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Integration of Electric Vehicles into Microgrids: Policy Implication for the Industrial Application of Carbon Neutralisation in China

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Abstract: With the dynamic development of renewable energies, energy storage devices, and electric vehicles, microgrids have been playing an increasingly vital role in smart power grids. Under the recent development of carbon neutralisation, microgrid systems containing multiple clean energy sources have become significant modules for energy conservation and emission reduction. Considering technological and environmental elements, we investigated the economic operation of microgrids with the integration of electric vehicles. In this paper, carbon trading mechanisms and operation scheduling strategies are analysed in the simulation models. Then, transaction costs and power balance are discussed. Industrial applications and policy implications are also presented.

Keywords: electric vehicle; carbon neutralisation; microgrid; energy storage; economic operation; carbon trading

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1. Introduction

The exploitation of fossil energy has shifted humanity's focus from agriculture to industrialisation. Industrialisation has driven the tremendous advancement of civilisation for over two centuries. The predicted total volume of CO_2 created by fossil fuels is estimated to be 2.2 trillion tons [1]. In recent years, fossil fuel-based energy utilisation models have resulted in serious carbon emissions and global warming. Greta Thunberg, a Swedish teenage girl and a world-renowned environmental activist, warned at the 2020 Davos Forum to "stop investing in fossil fuels immediately, or explain to your children why you did not protect them from the climate chaos you create" [2]. In the past decade, the power industry has actively promoted energy conservation and emission reduction. However, due to economic costs and load constraints, wind and solar curtailment persists [3–6]. With recent policy incentives, carbon neutralisation and the vigorous development of electric vehicles and renewable energies have become inevitable trends in the power industry [7–9]. As a comprehensive integrated technology combining multiple types of renewable energies, the microgrid can increase the utilisation of wind power and solar energy, reducing carbon emissions [10,11]. Renewable energy sources, such as wind power and solar energy, are unstable and intermittent due to unpredictable weather conditions (e.g., heatwaves, tropical cyclone, storms) during generation. Thus, applying these valuable electric energies continuously and stably is difficult [12]. Ultimately, it is imperative to contribute to energy conservation and carbon neutralisation.

Since 1906, the average global temperature has increased by 1.1 °C [1]. To effectively address the adverse effects of global warming on human society, the 2015 United Nations Framework Convention on Climate Change (UNFCCC) was held in Paris, France. The consensus of keeping global warming under 2 °C was reached. Countries worldwide have further clarified their scope of greenhouse gas emission reduction. Different from the 1997 Kyoto Protocol, the Paris Agreement allowed each party to clarify their submission on greenhouse gas emission reductions through a bottom-up approach based on their emission reduction responsibilities and capabilities, which were defined as Nationally Determined Contributions (NDCs) targets [13]. In China, President Xi Jinping has emphasised the importance of environmental protection and ecological civilisation since the 18th National Congress of the Communist Party of China [14]. This mechanism can avoid problems of selection and formulation of emission reduction responsibility allocation options among countries.

The carbon trading mechanism allows trading entities to adjust their carbon emission rights through trading and exchange within a certain range to achieve regional carbon reduction at the lowest cost. However, compared with the carbon tax, the policy setting and design process of the carbon trading mechanism are more sophisticated and complicated. Setting the appropriate amount of regionally total carbon emission rights and determining the coverage and allocation of appropriate initial carbon emission rights for various industrial sectors are extremely challenging for policy makers.

Carbon trading mechanisms have provided economic incentives for market players to reduce carbon emissions and promote the utilisation of renewable energies and electric vehicles [15]. The introduction of carbon trading mechanisms no longer defines carbon as emission costs, but additional economic gains through carbon trading [16]. Regulation has been deployed to encourage the power industry to transform its energy structure and to improve technological innovation, achieving an environmentally economic operation model. Ref. [17] considered the economic impact of carbon emission allowances on scheduling strategies. Ref. [18] established a mathematical model for calculating carbon transaction costs based on carbon emission intervals. Ref. [19] constructed an optimal dispatch model for large-scale solar farms accessing smart grids under carbon trading mechanisms, which examined the low-carbon performance of the proposed system, especially in the post-COVID-19 era. The microgrid provides an efficient approach to facilitate the high penetration of renewable energies and electric vehicles into the power grid [20–22], serving as an important link in energy saving and emission reduction. The rapid growth of electric vehicles has essentially affected the development of microgrids in the smart power system [23], which can further stimulate the achievement of carbon neutralisation [24]. The dynamic increase in carbon emissions in China can be neutralised with the promotion and penetration of electric vehicles [25].

We investigated the economic operation of microgrids with the integration of electric vehicles and renewable energies, including wind power and solar energy. In this paper, a microgrid optimal dispatch model is constructed. Carbon trading mechanisms and operation scheduling strategies are analysed through the simulation models. Transaction costs in economic dispatch and power balance are discussed. The related constraints of balance are designed to reduce the carbon emissions of the microgrid system, increase the utilisation of renewable energies, and promote carbon neutralisation in the power industry. Industrial and policy implications are provided in the conclusion.

The remainder of this paper is structured as follows. Section 2 presents the research methodology. Section 3 presents a robust low-carbon economic dispatch model. Sections 4 and 5 provide industrial applications and policy implications in carbon neutralisation, respectively. Section 6 summarises and discusses future research directions.

2. Research Methodology

Electric vehicles have been playing an increasingly vital role in the smart grid and power system technology, owing to updated charging technology, financial subsidies, and low cruise costs. With the expansion of the scale of using electric vehicles, the operational model of the microgrid must be modified accordingly. Electric vehicles have adjustable charging and discharging properties, and they have a dual role when they are connected to the grid: they can be used as a load to charge and as a power source to supply power to the microgrid. Therefore, research to incorporate electric vehicles into the microgrid to optimise the allocation of microgrid resources can improve the economic and stable operation of the microgrid, which will further enhance the dynamic performance of the main power grid. In this paper, we propose a microgrid economic dispatch model containing electric vehicles, wind power, solar energy, and energy storage devices. In addition, carbon neutralisation and carbon emission costs are added to the model as constraints. A standard structure of a microgrid connected to the main grid containing wind power, solar energy, electric vehicles, and energy storage devices is shown in Figure 1.

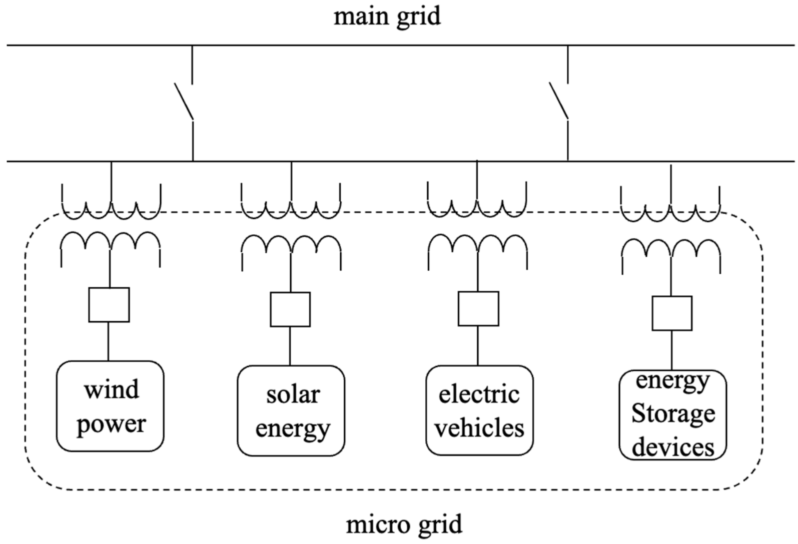

Figure 1. Sample structure of a microgrid connected to a main electric grid.

3. Low-Carbon Dispatch Model

The microgrid system is connected to the main grid and comprises electric vehicles, wind power, photovoltaic power generation, and storage batteries. If the electricity purchased by the microgrid from the main grid is generated by thermal power units, the microgrid's free carbon emission quota is:

$$C_m = \mu \sum_{t=1}^{T} \left(P_w \cdot t + P_s \cdot t + P_{ev} \cdot t - P_g \cdot t \right). \quad (1)$$

where:

C_m is the carbon emission quota of the microgrid;
μ is the co-efficiency as regulated by related authorities;
t is the time duration of the operation;
P_w is the electric power generated by the wind turbines;
P_s is the electric power generated from solar energy;
P_{ev} is the electric power charged by or used by electric vehicles connected to the microgrids, which can be positive or negative; and
P_g is the electric power purchased from the main grid.

Carbon emissions are lower than quotas, resulting in carbon emission benefits. Low carbon emissions can generate substantial carbon trading benefits and may even offset the increase in costs caused by gas turbine power generation from the main grid. This fully mobilises energy saving and emission reduction in the power generation industry.

To prevent excessive charging and discharging of the energy storage devices, charging constraints are introduced to fulfil upper and lower limits:

$$0 \le P_b \le P_{b,max}. \quad (2)$$

where:

P_b is the electric power saved in the energy storage devices; and

$P_{b,max}$ is the maximum charging capacity of the energy storage devices.

The trading data disclosed by the two leading carbon trading pilot centres in China, i.e., the Beijing Trading Centre and the Guangzhou Trading Centre, reveal a significant gap between the carbon trading patterns of northern and southern China, although the annual cumulative carbon emission rights and trading turnovers are close to each other, both being approximately 26 million tons at around USD 170 million [26,27], as shown in Figure 2.

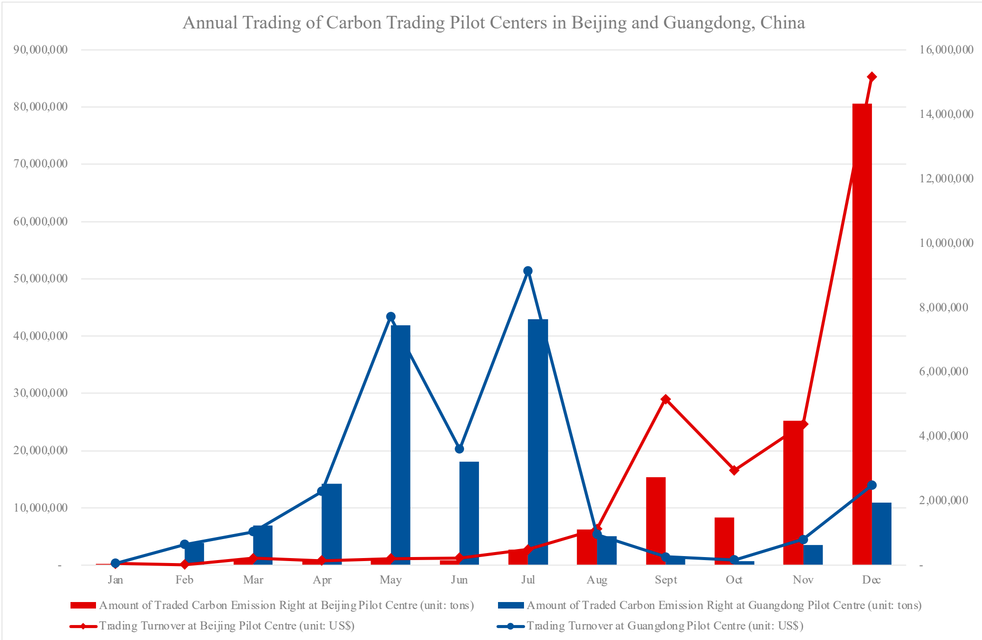

Figure 2. Annual turnover of carbon trading pilot centres in China in 2021.

The peak trading season in Guangzhou is summer, mainly May to July; meanwhile, the peak trading season in Beijing is mainly November and December. The reason is due to different details on policy execution and settlement regimes. Market players in Guangzhou must face the mid-term inspection of carbon emissions, which is an important policy incentive for the market players with high carbon emission to increase their trading for sufficient emission right in the summer. Meanwhile, the market players in Beijing have only a year-end examination of their carbon emissions, and thus tend to wait until the year's end to complete their carbon trading. In addition to the different settlement regimes, another major reason is the different patterns of energy consumption between northern and southern China due to different weather conditions.

The above-mentioned pilot centres are only at the regional level, and can only provide a carbon trading platform for enterprises within their administrative regions. In July 2021, a national-level trading platform was launched in Shanghai under a trial mode. More information is to be released in the near future. With the official launch of the national carbon emission rights trading market, government authorities can utilise the market and pricing mechanism to regulate the use of carbon emission rights. When the carbon trading price is overly high, the carbon emission quota allocated to the industrial manufacturer may be reduced. Meanwhile, the pressure on the manufacturer to reduce emissions increases will drive the enterprise to spend more money to purchase carbon emission rights, which is not conducive to its production and operation. Therefore, an appropriate adjustment in the carbon trading price may not only reduce the emission reduction pressure of emission enterprises, but also effectively increase the manufactory output and broaden the eligible industrial sectors of the carbon quota mechanism.

4. Industrial Applications

By the end of 2020, the cumulative installed capacity of power generation from renewable energies reached 535,000 MW in China, a year-on-year increase of 29.4%, accounting for 24.3% of the total installed capacity. The newly installed capacity of renewable energy power generation in 2020 reached 120,000 MW, accounting for 63% of the total installed capacity of renewable energies in the whole nation [28]. Furthermore, the national power generation from renewable energies achieved 10% of the total power generation, highlighting a considerable improvement in renewable energy utilisation.

Under the guidance of the development goals of the electric power system, the future development of the new energy industry has shown a trend of deploying more renewable energies and electric vehicles. Distributed power generation, microgrids, and integration with electric vehicles have gained considerable importance in the industry. The widespread use of microgrids has intensified the demand for flexible adjustment resources, such as energy storage devices.

The shift from centralised generation to distributed generation has attracted the interest of academics, policy makers, and industrial engineers, thereby accelerating the development of microgrid systems. Energy storage devices are among the essential factors to facilitate such a trend. In addition to distributed renewable energy resources, such as roof-top wind turbines and solar panels, fuel cells are considered a clean and flexible option for promising energy resources in microgrid application [29]. Flow batteries have also been revived recently, especially for large-scale energy storage systems in microgrids, due to their low cost and eco-friendly materials, even with favourable design flexibility [30].

In recent years, electric vehicle sales have grown rapidly due to the incentive financial subsidy policy. The government's subsidy policy has greatly stimulated enthusiasm to invest in the electric vehicle industry. Domestic sales rose sharply with the implementation of the subsidy policy. Due to policy relaxation and tax benefits, electric vehicle manufacturers have also increased. The driving range and the safety of the power battery are constantly improving. Power battery technology is constantly advancing. Power semiconductor technology, intelligent drive technology, and power component integration technology have improved to increase power density, reduce losses, and ensure reliability. The main domestic charging method is AC slow charging, supplemented by DC fast charging. Convenience will be an important concern in the future. Microgrid power generation is in a low-carbon mode, interacting power transmission with the main grid. The sum of the total power generation in the microgrid is equal to the total load value in the microgrid, which satisfies the balance of supply and demand. When the load is low, the microgrid sells electricity to the main grid, the battery is charged, and the output of wind power and solar energy drops. When the load peaks, the output of wind power and solar energy increases, and the battery discharges to the main grid.

The electric vehicle industry policy aims to promote the development of the new automobile industry. Ref. [31] predicted electric vehicle sales in the next few years, as shown in Figure 3. In the implementation process, policy formulation has faced challenges from various aspects, including technical, financial, and environmental issues. Related policies and their implementation have encountered a lack of references. Therefore, policy formulation must be further improved. The competent authority shall formulate long-term policy plans considering standardisation and stability. The transition period of the policy should be well connected to ensure continuity and predictability, which will gradually form legal documents.

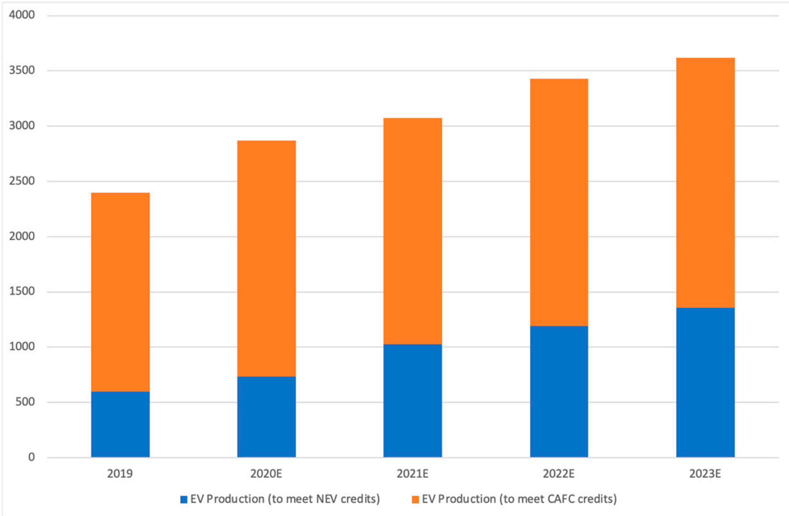

Figure 3. Predicted increase in EV production in China (unit: thousand).

To accommodate the flexibility of the microgrid system, energy storage devices of electric vehicles should be light with the potential to possess high energy density. The application of lithium batteries in recent years has been proven to be a feasible solution. The integration of lithium batteries in electric vehicles can significantly reduce carbon emissions and road-side air pollution [32].

Generation units of renewable energies are small in capacity, large in number, scattered in locations, and diverse in characteristics. Power electronic equipment adopts discrete control based on fast switching, which makes a fundamental change in the control mode of the distributed microgrid power system and has continuous adjustment and control capabilities.

The form of the power system has transformed from the traditional large power grid to the complementary symbiosis of the large power grid and the microgrids. The power system must not only satisfy the access and consumption of centralised new energy but also support the access and withdrawal of distributed power generation. Wind power and solar energy will become the installed capacity of electricity supply as well as bear the responsibility for the safe and stable operation of the power system.

China has launched carbon emission trading pilot schemes in eight regions, actively exploring the trading mechanism and future direction of the carbon trading market. In 2011, China first opened carbon emission rights in seven regions, Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangzhou, and Shenzhen. In 2017, Fujian joined as the eighth pilot region. Each pilot region followed a similar carbon emission measurement approach; however, the coverage for industrial sectors varied [33]. The development in those eight pilot regions built a solid foundation for the national carbon trading platform in the next stage.

The carbon trading pilot centre in Beijing is the most representative of the eight centres to reflect the carbon emission and trading situation in northern China. Meanwhile, the carbon trading pilot centre in Guangzhou is the most representative of the situation in southern China.

The essential purpose of running an enterprise is for production and sales. The reason why companies with emission pressure are willing to reduce emissions is that excess carbon emission rights exist that can be traded in the carbon trading market for profit. Therefore, related government authorities should encourage enterprises to invest in research and develop emission reduction technologies to reduce the operational and environmental costs of emission reduction. Furthermore, guidelines for consumers to buy low-carbon products will also boost market demand and increase production and sales revenue for enterprises.

5. Policy Implications

The power production structure has undergone profound changes. The primary energy supply for the new power system will shift from stable and controllable conventional energy sources, such as coal, gas, and water, to new energy, such as wind power and solar energy. The technical foundation of the power system has undergone significant changes. The synchronous operation of the AC power system of the new energy unit is driven by the physical characteristics of the steering control algorithm. This is a time to construct a carbon emission management system and a supervision system for low-carbon and green energy development [1]. Moreover, the policy support for industry–university research cooperation and policy support for new and in-depth collaboration between industry, academia, and research led by energy automobile companies must be strengthened. The support and incentives for technology innovation will provide a platform to encourage knowledge transfer and the transformation of scientific and technological achievements related to the automobile and power industry, which will encourage cooperation and integration amongst enterprises and research institutes, including collaborative technology development and industrialisation. The government may introduce various innovation and technology funds to support academic institutions and firms to purchase equipment and recruit research personnel.

Regarding subsidies and tax policies, direct subsidies should be gradually reduced, and low-interest loans and other financial policy support should be increased. The policy scope should consider the whole business chain of the electric vehicle industry. Subsidy policy can be returned to consumers to expand consumer demand. The requirements for products have driven automobile companies to invest in research and development. Subsidies and tax policies have also strengthened review and supervision, thereby increasing the execution power on regulations and laws. Other supporting policies, such as purchase discounts and exemption from traffic restrictions, will also improve the advantages and consumers' willingness to drive electric vehicles.

In addition to the global economic crisis and other factors, issues persist, such as the setting of the total amount of carbon emission rights, the determination of industry coverage, and the allocation of initial carbon emission rights in the design process of the carbon trading mechanism, which have become obstacles to the construction process of carbon trading markets in various countries and have affected the carbon trading mechanism. Government authorities can consider formulating the guidance price of carbon emission rights based on the emission reduction target and the industrial average emission reduction cost. The decision-making behaviours of automobile manufacturers under the carbon trading mechanism include energy intensity, carbon credit evaluation decisions, production decisions, automobile pricing decisions, and carbon credit accounting and trading considering energy intensity. In addition, car manufacturers can interact with car users when selling cars.

Given that information on China's carbon market has not been fully disclosed, investors' decisions based on known information are sophisticated, which exacerbates the randomness of investment decisions and expected yield from carbon trading in the market [34,35]. Therefore, the transparent information disclosure system in the carbon trading market must be improved. The current pricing mechanism in carbon trading pilot centres cannot fully reflect market information. Thus, market pricing efficiency must be improved. Furthermore, establishing appropriate mechanisms to prevent insider trading is essential for controlling market risks. In addition, an adjustment mechanism to effectively prevent abnormal price fluctuations and a risk prevention and control mechanism to prevent market manipulation should be established to form an effective price formation that reflects factors such as supply and demand, emission reduction costs, and so on.

To stimulate carbon trading activities in the pilot centres, government authorities can consider guiding relevant enterprises to increase their willingness to trade spontaneously in the carbon market by providing financial incentives and stimulation mechanisms. On the one hand, penalties for companies that fail to comply with the carbon emission targets should be implemented; on the other hand, more tax incentives and green credits to companies that actively participate in carbon trading and achieve the carbon emission targets should be provided. Such a stimulative mechanism can enhance the enthusiasm of companies to seek profit through active trading activities or to reduce carbon emissions.

Furthermore, the electric vehicle industry faces a challenge of long-term capital occupation and substantial initial financial investment. Based on the experiences of the conventional automobile industry, corporate investment and financing can appropriately reduce financing costs. Financing channels, such as corporate loans and bonds, must be broadened, and banks, financial intermediaries, and credit guarantee centres must be encouraged to provide priority services for electric automobile companies, moderately relax conditions, lower interest rates, and introduce foreign capital. Concurrently, a risk prevention and control mechanism should be implemented.

6. Conclusions and Future Work

In this paper, we proposed and analysed a multi-source microgrid economic dispatch model to reduce carbon emissions. The implemented carbon trading mechanism contributes to achieving carbon emissions control. Companies with surplus carbon emission quotas can increase their additional income by selling such quotas to reduce the total generation and operation cost of the power system. The low-carbon dispatch model enables wind power, solar energy, electric vehicles, and other distributed power generation units to benefit from carbon trading and to reduce the operation costs while expanding the microgrid system, which ultimately reduces the total cost of the power system.

The cost of distributed generation from renewable energies in microgrids is relatively higher than that of conventional generation. When the power generation exceeds a certain range, the system can sacrifice a certain economy to increase the penetration rate of new energy, thereby reducing the carbon emissions of the system and improving the environmental protection of the system.

The issuance and implementation of industrial policies on electric vehicles have become important factors that promote rapid development. With the advent of the post-subsidy era, the electric vehicle industry continues to face challenges related to core technologies and structures. Therefore, industrial policies must be continuously improved to promote the healthy and rapid development of the industry.

With the continuous introduction of new carbon trading-related financial products in China, the volatility of the carbon trading market may be affected by emerging factors. Future research must entail a comprehensive analysis and volatility assessment of the incentives for carbon trading volatility. Furthermore, automobile users are not included in the current emission reduction framework in China. To achieve carbon neutralisation, automobile users, such as the general public who drive EVs, should also be included.

Future study must incorporate related economic and microgrid management indicators into our mathematical model to enrich simulation scenarios with consideration of climate values. As such, it may contribute to the interdisciplinary research direction in the future. Moreover, future research must develop a climate-resilient infrastructure on how to minimise the vulnerabilities or risks influenced by climate change and improve climate resilience [36,37].

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