Renewable Energy and Power Quality Journal
https://repqj.com/index.php/repqj/index
RE&PQJ, Vol. 23, No. 1, 2025

Implementing a Carbon Credit System for New Energy Vehicle Charging and Swapping Infrastructure

Li Zhang*, Bao Wang, Jianxiong Jia, Yue Yu, Zhumeng Song

Economic & Technology Research Institute of State Gird Anhui Electric Power Co. Ltd., Hefei, 230022, Anhui Province, China
*Corresponding author's email: ahy9032@126.com

Abstract. Traditional carbon emission accounting for new energy vehicle (NEV) charging and swapping infrastructure often focuses on vehicle operation while neglecting temporal load variations and renewable energy integration. This study proposes a carbon credit system to drive the green transformation of the NEV industry by developing a precise carbon emission accounting method and effective incentives. An emission reduction model was constructed for private vehicles and public charging/swapping stations, considering seasonal power load changes and renewable energy characteristics. Dynamic grid carbon emission factors and renewable energy yield curves are applied for accurate calculations while using real-world charging data. Private vehicle reductions were benchmarked against traditional fuel vehicles, while public stations analyzed carbon differences based on peak-valley electricity use. Results show the system can reduce 299,000 tons of CO_2 in 2023, boost renewable energy consumption by 160,000 kW per 5% load increase, and cut peak grid demand by 10%-equivalent to a 330,000 kW gap or the output of a 300,000 kW supercritical plant. The carbon credit system effectively lowers transportation emissions, alleviates grid pressure, and fosters coordinated, green development of NEVs and power systems.

Key words. Charging and Swapping, Infrastructure Construction, Carbon Credit System, New Energy Vehicles, Public Charging and Swapping Stations

1. Introduction

In the context of global climate change and sustainable development, promoting and applying new energy vehicle NEV is widely regarded as an important way to reduce greenhouse gas emissions. Transportation [1] is one of the main factors leading to gas emissions and environmental pollution. Burning fossil fuels in vehicles produces large amounts of greenhouse gases such as carbon dioxide, which negatively impact on air quality and climate change. NEV [2,3] emits almost no direct carbon dioxide during operation, becoming a necessary solution to address climate change and reduce air pollution. Although the promotion of NEV has made some progress, the carbon emission issue still needs attention to during the construction and operation of charging and battery replacement infrastructure. Traditional research focuses on the carbon emissions of vehicles during operation. Still, it often ignores the carbon footprint of charging and battery replacement, which has significant carbon emission differences due to factors such as power sources and time periods. With policy support and market demand, the sales of NEV have been rising year by year, and the construction of related charging and battery replacement infrastructure [4] has also been accelerated. By the end of 2022, China has built more than 3 million charging piles, providing important support for the development of NEV. The power source of charging and swapping stations relies on traditional energy, resulting in higher indirect carbon emissions during their operation. How to scientifically and reasonably calculate the carbon emissions of charging and swapping infrastructure and establish an effective carbon credit system has become a key link in promoting the green transformation of the NEV industry.

Establishing a carbon credit system can promote the green development of charging and battery-swapping infrastructure [5,6] and provide incentives for NEV users and operators to reduce carbon emissions. By building a scientific carbon emission accounting method, combined with the carbon emission factors of the dynamic power grid and the new energy output curve, the carbon emission reduction effects in different time periods and scenarios can be accurately evaluated, forming a comprehensive carbon credit system. By establishing personal carbon accounts, users' emission reduction can be quantified into redeemable carbon credits, which can help the public's awareness and participation in environmental protection and promote the popularization of green travel. The carbon credit system for NEV charging and swapping infrastructure is an important part of achieving green and low-carbon transformation. It is not only a practical need to cope with climate change, but also an effective means to promote sustainable development.

For NEV charging and battery replacement, a scientific emission reduction accounting method can evaluate the environmental benefits of electric vehicles and guide policy formulation and the improvement of market mechanisms. Academia and industry have conducted extensive explorations on emission reduction accounting methods, involving multiple dimensions, including the calculation of baseline emissions [7], the construction of emission reduction scenarios [8], and the consideration of dynamic factors. Baseline emissions calculations rely on the emission standards of traditional fuel vehicles as a reference point to assess the actual emission reduction effect of electric vehicles under specific conditions. The construction of emission reduction scenarios involves many factors, including the carbon emission intensity of the power grid, the proportion of renewable energy, and changes in power load. These factors may vary significantly in different seasons and periods, and the introduction of dynamic grid carbon emission factors [9] is the key to improving the accuracy of calculations. Chen Yu,[10] achieved more accurate calculation of emission reductions based on actual charging behavior data, through comprehensive analysis of user charging habits, charging facility operation modes, and new energy output curves. McDuffie Erin E's research [11] built an emission reduction accounting framework applicable to specific areas or time periods through long-term monitoring and data accumulation, providing a scientific basis for the construction and operation of charging infrastructure. Research on emission reduction accounting methods for charging and swapping infrastructure is also evolving and is gradually moving towards personalization and intelligence. The use of big data and artificial intelligence technologies [12,13] to conduct a comprehensive analysis of power load, user behavior and environmental impact can further improve the flexibility and real-time performance of accounting. Systematic emission reduction accounting methods [14,15] can not only help the industry evaluate the environmental value of NEV, but also provide a solid theoretical basis and practical guidance for the formulation of future policies and the design of market incentive mechanisms. By deepening the research on emission reduction accounting methods, it can more effectively promote the green development of the NEV industry and achieve a higher level of sustainable transportation goals.

Research on NEV charging and battery swapping and carbon credit system has received extensive attention in recent years. As an important part of promoting green transportation and sustainable development, it involves policy design and the construction of market mechanisms. The charging and battery swapping mode of NEV is regarded as an effective way to increase the popularity and efficiency of electric vehicles. Compared with traditional charging methods, the battery swap model [16,17] can significantly shorten the charging time of vehicles, improve user convenience, and optimize the grid load through centralized charging and intelligent scheduling. The successful promotion of the charging and battery swap model depends on the layout and construction of charging and battery swap facilities, as well as the corresponding operation and management strategies. The popularization of NEV charging and battery swap [18] is inseparable from the support of relevant policies, including subsidy policies, tax incentives, and financial support for infrastructure construction. The formulation of these policies needs to fully consider market demand and technological development trends. Research on the carbon credit system is also deepening, providing economic incentives for reducing carbon emissions. By establishing carbon accounts for individuals and enterprises, the carbon emission reductions during the use of NEV are recorded and converted into tradable carbon credits. The carbon credit system [19] not only promotes low-carbon behavior of enterprises and individuals, but also provides a basis for the government to monitor and evaluate the effects of emission reduction. Researchers have conducted a systematic analysis of the accounting methods, trading mechanisms and market supervision of carbon credits, and explored how to effectively implement this system in different regions and industries. Fu Wenxi's research [20] proposed that the calculation of carbon credits can be made more accurate by introducing dynamic carbon emission factors, taking into account the sources of electricity and their carbon emission intensity at different times and locations, thereby ensuring the fairness and rationality of carbon credits. In recent years, the management and control technologies of electric vehicle charging and battery swapping infrastructure have been widely studied. The hybrid battery charging and logistics scheduling model in the continuous time domain optimizes the coordinated scheduling of battery charging and logistics [21]. The battery charging and battery swapping system participating in the joint power and transportation network demand response explores the interactive optimization of the power and transportation networks [22]. These studies provide theoretical and practical support for the efficient management of charging and battery swapping systems, laying the foundation for this study. The research on NEV charging and battery replacement and carbon credit system provides theoretical support and practical guidance for promoting the development of green transportation. By continuously optimizing the layout and management of charging and battery replacement facilities, combined with a scientific carbon credit system, it can effectively promote the popularization of NEV, improve social and economic benefits, and lay a solid foundation for achieving the goal of a low-carbon society.

This study breaks through the limitation of traditional carbon emission accounting models that only focus on carbon emissions during vehicle operation. It incorporates the temporal and spatial differences in load during charging and swapping and the characteristics of new energy consumption into the model, and constructs a two-layer emission reduction accounting framework for private cars and public charging and swapping stations. This accounting method can accurately reflect the changes in power load in different periods and seasons through dynamic grid carbon emission factors and new energy output characteristic curves, significantly improving the scientificity and applicability of carbon emission accounting, and filling the gap in existing research on the accurate calculation of emission reductions affected by load fluctuations. This paper establishes an incentive mechanism for the carbon credit system, which guides users to charge during off-peak hours by accurately analyzing the electricity demand during off-peak hours, thereby improving the consumption capacity of new energy. This incentive mechanism not only significantly reduces the charging cost of users, but also improves the efficiency of the system's use of new energy power generation, providing an effective path to reduce peak power loads and relieve pressure on the power system. This paper has high innovation and application value in the construction and implementation of the carbon credit system for NEV charging and swapping infrastructure, and provides a scientific basis and innovative ideas for the formulation of future low-carbon transportation policies and new energy consumption strategies.

2. Constructing an Emission Reduction Accounting Model

A. Calculation of Emission Reductions from Charging of New Energy Private Vehicles

A province in China was selected as the research area, and the average carbon emission level of motorized modes such as private cars, taxis, rail transit, ground buses, and ferries was taken as the baseline scenario. The emission reduction was calculated by comparing it with the emission reduction scenario of new energy passenger vehicles. The data sources for this study include actual charging and battery swapping behavior data of new energy vehicle users, power grid operation data, and regional new energy power generation output curves. The data collection method mainly obtains user behavior data through the new energy vehicle charging and swapping operation platform, covering charging time, frequency, electricity demand, etc. It obtains dynamic grid carbon emission factors and peak and valley load data through the power company dispatching system, and obtains photovoltaic and wind power output data in different time periods through meteorological departments and new energy power generation companies. To ensure the accuracy and timeliness of the data, multi-source data fusion technology is used for integration, and abnormal data is screened and cleaned to construct a high-quality research data set, providing solid data support for model development and analysis.

The calculation boundary is within the province. If the travel route exceeds the province, the driving distance beyond the scope can not be included in the emission reduction calculation, and the scenario emission reduction can be calculated as carbon dioxide emissions. The minimum unit of the monitoring period is a natural day, and the emission reduction calculation ensures that the emission reduction corresponds to the monitoring period.

The travel scenario comparison of fuel vehicles and NEV is shown in Figure 1.

Figure 1. Travel scenarios

Fuel vehicles [23,24] rely on traditional fossil fuels, produce large amounts of carbon dioxide and other pollutants, and have serious impacts on the environment. NEV [25,26] use electricity to drive, significantly reducing greenhouse gas emissions. Fuel vehicles have high operating costs, including oil price fluctuations and maintenance costs. NEV are often more economical in terms of electricity costs and daily maintenance. In addition, NEV are more energy efficient than fuel vehicles, have higher energy conversion efficiency, and consume less energy for the same driving distance. In terms of policy support and infrastructure construction, many countries and regions have increased their support for NEV, including the construction of charging stations and car purchase subsidies, which further promoted the popularization and development of NEV.

Baseline emissions refer to the estimated emission levels of traditional fuel vehicles without the use of NEV. The calculation formula for baseline emissions is as follows:

$$E_{baseline} = \sum_{i=1}^{n} D_i \times EF_{baseline} \quad (1)$$

$E_{baseline}$ represents the baseline scenario travel emissions, D_i is the driving distance of the i-th trip. $EF_{baseline}$ represents the baseline scenario emission factor.

The emission reduction scenario emissions refer to the emissions when using NEV, and the formula is:

$$E_{reduction} = \sum_{j=1}^{m} \sum_{i=1}^{n_j} D_{ji} \times EF_{reduction,j} \quad (2)$$

$E_{reduction}$ represents the emissions of a user driving a new energy passenger car, and D_{ji} represents the driving distance of the i-th trip of user j driving a new energy passenger car. $EF_{reduction,j}$ represents the carbon dioxide emission factor of user j driving a new energy passenger car.

This paper has effectively avoided potential carbon leakage problems, including non-driving power consumption and battery replacement activities, so leakage emissions are not considered. Emission reduction accounting is to calculate the carbon emission reduction generated by travel relative to the baseline scenario, and the formula is:

$$\Delta E = E_{baseline} - E_{reduction} \quad (3)$$

B. *Calculation of Emission Reductions at Public Charging and Swapping Stations*

The emission reduction calculation at public charging and swapping stations [27,28] accurately evaluates the carbon emission reduction effect achieved during the charging and swapping of NEV, providing data support for policy formulation and industry standards. Emission reduction calculations [29,30] help promote the optimal configuration of charging and swapping infrastructure, improve the absorption capacity of new energy, promote the low-carbon transformation of the power system, and promote the overall transformation of society to a low-carbon economy.

A public charging and swapping station is shown in Figure 2.

Figure 2. Public charging and swapping stations

There are significant differences in service models and operational characteristics between charging stations and battery replacement stations. Through comparison, the carbon emission reduction benefits and optimization potential of different infrastructures are clarified. Charging stations mainly focus on load regulation capabilities and user behavior adaptability under time-of-use electricity prices, while battery replacement stations emphasize the balancing role of battery energy storage and the efficiency of rapid energy supply. This distinction helps optimize energy utilization efficiency, formulate differentiated low-carbon policies, and rationally plan infrastructure layout, thereby improving the overall green development level of the new energy vehicle industry. To ensure the timeliness of data collection and the fairness of user participation, the time node for data statistics is set from 0:00 on the first natural day of each month to 24:00 on the last natural day. The baseline scenario is divided into two scenarios: spring and autumn new energy consumption and winter and summer peak consumption. The months are divided into spring (February-June), summer (July-September), autumn (October-November), and winter (December-January), and further distinguished into three periods: peak, flat, and valley. As needed, peak, flat and valley periods are split into hourly levels to accommodate seasonal fluctuations in renewable energy output.

In spring and autumn, the baseline emissions calculation formula is:

$$BE1,p,i = EFelec \times ESt0,p,i (4)$$

$EFelec$ represents the carbon emission factor of the power grid. $ESt0,p,i$ represents the total electricity consumption of users in different peak, valley and normal periods in month i of the previous year.

The calculation formula for baseline emissions in winter and summer is:

$$BE2,p,i = EFelec \times ESt0,p,i (5)$$

The calculation formula for the emission reduction scenarios of registered public charging and swapping station users in different peak, valley and normal periods is:

$$PEp,i = EFelec \times ECp,i (6)$$

PEp,i is the emission reduction scenario of registered public charging and swapping station users in different peak, valley and normal periods of month i. ECp,i represents the electricity consumption of registered public charging and swapping station users in different peak, valley and normal periods of month i.

The calculation formula for emission reduction of electricity consumption of public charging and swapping stations is:

$$ERi = ERp,i + ERg,i + ERf,i (7)$$

ERp,i , ERg,i , and ERf,i represent the peak-period emission reduction, valley-period emission reduction, and normal-period emission reduction of registered public charging and swapping station users in month i.

The peak-period emission reduction calculation formula is:

$$ERp,i = BEp,i - PEp,i (8)$$

The baseline emission BEp,i is selected according to spring and autumn or winter and summer, and $BE1p,i$ and $BE2p,i$ are selected accordingly.

The calculation formula for valley period emission reduction is:

$$ERg,i = BEg,i - PEg,i (9)$$

The calculation formula for emission reduction in normal period is:

$$ERf,i = BEf,i - PEf,i (10)$$

3. Construction of Carbon Credit System

A. Dynamic Grid Carbon Emission Factor

The dynamic grid carbon emission factor [31,32] is the ratio of carbon dioxide emissions generated by grid power generation to the electricity consumed in a specific time period. The change of this factor is affected by many factors, including power generation structure, energy source, seasonal demand, climate conditions, etc., reflecting the environmental impact of the power grid under different operating conditions. Calculating the dynamic grid carbon emission factor helps to assess the carbon emission level of the power system.

The calculation of the dynamic grid carbon emission factor is:

$$EF_{\text{dynamic}} = \frac{\sum_{j=1}^{n} E_j \cdot CF_j}{\sum_{j=1}^{n} E_j} (11)$$

B. New Energy Output Characteristics

The output characteristics of renewable energy [33,34] mainly refer to the power generation capacity of renewable energy in different time periods and its changing patterns. The power generation characteristics of renewable energy are greatly affected by natural conditions, resulting in time-varying and uncertain output. Analyzing the output characteristics of renewable energy is crucial for optimizing power system dispatch, improving the absorption capacity of renewable energy, and achieving low-carbon goals.

Output is the actual electrical energy generated by power generation equipment in a specific period of time. Output characteristics describe the output of renewable energy power generation in different time periods, including peak output, valley output, and average output.

Peak output is the maximum output power that renewable energy power generation equipment can achieve in a certain period of time.

$$P_{\text{peak}} = \max(P_t)(t \in [t_1, t_2])(12)$$

In formula 12, P_t is the output value at time t, and $[t_1, t_2]$ is the time period considered.

The valley output is the minimum output power that the new energy power generation equipment can achieve within a certain time period.

$$P_{valley} = \min(P_t)(t \in [t_1, t_2])(13)$$

Average output is the average power generated over a certain period of time.

$$P_{avg} = \frac{1}{T}\sum_{t=t_1}^{t_2} P_t (14)$$

In formula 14, T is the total duration of the time period.

C. *Incentive Mechanism*

The carbon credit system [35,36] is an important mechanism for addressing climate change. It promotes the achievement of emission reduction targets through the management and trading of carbon emissions. Carbon credits are tradable units generated by reducing or avoiding greenhouse gas emissions. Each unit of carbon credit is equivalent to a reduction of one ton of carbon dioxide. Carbon credits incentivize emission reductions through market-based means and promote various economic entities to implement low-carbon technologies and clean energy projects.

The carbon credit system is shown in Figure 3.

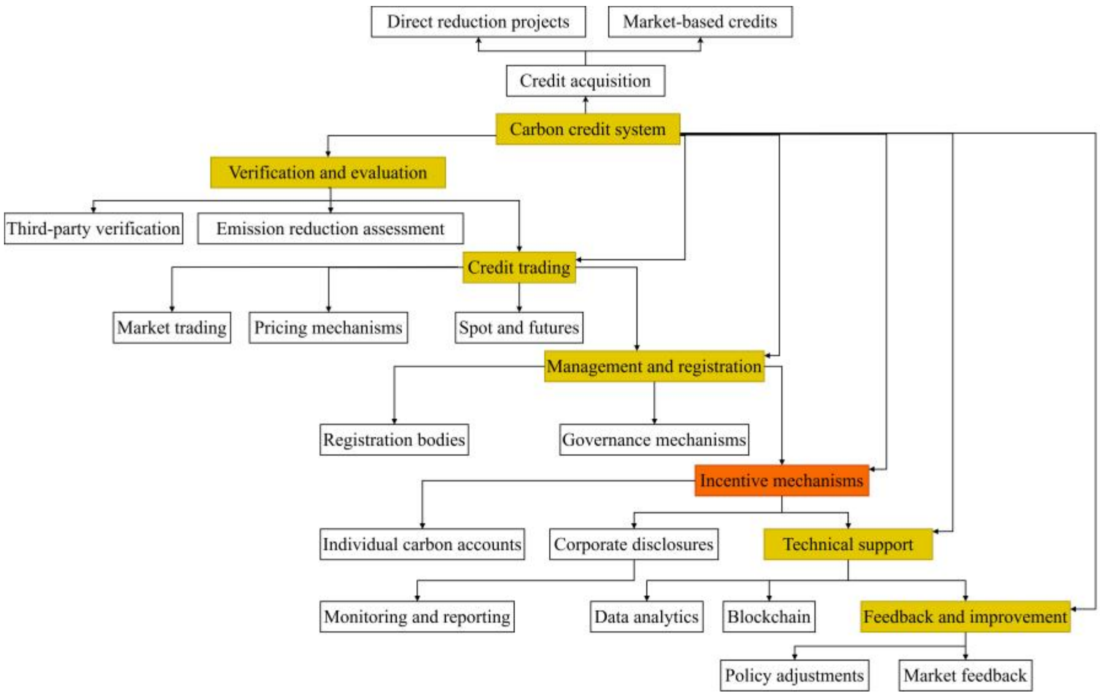

Figure 3. Carbon credit system

The main goal of the carbon credit system is to reduce greenhouse gas emissions and encourage enterprises and individuals to participate in low-carbon transformation through market-based mechanisms. The carbon credit system provides economic incentives for enterprises and individuals to reduce emissions. Through carbon credit trading, enterprises can sell the saved carbon credits and obtain economic benefits. This market-based incentive mechanism encourages companies to increase investment in low-carbon technologies and clean energy, improve energy efficiency, and thus achieve emission reduction targets. The carbon credit system uses the carbon market to realize the flow and trading of carbon credits, so that carbon emission rights and emission reduction costs are reasonably allocated and optimized in the market. Low-emission companies increase their income by selling carbon credits, while high-emission companies can purchase carbon credits to meet compliance requirements.

The carbon credit system indirectly encourages the promotion and use of renewable energy. Under the carbon credit system, investments in renewable energy projects can earn carbon credits to further promote green energy transformation. The carbon credit system monetizes environmental responsibility, achieving economic benefits while promoting the fulfillment of corporate social responsibility. By participating in the carbon credit market, companies can reduce carbon emissions, show the public their low-carbon efforts, and enhance their social image.

The carbon credit acquisition mechanism includes direct emission reduction and market trading. Companies or individuals achieve emission reduction through energy-saving technologies, improving energy efficiency, or using clean energy projects to obtain carbon credits. The baseline in direct emission reduction projects is the standard emission without taking any low-carbon measures, and all emission reduction effects are calculated based on the baseline. The carbon credit system supports the trading of carbon credits in voluntary or mandatory markets. Enterprises can buy or sell carbon credits on carbon exchanges to achieve emission reduction targets. The trading market provides two trading forms: spot and futures, which can flexibly meet the emission reduction needs of enterprises.

A dedicated carbon trading market [37,38] is established to provide a transparent and secure environment for carbon credit trading. The trading platform should have functions such as real-time trading, information disclosure and risk control, and support diversified trading methods such as spot trading and futures trading to enhance market liquidity. The incentive mechanism in the carbon credit system is designed to enhance the participation enthusiasm of enterprises and individuals and enhance their low-carbon awareness.

Personal carbon accounts provide participants with carbon accounts to record their acquisition, use and trading of carbon credits. Individuals can obtain carbon credits by reducing carbon emissions, reducing the use of private cars, increasing green consumption, etc. The points in the carbon account can be used to redeem rewards, discounts or tax reduction policies, etc.

Corporate carbon footprint disclosure: Through the carbon credit system, companies can record and disclose their carbon footprints and obtain credits based on their emission reduction results. This transparent disclosure mechanism not only helps companies fulfill their social responsibilities, but also enables them to establish a good image among the public and enhance their market competitiveness.

4. Results

A. Distribution Transformer Load at Public Charging and Swapping Stations

Based on the actual collected load characteristics of public charging and swapping stations, the peak, flat and valley periods are further distinguished. The load data of a province in China in 2023 is analyzed.

The average daily load of the monthly charging station is shown in Figure 4.

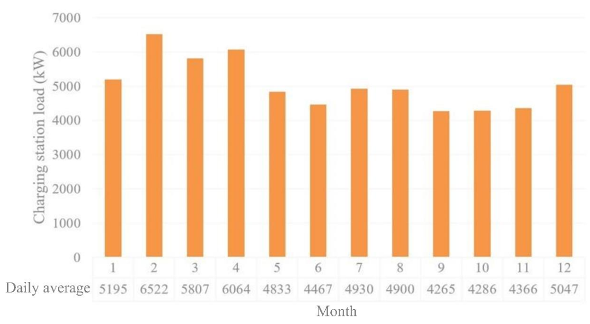

Figure 4. Monthly average daily load of charging stations

Figure 4 shows the monthly average daily load of charging stations. The horizontal axis 1-12 represents the months, and the average daily load corresponds to each month. In general, the public charging station shows a peak load in February-April and a trough load in May, June and September-November. The average daily load during off-peak hours only accounts for 65.39% of the average daily load during peak hours. It is worth noting that during the "peak summer" period from July to August, charging stations did not experience the same annual peak as other traditional power terminals, and the average daily load demand was lower than in winter.

The load curves of public charging stations in different months are shown in Figure 5.

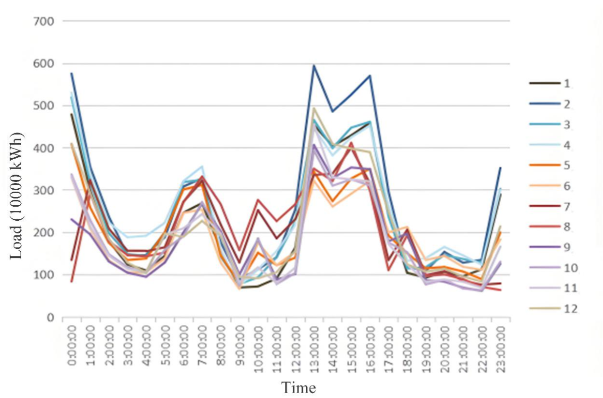

Figure 5. Public charging station load curves in different months

In Figure 5, the horizontal axis is the specific time point, and the vertical axis is the charging station load. Different colors represent January to December. Figure 5 further divides the peak, flat and valley periods in the monthly average load curve of the charging station into:

Annual load peak (February-April): The peak period is 0:00 to 2:00, 13:00 to 18:00, and the valley period is 2:00 to 6:00, 8:00-13:00, 18:00-24:00, and the other periods are flat periods. The annual load valley (May, June, September-November): The peak hours are 6:00-9:00 and 13:00-18:00, the valley hours are 2:00-6:00, 8:00-13:00 and 18:00-24:00, and the other hours are flat. The annual flat period 1 (January and December): The peak hours are 13:00-18:00, the valley hours are 2:00-6:00, 8:00-13:00 and 18:00-24:00, and the other hours are flat. The annual flat period 2 (July and August): The peak hours are 13:00-18:00, the valley hours are 2:00-6:00 and 18:00-24:00, and the other hours are flat.

The monthly average load curve for provincial regions is shown in Figure 6.

In Figure 6, the horizontal axis is the specific time point, and the vertical axis is the load (10,000 kW). Different colors represent January to December. The peak hours in summer (July-September) and winter (December-January) are from 15:00 to 24:00, the trough hours are from 0:00 to 7:00, and the other hours are flat. The peak hours in spring (February-June) and autumn (September-November) are from 20:00 to 24:00, the trough hours are from 0:00 to 6:00 and 10:00-15:00, and the other hours are flat. Comparative analysis shows that the peak and valley periods of the load of public charging and swapping stations are not consistent with the electricity consumption periods of the province. This is mainly reflected in the spring and autumn (February-June and October-November). The peak period of public charging and swapping stations corresponds to the valley period of electricity consumption in the province, while the valley period of public charging and swapping stations in winter and summer (December-January and July-September) corresponds to the peak period of electricity consumption in the province.

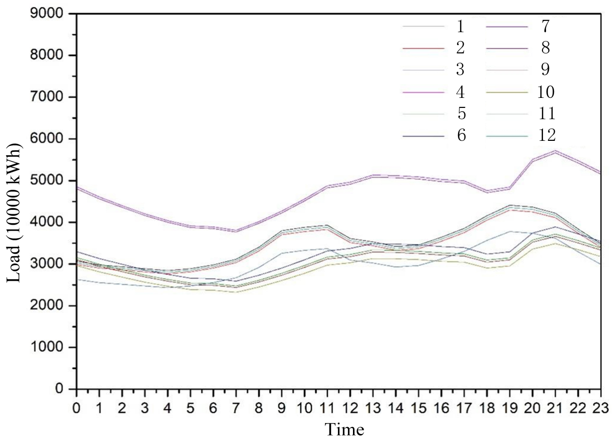

Figure 6. Monthly average load curve of provincial regions

B. *Results of New Energy Output Characteristics*

In the province, the installed capacity of new energy in City A is 3.9062 million kilowatts, of which 3.7812 million kilowatts are photovoltaic power and 125,000 kilowatts are wind power. Considering that wind power only accounts for 3.2% of the total installed capacity of new energy, the consumption of new energy only considers the output characteristics of photovoltaic power. The monthly average power generation of photovoltaic power is shown in Figure 7.

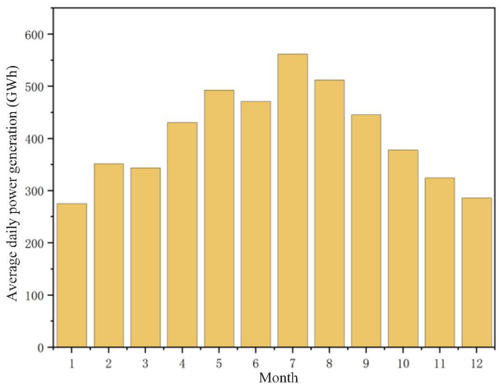

Figure 7. Monthly average photovoltaic power generation

The horizontal axis in Figure 7 is 12 months, and the vertical axis is the daily average power generation (10,000 kWh). The data covers the monthly average daily photovoltaic power generation from January to December 2023. Figure 7 shows the fluctuations in photovoltaic power generation data in the monthly average power generation. Photovoltaic power generation is higher from April to September, and the power generation is more balanced from October to March.

The average photovoltaic power generation curve at the hourly level is shown in Figure 8.

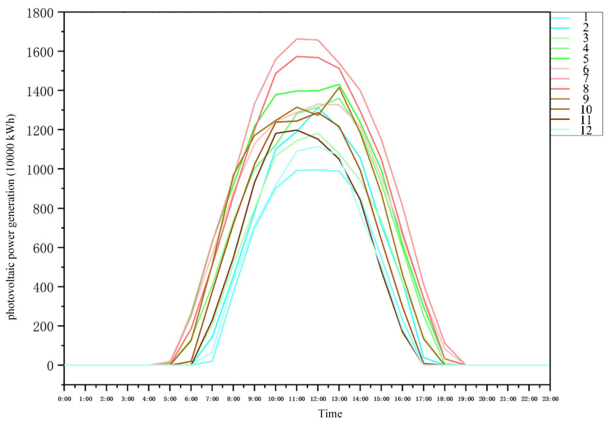

Figure 8. Photovoltaic hourly average power generation curve

Figure 8 shows the hourly fluctuations of photovoltaic power generation data in the monthly average power generation situation. The horizontal axis is the hourly level and the vertical axis is photovoltaic power generation (10,000 kWh). Photovoltaic power generation gradually increases from 6:00 to 10:00, reaches a peak from 10:00 to 14:00, and gradually decreases from 14:00 to 18:00. There is no power generation in other periods according to the light absorption time. It can be seen that with the change of seasonal sunshine time, the monthly average power generation is consistent with the trend of the hourly average power generation curve, and the data is representative.

C. *Dynamic Grid Carbon Emission Factor Analysis Results*

This paper uses power system timing software to simulate the output of various power sources according to the power load of the province in 2023. The power types are divided into energy storage (including pumped storage), external power (Zhundong DC (direct current)), thermal power (biomass, coal-fired power, gas-fired power plants and domestic waste power plants), hydropower, wind power, photovoltaic power, and load reduction is taken into account. The average output of various power sources on typical days in January, April, July and October in the province is shown in Table 1.

Table 1. The average output of various power sources on typical days in January, April, July and October in the province

	Average load (10000 kW)	Energy storage	External power	Thermal power	Hydropower	Wind power	Photovoltaic
January	3476.3	0.66%	5.41%	88.04%	0.51%	3.94%	1.44%
April	2768.29	0.00%	6.20%	64.82%	1.27%	7.19%	20.52%
July	4913.85	0.00%	4.77%	75.27%	0.66%	5.53%	13.77%
October	2858.66	0.00%	6.91%	74.72%	0.31%	7.27%	10.78%

The average carbon emission factor curve of the power grid in each month is shown in Figure 9.

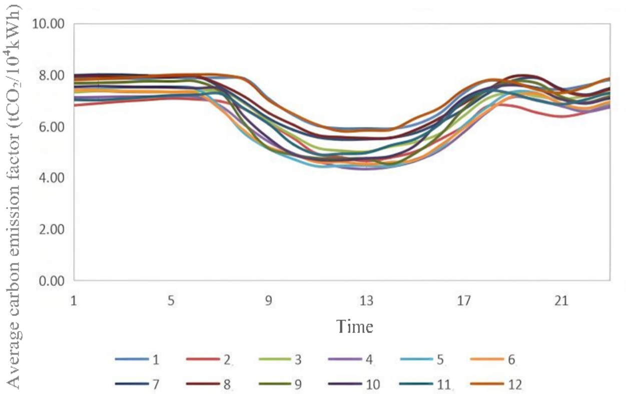

Figure 9. Average carbon emission factor curve of power grid in each month

Table 2. Carbon emission factors of the power grid during peak, valley and normal periods in different months

Months and seasons	Grid carbon emission factor (tCO_2/104 kWh)		
	Peak Period	Off-peak period	Mid-peak period
1	6.4433	7.4840	6.3617
2	5.8970	4.7809	6.2889
3	6.2444	4.9926	6.6512
4	5.7912	4.2688	6.2336
5	6.0425	4.2476	6.2905
6	6.0304	4.4025	6.2804
7	6.8302	7.2694	5.5895
8	6.8232	7.3485	5.7039
9	6.4662	6.8439	4.7295
10	6.5669	4.7236	6.4771
11	6.3255	5.0387	6.5081
12	6.9007	7.4328	6.0548
Summer	6.7065	7.1539	5.3409
Spring and autumn	6.1283	4.6364	6.3900
Winter	6.3988	6.1069	6.1718

In Figure 9, the horizontal axis is 24 hours a day, and the vertical axis is the average carbon emission factor ($tCO_2/10^4kWh$). Different colors represent January to December. At the peak of power load, the increase in power consumption of public charging and swapping stations is not only not conducive to the load reduction of the power grid, but also increases carbon dioxide emissions. At the same time, if the power consumption behavior of public charging and swapping stations is changed to increase the power consumption in valley and normal times, it can not only help promote the consumption of new energy, but also reduce carbon dioxide emissions compared with peak power consumption. The carbon emission factors of the power grid during peak, valley and normal periods in different months are shown in Table 2.

By establishing time- and season-based baseline scenarios for public charging and swapping stations based on the load of public charging and swapping stations, the characteristics of new energy output, and the dynamic carbon emission factor data of the power grid, it can organically combine the three of reducing peak loads in summer and winter, promoting the consumption of new energy during the midday valley period in spring and autumn, and reducing carbon emissions from electricity consumption at public charging and swapping stations.

New energy consumption scenarios in spring and autumn: The peak load of public charging and swapping stations in spring and autumn mainly occurs between 13:00 and 18:00 in the afternoon, which corresponds to the peak time of photovoltaic power generation during the day. The situation of new energy consumption is relatively severe, and the overall carbon emission factor of the power grid is relatively low. Through the setting of the baseline scenario, public charging and swapping stations are encouraged to continue to increase the power load during the peak time in the afternoon in spring and autumn, which not only promotes the consumption of new energy, but also significantly reduces carbon dioxide emissions compared with the same power consumption in valleys and normal times. At the same time, because the actual demand in the early morning hours (0:00-8:00) in spring and autumn is lower than that in winter and summer, and the public charging and swapping station area curve and photovoltaic curve in May and June are closer to those in February and April in spring, and there are also significant differences with the load curves in July and August, the power saving and emission reduction behaviors of public charging and swapping stations during the peak hours of electricity consumption at noon in spring and autumn should be partially offset, and public charging and swapping stations are encouraged to reduce electricity consumption and carbon emissions during other periods.

Peak summer and winter scenarios: The electricity load is high during the peak summer and winter periods, especially the peak load, which puts great pressure on the safe operation of the power grid. From the load curve of public charging and swapping stations, the peak load period of public charging and swapping stations in summer and winter is 13:00-18:00, which is consistent with spring and autumn, indicating that the electricity consumption behavior of public charging and swapping stations is different from that of residents' daily life and is not affected by seasons. In the summer from July to September and the winter from December to January, the peak electricity consumption period is from 15:00 to 24:00, and the off-peak period is from 0:00 to 7:00. The power load of public charging stations in summer and winter needs to be reduced during the peak and off-peak periods to ensure the safety and stability of the large power grid and reduce carbon dioxide emissions. Taking into account the characteristics of daytime photovoltaic output and the characteristics of large power grid power load, the peak hours in summer and winter are adjusted to 13:00-18:00, the valley hours are adjusted to 0:00-6:00 and 18:00-24:00, and the normal hours are adjusted to 6:00-13:00.

D. Forecast Reduction of Carbon Dioxide Emissions

The province has 11.92 million motor vehicles. Based on the 50% share of private cars and an average annual mileage of 10,000 kilometers, the annual carbon dioxide emissions from private cars in the province are about 7.74 million tons. By the end of 2023, the province has about 600,000 NEV. By promoting the implementation of the carbon credit system for NEV charging and battery swapping infrastructure, these NEV can reduce carbon dioxide emissions compared to the same number of gasoline vehicles, as shown in Figure 10.

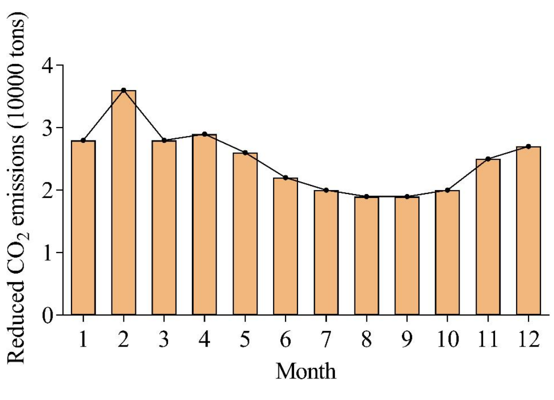

Figure 10. Reduced carbon dioxide emissions

From the 12-month data, it can be seen that the amount of carbon dioxide emissions that can be reduced by NEV in different months is different. The lines in Figure 10 are data change trends. But overall, by promoting the implementation of the carbon credit system for NEV charging and battery replacement infrastructure, the application of NEV can significantly reduce carbon dioxide emissions. In 2023, NEV can reduce carbon dioxide emissions by 299,000 tons per year compared to the same number of gasoline vehicles. The reduction in carbon dioxide emissions was most significant in the second month, reaching 36,000 tons.

The carbon credit system for NEV charging and swapping infrastructure encourages charging and swapping station operators and NEV users to adopt low-carbon electricity consumption behaviors. By managing the load of charging and swapping stations and optimizing electricity consumption periods, the peak and valley electricity price policy is linked to the carbon emission factor, so that operators can obtain more carbon credits during off-peak periods, thereby reducing the emission burden. These carbon credits can be converted into financial subsidies or electricity discounts, further encouraging charging and swapping stations and users to participate in low-carbon behavior. Reducing carbon dioxide emissions through incentive mechanisms can help reduce overall carbon emissions and promote green travel.

E. Promote the Consumption of Electricity in Valley Sections of New Energy Sources

The results of the impact of public charging and swapping stations on energy consumption capacity by rationally utilizing valley section electricity and improving electricity load are shown in Figure 11.

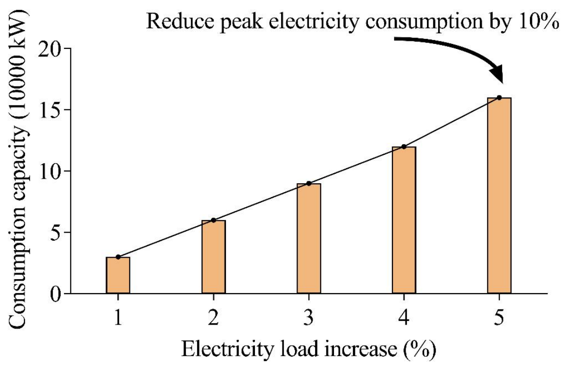

Figure 11. Impact of increasing electricity load on energy consumption capacity

The carbon credit system for NEV charging and swapping infrastructure can improve the flexibility of overall electricity load and achieve effective energy management and carbon emission reduction by encouraging charging and swapping stations to use new energy electricity during the low load period of the power grid. Through the incentive mechanism of the carbon credit system, the charging and swapping infrastructure can more actively shift the electricity load to off-peak hours. In this way, for every 5% increase in load usage, the absorption capacity of new energy electricity can increase by 160,000 kilowatts, effectively reducing the demand for fossil energy. This optimization measure reduces the demand for electricity during the peak period of the power grid, and is expected to reduce the peak power consumption by 10%. The total power of public charging and swapping stations is about 3.34 million kilowatts, which is equivalent to filling the power gap of 330,000 kilowatts, improving the stability and efficiency of the power grid operation and effectively reducing the power supply pressure during the peak period. The carbon credit system provides NEV owners and operators with quantifiable benefits from carbon emissions, encourages the use of clean energy through credit points and subsidies, and promotes the clean consumption and low-carbon transformation of new energy. This move not only helps to reduce the peak load of the power grid and increase the proportion of new energy utilization, but also provides effective institutional support and market driving force for achieving the goal of "carbon peak and carbon neutrality".

5. Discussions

The emission reduction accounting model proposed in this paper effectively integrates the carbon emission data of private cars and public charging and swapping stations. Based on the dynamic grid carbon emission factors and new energy output characteristics, the carbon emissions in different time periods and seasons can be accurately calculated. This method not only solves the time and space load differences ignored by previous studies, but also provides a scientific basis for policy making and can comprehensively measure the carbon emission reduction potential of NEV during charging. Through refined accounting methods, accurate and reliable calculation of emission reduction data provides important support for the implementation of the carbon credit system.

The carbon credit system in this paper has achieved remarkable results in improving the capacity of new energy consumption, especially in the rational use of valley electricity. By charging during off-peak hours and increasing electricity load, the capacity of new energy absorption is improved, effectively reducing the peak pressure of the power grid and the demand for fossil fuel electricity. This move not only eased the tension during peak load periods in the power system, but also significantly reduced carbon dioxide emissions, promoted the green and coordinated development of the power system and NEV, and provided a more stable market environment for the use of new energy.

Through the incentive system, users are actively guided to charge during off-peak hours, further reducing electricity costs and increasing the proportion of clean energy use. This mechanism provides users with direct economic incentives and effectively promotes green and low-carbon consumption behaviors. The rational design of incentive policies makes users more motivated to participate, promotes the optimal use of NEV charging infrastructure, and lays the foundation for achieving the carbon reduction goals of the whole society.

The climate characteristics of different regions may significantly affect the output characteristics of new energy sources. For example, the availability of solar photovoltaic and wind energy is significantly different in high-latitude cold regions and tropical regions, which is directly related to the accuracy of dynamic grid carbon emission factors. In addition, the proportion of fossil fuels and renewable energy in the power structure of each region will also lead to differences in carbon emission reduction benefits. For example, regions with a high proportion of renewable energy are more likely to achieve significant carbon emission reductions, while a power structure dominated by coal may weaken the model effect. Therefore, when promoting the model, parameter adjustment and adaptive optimization need to be carried out according to the climate conditions, energy structure and electricity load characteristics of the specific region. At the same time, differences in regional policy support and electricity market mechanisms should be considered, which will affect the design and implementation of incentive mechanisms. Future research can be based on pilot applications in typical areas to verify the applicability of the model in different energy and climate environments around the world, and propose an optimization framework with universal applicability and flexibility, thereby enhancing the promotion value of the model.

6. Conclusions

This paper verifies the significant effects of carbon emission reduction and new energy consumption by implementing the carbon credit system for NEV charging and swapping infrastructure. The emission reduction accounting model constructed in this paper combines the electricity consumption characteristics of private cars and public charging and swapping stations, uses dynamic grid carbon emission factors and new energy output curves, and carefully analyzes the load changes in different periods and seasons, providing high-precision carbon emissions estimates and more effective incentive mechanisms. This paper constructs a complete carbon credit system framework, which not only standardizes the carbon emission accounting process in the field of NEV, but also designs multi-dimensional point incentives for power load and new energy consumption during peak and valley periods, promoting users' active participation in the use of low-carbon energy. This paper effectively improves the capacity of new energy consumption, alleviates the peak load of the power grid, and improves the capacity of new energy absorption by transferring the load of electricity in the valley section, which not only helps to alleviate the pressure on the power grid, but also promotes the use of clean energy. It is recommended to formulate subsidy policies for new energy vehicles, encourage the use of low-carbon electricity, optimize the peak and valley electricity price mechanism, promote the construction of smart charging and swapping infrastructure, and establish a national unified carbon credit trading platform to enhance carbon emission reduction benefits and promote the development of a low-carbon economy. However, the applicability of the carbon emission calculation model in different regions still needs to be further verified, especially for regions with significant differences in seasonal and geographical characteristics. Future research should further deepen the collection of real-time data and accurate modeling to improve the system's applicability and promotion value.

Acknowledgment

None

Consent to Publish

The manuscript has neither been previously published nor is under consideration by any other journal. The authors have all approved the content of the paper.

Funding

None

Author Contribution

[Li Zhang]: Developed and planned the study, performed experiments, and interpreted results. Edited and refined the manuscript with a focus on critical intellectual contributions.

[Bao Wang, Jianxiong Jia]: Participated in collecting, assessing, and interpreting the date. Made significant contributions to date interpretation and manuscript preparation.

[Yue Yu, Zhumeng Song]: Provided substantial intellectual input during the drafting and revision of the manuscript.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

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