

Optimization Model of Emission Reduction Benefits based on Integrated

Development of Electric Vehicle and Power grid

Jia Zhao, Haifeng Fang, Yueyan Zhu, YuKe Li, YiSong Chen, Shu Wang

[Abstract] Under the goal of carbon peak and carbon neutrality, the carbon emission reduction of the automobile industry has attracted more and more attention in recent years. Electric vehicle has the dual attributes of power load and energy storage unit. With the increase of the number of electric vehicles, reducing carbon emissions through the collaborative interaction between electric vehicle and power network will become an important way to control carbon emissions in the automotive field. In this study, an optimization model of emission reduction benefits based on integrated development of electric vehicle and power grid is proposed, which explores the best technical way of synergy between power grid and electric vehicle, achieves the best carbon reduction effect and provides a model basis for large-scale demonstration application. Numerical simulations based on the real case in Beijing are conducted to validate the effectiveness of the proposed method.

Keywords: Electric Vehicle; Power Grid; Carbon Reduction Benefit; Multi-objective Optimization Model

Introduction

Under the goal of carbon peak and carbon neutrality, the integrated development of electric vehicles and power grid is an important way to reduce carbon emissions of automobile industry. At present, Chinese large power grid structure dominated by thermal power which does not give full play to the advantages of life cycle cost, energy conservation and emission reduction of Electric vehicles (EV). At the same time, due to the limited power grid capacity, the waste of clean energy (wind, solar and water) is becoming more and more serious. In addition, large electric vehicles have strong energy storage and discharge capacity, but they do not play a role in promoting the self-coordination and supervision of green energy in large power grid. Electric vehicles

can be charged with renewable energy and can use standby power supply or space to adjust the frequency of the power grid, so as to effectively solve the problem of "abandoning wind and solar energy".^[1] At the same time, only by using a large number of renewable energy resources for power generation, electric vehicles can effectively reduce the overall carbon emission of the fuel cycle, truly realize vehicle clean power generation and reduce the carbon emission of the automotive industry.

With the increasing popularity of electric vehicles and distributed energy generation in the power grid, the resulting problems have attracted more and more attention in the industry. By 2021, there are more than 90 pilot demonstration projects for the integrated development of electric vehicles and power grids in the world, of which only one is in China, and the relevant standards, regulations and policies are not perfect. This study explores the best technical way of cooperation between power grid and electric vehicle, realizes the best carbon emission reduction effect, and provides a model basis for large-scale demonstration application. The output power of renewable energy is random and fluctuating, and the grid connection time of electric vehicles is uncertain and pulsed.

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1 Current status of research

At present, the research on the integrated development of EVs and power grids^[2] is mainly focused on integrate energy conservation and emission reduction with economic benefits. Among them, regarding the estimation of carbon emissions, some scholars have proposed an orderly charging strategy that synergizes EVs and renewable energy in the carbon market by establishing an EVs charging model. The results show that the marginal carbon emission is 50% higher in the case of disordered charging than in the case of ordered charging. For carbon dioxide emissions and economic calculations^[3], scholars have established a unit operation model to conduct analysis with the goal of minimizing the operating cost of the generating unit and carbon dioxide emissions^[4], some scholars use a two-stage orderly charging optimization model to analyze the general charging rules of users and charging stations in ordinary residential communities^[5]. Some researches introduced the carbon dioxide price mechanism, and proposed the power generation plan model from the three aspects of wind energy utilization, power generation plan optimization and wind power participation in the day-a-day scheduling^[6], some scholars consider energy and environmental benefits, and establish a multi-objective optimization model with the least power consumption, the best environmental benefits and the highest degree of stability, to verify the impact of energy conservation, emission reduction and environmental benefits^[7].

Based on above research works, the current research on the coordinated development of EV and smart grids generally has the following problems. Firstly, it is generally in the stage of theoretical exploration, and theoretical research lacks large-scale demonstration and promotion; Secondly, it is generally concerned about the calculation of economic benefits. The analysis of social benefits has not been in-depth; in addition, although the existing research on the analysis of social benefits is for renewable energy consumption scenarios, they are generally idealized the calculations, and the guiding significance for reality needs to be further improved. Therefore, this study takes Beijing

city in China as real simulation case, based on proposed optimization model, specifically analyzes the carbon reduction benefits of the integrated development of EVs, power grids, and conducts forward-looking research to provide a model basis for large-scale demonstration and promotion of the integrated development of EVs and power grids.

2 Stochastic prediction for EV users charging behavior

2.1 Analysis of charging and driving behavior of EVs

The main factors affecting the charging load of electric vehicles are battery characteristics and user behavior characteristics. User behavior characteristics are the key factors affecting the power demand of electric vehicles, including daily mileage, travel start and end time. The daily mileage can reflect the electric energy consumed by the vehicle in a day. It is generally considered that the end of the journey is the time when the vehicle starts charging. Through the investigation and statistical results, the parameters such as daily driving mileage, started charging time and charging duration of electric vehicles are analyzed, and the statistical data are standardized in this section.

(1) Daily mileage

The daily mileage satisfies the log-normal distribution^[8], and its probability density function is the formula (2.1)

$$f_{LD}(x) = \frac{1}{x\sigma_D\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu_D)^2}{2\sigma_D^2}\right] \quad (2.1)$$

In the above formula, μ_D represents the daily mileage, σ_D represents standard deviation of the daily mileage, x is the daily mileage, $\mu_D = 3.20$, $\sigma_D = 0.88$.

(2) The start and end time of the trip is the time after the end of the last trip of the user as the start time of charging. The formula for calculating the probability

density at the beginning of the trip is [9]:

$$f_e(x) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x+24-\mu_e)^2}{2\sigma_e^2}\right], & 0 < x \leq (\mu_e - 12) \\ \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu_e)^2}{2\sigma_e^2}\right], & (\mu_e - 12) < x \leq 24 \end{cases} \quad (2.2)$$

In the above formula, $\mu_e = 17.6$, $\sigma_e = 3.16$.

(3) Charging duration

The charging duration is related to the daily driving distance and the power consumption per 100 kilometers, and the calculation expression is [10]:

$$H = \frac{xW_e}{100P_c} \quad (2.3)$$

In the above formula, H is the charging time, x is the daily driving distance, W_e represents the power consumption per 100 kilometers, P_c represents charging power.

Based on equations (2.1) ~ (2.3), we can get the start charging time and charging duration of electric vehicles. Monte Carlo simulation [11] is a stochastic simulation method based on probability and statistics. It generally uses random numbers to specify a probability model for complex problems, so that the solution of complex problems is consistent with some characteristics of random variables in the model, so as to achieve the purpose of solution. The specific steps are as follows:

- 1) Determine the number of EVs as n , the capacity of the car battery, the size of the charging power, and the number of cycles of the algorithm N ;
- 2) Randomly extract the initial charging time and initial SOC;
- 3) Calculate the charging time according to formula 2.3;
- 4) Repeat steps 2) and 3) to obtain the daily load of all EVs;
- 5) Add the daily load of all cars, that is, the total daily load curve;
- 6) Repeat the above steps 1)-5) N times to obtain N total daily load curve data;
- 7) Take the average value of the N groups of data

corresponding to the same time to get the final daily load curve of the charging station.

3 Construction of carbon reduction benefit model

3.1 Carbon emission model under disorderly charging

The time fluctuation effect of clean energy and the space motion effect of electric vehicles lead to different carbon emissions corresponding to the charging behavior of electric vehicles in different regions and different time periods. Based on the transmission efficiency model proposed in the literature, the impact of disorderly charging of electric vehicles at different times and regions on the output growth of power generation equipment, as well as the corresponding carbon emission growth and carbon emission benefit calculation are analyzed. In order to describe the dynamic characteristics of electric vehicles, some studies have pointed out that the state of charge (SOC) of batteries conforms to Gaussian distribution when electric vehicles are connected to, left and connected to the power grid. Therefore, for the disordered charging of electric vehicles, Monte Carlo method can be used to model each electric vehicle. According to the daily charging load curve of electric vehicles, the carbon emission intensity of power generation equipment and the relevant parameters of the marginal output growth factor obtained according to the steps in Section 2.1, calculate the total carbon emission benefits of all electric vehicles under the disordered charging scenario through formula (3.1). In other words, the carbon emission cost of electric vehicles.

$$w_n = \sum_{n=1}^N \sum_{t=1}^M \sum_{i=1}^I \sum_{j=1}^J r \cdot c_t^j \cdot P_{n,t}^i \cdot \Delta T \quad (3.1)$$

In the above formula, w_n is the carbon emission benefit under the scenario of disorderly charging of EVs n ; ΔT is the time interval for electric vehicle charging; I and J is the number of load nodes and power nodes

in the grid respectively; r is daily carbon trading price in the carbon market. c_t^j is the carbon emission intensity of the power generation equipment j at the power node location at the moment, N is the number of EVs, $P_{n,t}^i$ is charging power for electric vehicle n at node i at time t .

3.2 Carbon emission benefit model of orderly charging and discharging

The dynamic output characteristics of clean energy lead to the different proportion of instantaneous power supply in the power grid. In order to reduce the carbon emissions, a dynamic carbon cost model for orderly charging and discharging of electric vehicles is established. The objective function of the model takes carbon price, carbon emission intensity and marginal output growth factor as parameters and minimizes the total carbon emission by optimizing the charge and discharge power of electric vehicles in different regions and at different times. The model considers the constraints of electric vehicle driving characteristics, maximum charging power, battery capacity and driving demand.

(1) Objective function

The objective function is to minimize the total carbon emissions corresponding to the charging and discharging of EVs in the grid. The decision variable of the optimization problem is the charging and discharging decisions of each electric vehicle. The objective function is:

$$\min w_2 = \sum_{n=1}^N \sum_{t=1}^M \sum_{i=1}^I \sum_{j=1}^J r \cdot c_t^j \cdot \pi_{n,t}^i \cdot P_{n,t}^i \cdot \Delta T \quad (3.2)$$

In the above formula, w_2 is the total carbon cost under the orderly charging scenario, $\pi_{n,t}^i$ is the charging or discharging decision variable of the electric vehicle n at the power node i at time t . $\pi_{n,t}^i = -1$ is the electric vehicle discharging state; $\pi_{n,t}^i = 0$ is in a non-charging

and discharging state. If only the carbon emission benefit calculation under the orderly charging strategy of EVs is studied, the value of the decision variable $\pi_{n,t}^i$ is only selected at 1 or 0.

(2) Constraints

Taking into account the charging and discharging power limit of EVs, formula (3.3) expresses that the charging and discharging power of EVs in any dispatchable interval (between the moments when they are connected to and when they leave the grid) shall not be greater than the maximum power \bar{P}_n . For EVs that have not yet been connected to the power grid ($t < t_n^a$) or have left the power grid ($t_n^d \leq t$), the charge and discharge power is constant at zero, t_n^a and t_n^d are the time when the electric vehicle is connects to and leaves the power grid, respectively.

$$P_{n,t}^i = \begin{cases} 0 & 1 \leq t < t_n^a \\ [0, \bar{P}_n] & t_n^a \leq t < t_n^d \\ 0 & t_n^d \leq t \leq M \end{cases} \quad \forall n, t, i \quad (3.3)$$

Formula (3.4) is the electric vehicle battery capacity constraint, SOC_n^a and E_n is the initial and total battery capacity of the electric vehicle, respectively; \overline{SOC} is the upper bound of the battery SOC . This constraint expresses that for any time m , the sum of the initial SOC and cumulative charge and discharge of the EVs must not be greater than the upper bound of the battery SOC .

$$SOC_n^a + \frac{\sum_{t=1}^m \pi_{n,t}^i P_{n,t}^i \cdot \Delta T}{E_n} \geq \overline{SOC} \quad \forall n, m, i \quad (3.4)$$

In order to meet the travel needs of electric vehicle users on the second day, formula (4.5) ensures that the SOC of the electric vehicle at the time of departure shall not be less than the expected value.

$$SOC_n^a + \frac{\sum_{t=t_n^a}^{t_n^b} \pi_{n,t}^i P_{n,t}^i \cdot \Delta T}{E_n} \geq SOC_d \quad \forall n, i \quad (3.5)$$

In the above formula, SOC_d is the expected value that the electric vehicle needs to achieve at the moment of departure.

4 Simulation results

4.1 Parameter settings of emission reduction benefit analysis model

In this study, we take Beijing city in China as a typical demonstration case to analyze the emission reduction benefits of orderly charging and discharging. This project uses coal-fired units as traditional energy sources, and wind power and photovoltaic output as renewable energy sources. At the same time, it is assumed that all electric vehicle users can participate in the charging and discharging decision-making model.

All the input data involved in the calculation

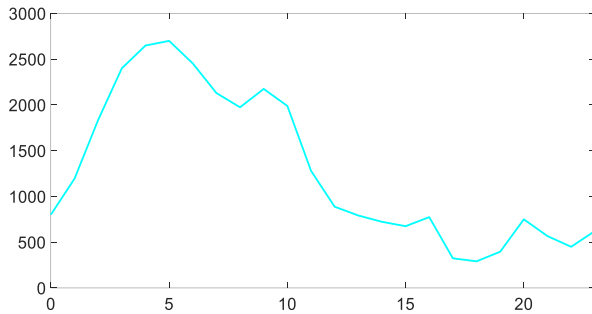


Figure 1 Average historical data of curtailment of wind power in Beijing(kW, Y-axis) during 24hours ((X-axis))

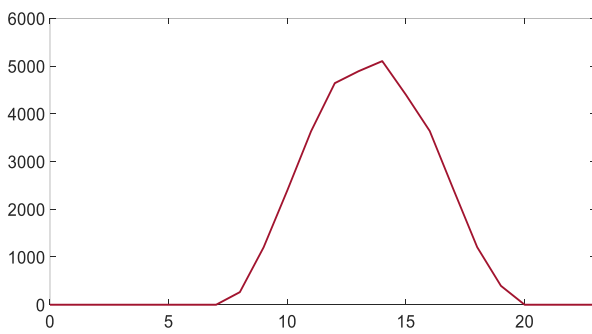


Figure 2 Beijing's average historical data of curtailment of photovoltaic power (kW, Y-axis) during 24hours (X-axis)

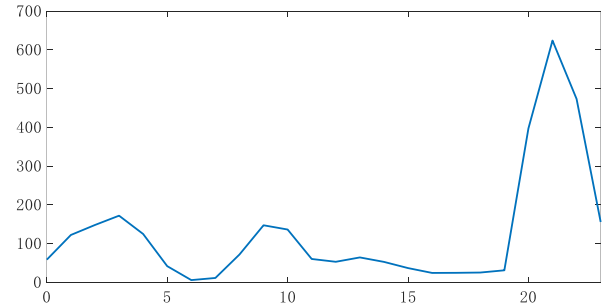


Figure 3 Charging load of EVs (kW, Y-axis) under disorderly charging scenarios for 24 hours(X-axis)

example model are as follows: For traditional energy, the carbon emission of coal-fired units is mainly determined by coal combustion (2.75% of coal production, 0.32% of coal field gas, 3.48% of coal transportation, Coal combustion is 91.66% and power plant desulfurization is 1.80%). The carbon emission intensity of traditional energy is a fixed value of 0.997kg/kWh. The carbon transaction price (transaction price) in the carbon market is 74.6 RMB/t^[12]. Regarding renewable energy power generation, as of the end of 2020, national photovoltaic projects have generated 260.5 billion kWh^[13], wind power projects have generated 466.5 billion kWh, and renewable energy has generated a total of 727 billion kWh. Among them, the annual photovoltaic power generation in Beijing is 620 million kWh, and the wind power generation is 370 million kWh^[14]. The annual power generation of new energy sources totals 990 million kilowatt-hours. The national average curtailment rate and solar curtailment rate in 2020 are 3% and 2% respectively^[15], whose total amount is about 19.2 billion kWh. In addition, the rate of curtailment of renewable energy in Beijing is the same as the rate of curtailment of wind and solar in the country, totaling approximately 23.5 million kWh. The total annual wind power and photovoltaic power generation in Beijing is predicted through a typical output curve. The wind power output model adopts the Weibull distribution, and the photovoltaic output model meets the normal distribution curve. Thus, the daily curtailment curve of Beijing's photovoltaic and wind power is obtained, as shown in Figure 1. The basic electricity load curve of Beijing refers to the load statistics of the National Energy Administration in

2020^[16].

This project uses a 118-node power distribution system^[17] to simulate Beijing's power distribution network structure, and then distributes the load curve of Beijing in various time periods evenly to each node as the basic electricity load of each node in Beijing. In addition, for other parameters, this project assumes that the battery capacity of EVs is referred to "BYD E6"^[18], and the battery capacity is 82.5 kWh. In addition, the minimum and maximum values of the initial SOC of EVs are 0.2 and 1, respectively; the earliest time for EVs to connect to and leave the grid is set to 13:00 and 13:00 on the second day, respectively. The total optimization time is 24h, and the optimization interval is 1h. The output is the decision variable representing the charging and discharging decision of each period of the electric vehicle.

For calculating and predicting the charging load curve of Beijing EVs at each time, the calculation method refers to the formulas (3.1)~(3.5) as shown in the third chapter. As of the end of 2020, the number of EVs in Beijing is about 400,000^[19]. It is assumed that the probability distribution model and parameters of the time when the electric vehicle is connected to the grid and the charging time satisfy the equations (3.1) and (3.2). In addition, for the initial SOC of an electric vehicle, it is assumed that it conforms to a Gaussian distribution with a mean value of 0.3 and a variance of 0.1. The charging power of EVs is 30kW. Then, Monte Carlo sampling is used to sample the probability distribution of the charging start time, and the daily charging load curve of EVs in Beijing is shown in Figure 1 and Figure 2.

4.2 Carbon reduction results of different coordinated pathways in Beijing

Figure 3 shows the charging load curve of EVs under the disorderly charging scenario in Beijing. It can be seen from Figure 3 that the charging power reaches its peak at 21:00. Then, as time goes by, the electric vehicle is gradually fully charged, and the charging power decreases. Starting at 06:00 on the second day, the charging power reaches the lowest value, which indicates that most EVs are fully charged and can meet

the travel needs on the second day.

In order to obtain the carbon emission result of orderly charge-discharge, the value range of decision variable $\pi_{n,t}^i$ of Equation (3.2) is 0, -1 and 1. The final experimental results of carbon emissions and carbon costs under the disordered, orderly charging and orderly charging and discharging scenarios calculated by the

Table 2 Carbon emissions and costs of three coordinated pathways in Beijing in 2020

	Carbon emissions	Carbon cost
Disorderly charging	1.1139 million tons	83.09 million RMB
Orderly charging	1.1115 million tons	82.92million RMB
V2G	0.9781 million tons	72.96million RMB

models 3.1 and 3.2 as shows table 2.

It can be seen from table 2 that the carbon emission under the orderly charging scenario is significantly lower than that under the disordered charging scenario. Compared with disorderly charging, the carbon emission of orderly charging is reduced by nearly 2400 tons. The reason is that in the orderly charging scenario, electric vehicle charging is mainly provided by renewable power generation equipment. Therefore, electric vehicle charging can make more use of renewable energy, so as to reduce carbon emissions and carbon costs. In addition, compared with the disordered charging scenario, the carbon emission of orderly charging and discharging is reduced by nearly 135800 tons. The main reason is that the energy storage and charge discharge control of electric vehicles will effectively inhibit the impact of renewable energy on the power grid. The load peak valley difference is reduced, the average load rate and power generation efficiency are improved, and the goal of reducing carbon emission is realized.

4.3Macro-quantitative analysis of emission reduction results of disorderly and orderly charging and discharging based on new energy consumption

According to China new energy vehicle inventory in 2020, the total number of existing EVs is about 4.92 million; the national electric vehicle charging load curve is still calculated with reference to the load

forecasting method in Chapter 2.1. In 2020, the national average curtailment rate and solar curtailment rate are 3% and 2% respectively, which means approximately

Table 3 Carbon emissions and carbon costs under the nationwide disorderly, orderly charging and orderly charging and discharging scenarios in 2020

	Carbon emissions	Carbon cost
Disorderly charging	137 billion tons	102.2 billion RMB
Orderly charging/V2G	0	0

19.2 billion kWh. Table 3 shows the final experimental results of carbon emissions and carbon costs under the national disordered, orderly charging and orderly charging and discharging scenarios in 2020 calculated by models 3.1 and 3.2.

It can be seen from Table 3 that the orderly charging and orderly charging and discharging of EVs in 2020 will play a significant role in China carbon emission reduction. Compared with disorderly charging, the orderly charging management of EVs has reduced China total carbon emissions from 137 billion tons to 0 billion tons in 2020, achieving the goal of zero carbon emissions and saving in China 1.022 billion RMB. This is mainly due to the fact that the total amount of electricity curtailed by new energy in the country is higher than the total charge of EVs. Therefore, EVs have completely absorbed the energy of waste light and wind, thus realizing orderly and orderly charging and discharging. zero emission. Although Beijing has completely absorbed new energy power generation, Beijing’s new energy power generation only accounts for 0.13% of the national new energy power generation. Therefore, the country's macro benefits are more obvious than Beijing’s carbon emission benefits.

With the rapid growth of China new energy capacity and power generation, it is estimated that the installed capacity of new energy power generation will reach 1.64 billion kilowatts by 2030, accounting for 43.2% of the installed capacity [20], which is an increase of nearly 25% compared to the installed capacity of new energy in 2020. Assuming that the wind curtailment rate is still the same as in 2020, the national average wind curtailment rate and solar curtailment rate are 3% and 2%

respectively, and a total of 24 billion kWh of new energy are discarded. At the same time, according to the "Energy-saving and New Energy Vehicle Technology Roadmap 2.0", the annual production and sales scale of

Table 4 The impact of disorderly, orderly charging and orderly charging and discharging on our country's carbon emissions and costs in 2030

	Carbon emissions	Carbon cost
Disorderly charging	105 million tons	7893 million RMB
Orderly charging	81 million tons	6042 million RMB
V2G	71 million tons	5296 million RMB

our country's new energy vehicles will also increase from 4.92 million in 2020 to 38 million in 2030. According to the above-mentioned new energy power generation and electric vehicle quantity statistics in 2030, this project calculates and obtains the impact of electric vehicle charging and discharging on our country's carbon emissions and costs in 2030. The calculation results are shown in Table 4.

As can be seen from table 4, in the case of disorderly charging, due to the significant increase in the number of electric vehicles, the required carbon emissions will increase by nearly 7.7 times compared with the carbon cost in 2020. However, due to the increased penetration of new energy and more electric vehicles participating in the charging and discharging plan, it is expected that by 2030, the orderly charging and orderly charging and discharging strategy will reduce carbon emissions by 81 million tons and 71 million tons respectively. This will save 1.851 billion yuan and 2.597 billion yuan in carbon emission costs.

It can be seen from the results that orderly charging and orderly charging and discharging will not achieve the goal of zero carbon emission in 2030. The main reason is that the growth rate of electric vehicles has far exceeded the expected growth of China's new energy power generation capacity. In 2030, large-scale access of electric vehicles and orderly charge discharge scheduling will still bring huge emission reduction benefits to China.

5 Conclusions

This paper compares and analyzes three paths for the integrated development of electric vehicles and power grid: disorderly charging, orderly charging and orderly charging and discharging. The results show that the carbon reduction effect of orderly charge and discharge is the best, followed by orderly charge and discharge. In the future, with the large-scale promotion of new energy vehicles, its carbon emission reduction benefits will be more obvious. From the perspective of social benefits, orderly charging and discharging will be the best way for the integrated development of electric vehicle and power grid. However, considering the actual situation such as economic benefits and technical level, the direct use of orderly charging and discharging will provide a greater way for the integrated development of electric vehicle and power grid. Therefore, starting with orderly charging, it is more realistic to promote the integrated development of electric vehicles and power grid. First,

it is suggested to provide construction or operation subsidies for intelligent charging infrastructure to make up for the cost difference at the initial stage of popularization and application; Second, strengthen the innovative support for technologies such as long-life power batteries, efficient charge and discharge and intelligent dispatching, and promote the orderly layout of charge and discharge technologies; Third, it is suggested to carry out a pilot demonstration of a new model of integrated development of electric vehicles and power grids, such as the demonstration of integrated charging infrastructure of photovoltaic charging, energy storage and charge discharge, and explore the best way to promote and apply on a large scale through pilot demonstration and system breakthrough.

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