumed in this paper.

In the battery swap mode, the power battery is charged at the battery swap station. The charging time varies by charging power. Due to the fluctuation and randomness of wind and solar power supply, the real-time charging power is uncontrollable. With the premise that the wind and solar power supply scale is determined based on the average power generation characteristics per hour, the battery swap station should reserve at least the number of power batteries that can meet the battery swap demand for one hour. Therefore, the minimum number of reserved power batteries meeting the 1-hour battery swap demand in the city is 29,400.

5.1 Reserved number of batteries to address wind and solar power variability

Under the condition of reserving the number of batteries for hourly battery swap, it is an ideal scenario that all batteries can be fully charged during the previous hour and used for battery swap in the next hour. However, the average hourly power generation varies due to the fluctuation of wind and solar power generation, and the sufficient supply cannot be guaranteed. Therefore, it is necessary to reserve more batteries during the non-battery swap period to address the issue that batteries cannot be fully charged during the working period.

Taking an average spring day as an example, as shown in Tab. 4, the total charging power is 2.74×10^{7} kWh from 18:00 to 6:59 on the next day; excluding 4.41×10^{6} kWh for the battery swap demand from 7:00 to 7:59, the remaining electricity power is 2.30×10^{7} kWh, which can charge 153,000 batteries; during the time window of 7:00–9:59, the charging power is less than the replacement power, and the power shortage is 3.24×10^{6} kWh; from 10:00 to 13:59, the charging power is greater than the replacement power, and the total power surplus is 7.49×10^{5} kWh; from 14:00 to 17:59, the charging power is less than the replacement power, and the power shortage is 2.44×10^{6} kWh. From 7:00 to 9:59, the power shortage is supplemented by the remaining power from 18:00 to 6:59 on the next day, and additional 22,000 batteries are needed; at the same time, 22,000 batteries have not been charged, of which 5,000 batteries can complete charging during 10:00–13:59 and are then used for the time window of 14:00–17:59. From 14:00 to 17:59, the power shortage is supplemented by the remaining power from 18:00 to 6:59 on the next day, and additional 11,000 batteries are needed.

It can be seen that, in spring, with the original 29,400 batteries reserved for battery swap, 33,000 additional batteries and a total of 62,400 batteries are needed to ensure the daily power consumption demand at battery swap stations. Similarly, the number of additional batteries needed to supplement the daily power shortage in other seasons can be estimated; the largest number of batteries to be reserved in the Summer is 106,400 (see Tab. 5).

5.2 Reserved number of batteries to address wind and solar power randomness

Under the conditions of wind power capacity of 5,700 MW, photoelectric power capacity of 5,600 MW, and total power capacity of 11,300 MW, the wind or photoelectric power generation may achieve full power generation of 11,300 MW or reduce to zero power generation in any hour given the randomness. As discussed in section 4.3, to address the randomness of wind and solar power generation, the battery charging current needs to be adjusted with the change

Tab. 4 Comparison of daily power generation and consumption in spring

Time	Generation/kWh	Consumption/kWh	Generation - Consumption /kWh	Battery surplus and deficit[1)] /104 pieces
18:00—6:59 next day	2.74×10^{7}	4.41×10^{6}	2.30×10^{7}	15.30
7:00—7:59	3.02×10^{6}	4.41×10^{6}	-1.39×10^{6}	−0.93
8:00—8:59	3.23×10^{6}	4.41×10^{6}	-1.18×10^{6}	−0.78
9:00—9:59	3.74×10^{6}	4.41×10^{6}	-6.73×10^{5}	−0.45
10:00—10:59	4.46×10^{6}	4.41×10^{6}	5.8×10^{4}	0.04
11:00—11:59	4.64×10^{6}	4.41×10^{6}	2.25×10^{5}	0.15
12:00—12:59	4.75×10^{6}	4.41×10^{6}	3.39×10^{5}	0.23
13:00—13:59	4.54×10^{6}	4.41×10^{6}	1.27×10^{5}	0.08
14:00—14:59	4.27×10^{6}	4.41×10^{6}	-1.42×10^{5}	−0.09
15:00—15:59	4.00×10^{6}	4.41×10^{6}	-4.15×10^{5}	−0.28
16:00—16:59	3.49×10^{6}	4.41×10^{6}	-9.16×10^{5}	−0.61
17:00—17:59	3.44×10^{6}	4.41×10^{6}	-9.69×10^{5}	−0.65
Total				3.3

Tab. 5 Storage quantity of batteries in different seasons

Item	Season			
	Spring	Summer	Autumn	Winter
Number of reserve batteries used for power exchange	2.94	2.94	2.94	2.94
Number of rechargeable reserve batteries	3.30	7.70	6.80	5.80
Total battery reserve	6.24	10.64	9.74	8.74

of power generation. Under full load, when 62,400 batteries are charged at the same time in spring, the charging rate of 1.2 C is needed for each battery need. When the charging capacity reaches 90%, the battery charging current will decrease significantly without adjustment ability. Therefore, considering that 50% of the total number of batteries can bear the full power adjustment at the same time, the charging rate of a single battery needs to be adjusted to 2.4 C. When 106,400 batteries are charged at the same time in summer and 50% of the batteries bear the full power adjustment, the charging rate of a single battery is 1.4 C. At present, the charging rate of lithium battery can reach 1.5–2 C. Therefore, under the existing technical conditions, considering the randomness of matching wind and solar power generation, the daily number of reserved 150 kWh power batteries in Beijing should be 106,400 with the universal battery swap mode. In the future, with the significant improvement of power battery charging rate capacity, the randomness of wind and solar power generation will not be a constraint for determining the number of reserved batteries.

6 Conclusion

Under the goal of carbon neutralization, fossil fuel vehicles in Beijing should be replaced by electric vehicles with a battery swap mode. Widely implementing the battery swap mode and using zero carbon energy to charge batteries serve as an effective way to achieve the goal of carbon emissions reduction and carbon neutralization in transportation. Given the resources of Beijing and its surrounding areas, Beijing's road traffic power supply can be provided by the wind power of the Zhangbei area, as well as the wind power transmitted to Beijing's power grid using high voltage flexible DC transmission technology. Considering the variability and randomness of wind and photoelectric power generation, with the existing lithium-ion battery technology and the universal battery swap mode, Beijing's road traffic needs 106,400 of 150 kWh power batteries reserved every day. Based on the estimation of 6.365 million motor vehicles in Beijing's road traffic in 2019, an average of 1.7 power batteries needs to be reserved for every 100 vehicles.

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