System dynamics modeling and analysis of the impact of regional carbon emissions by electric vehicles integration

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***Abstract*—In the pursuit of low-carbon development and achieving the dual carbon goals, the development of electric vehicles is an important driver. This paper aims to study the impact of electric vehicles on carbon emissions. Firstly, it analyzes the relationship between the scale of electric vehicles, vehicle-to-gird, and the structure of regional energy sources and carbon emissions. Then, three different strategies for the development of clean energy are constructed. Finally, a feedback model based on system dynamics is established to simulate the dynamic evolution process of reducing regional carbon emissions through the integration of electric vehicles into the grid. To validate the effectiveness of the model, a city in southwest China is selected as the research object, and simulation using Vensim software is conducted to analyze the impact of electric vehicle grid integration on reducing carbon emissions in three different scenarios. The simulation results show that the continuous expansion of the scale of electric vehicles will have a significant and positive effect on carbon emissions reduction. Vehicle-to-grid technology has great potential for reducing carbon emissions. The promotion of clean energy has a significant effect on reducing carbon emissions.**

Keywords-dual carbon targets; vehicle to gird; carbon emissions; energy-resource structure; system dynamic.

I. INTRODUCTION

Against the backdrop of continuous promotion of new energy vehicles in China, electric vehicles (EVs) are gradually replacing traditional fuel vehicles (CVs), which has become a strong pillar in achieving dual carbon goals. At the same time, the continuous progress of vehicle-to-grid (V2G) technology and the increase in clean energy utilization provide important guarantees for reducing carbon emissions.

With the popularization of EVs, the trend of their scale development has become a key focus of research. According to [1], it is predicted that by 2035, the number of pure electric vehicles will reach 120 million, with an annual charging capacity of 500 billion kWh. [2] uses the firefly algorithm to optimize the parameters of the gray prediction model for EV ownership and predicts that the number of EVs will continue to grow rapidly in a certain region from 2023 to 2033.

Studying the charging load of EVs is of great significance for energy management, grid stability, and environmental protection. [3] proposes a charging load prediction method for EVs that addresses issues such as poor reliability, complexity, variability, and uncertainty of charging load data. [4] proposes a novel encrypted deep learning model for predicting the charging demand of EVs at charging stations. [5] introduces a long short-term memory Bayesian neural network (LSTM-BNN) for predicting household loads under EV charging conditions, achieving accuracy similar to point forecasts.

Studying the impact of EVs on carbon emissions helps comprehensively assess their impact on the environment, climate, and sustainable energy development. [6] presents research on carbon emission flowchart theory and lifecycle models based on EVs and develops a carbon footprint management system. [7] proposes a carbon footprint management strategy for EVs, which can reduce the cost of carbon emissions per ton and improve the energy efficiency of renewable energy.

In conclusion, the current discussion on EVs mainly focuses on their economic benefits, while their potential for reducing carbon emissions is often overlooked. System dynamics, as a method for analyzing the interaction of complex systems, has unique advantages and can help reveal the inherent relationships and trends within the system. In the context of global low-carbon transformation, it is of great significance to explore how EVs can contribute to reducing carbon emissions and analyze them through system dynamics modeling and simulation.

II. THE COUPLING RELATIONSHIP BETWEEN ELECTRIC VEHICLES TO GIRD AND CARBON EMISSION REDUCTIONE

A. The Impact of theSscale Development of Electric Vehicles on Carbon Emissions

With the increasing awareness of environmental protection, EVs are gradually becoming the preferred mode of transportation for households, businesses, and government officials, leading to the development of the EV market. According to predictions, the number of EVs in China will reach 44.09 million by 2025, and this rapid growth trend will continue until 2030, with the number of EVs reaching 90.59 million by that year. In the scenario of scaled EV development, EVs have significant potential for carbon emissions reduction [8]. This study introduces the "EVs development scale module" in Figure 1 to analyze the changes in carbon emissions during the transition from conventional vehicles (CVs) to EVs.

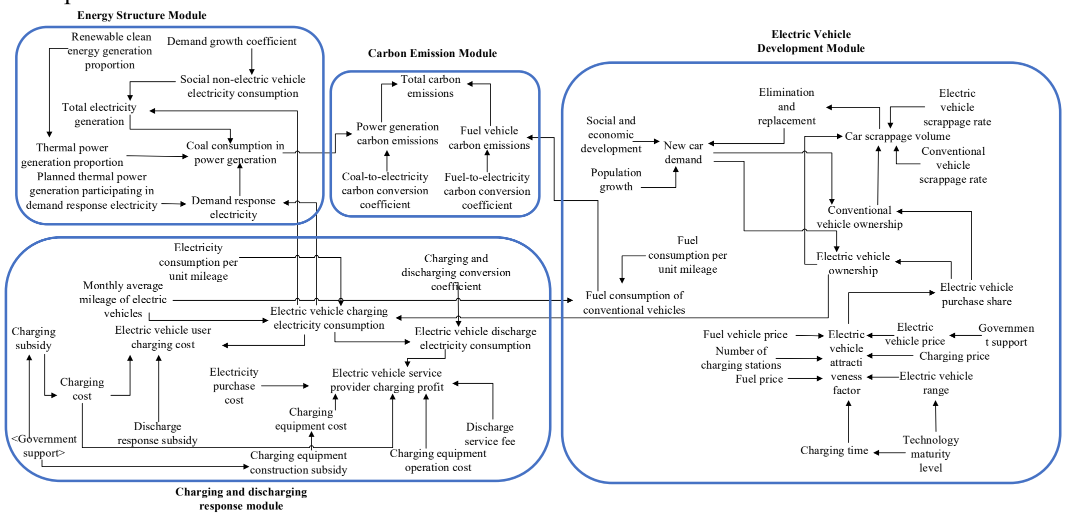

Figure 1. The relationship between EVs to grid and carbon emissions.

B. The Impact of Energy Grid Structure on Carbon Emissions

Since the reform and opening up, China has overly relied on the consumption of fossil energy resources to achieve economic growth, with coal consumption accounting for the largest proportion. In order to achieve carbon emission reduction goals, it is necessary to prioritize the utilization of clean energy and reduce the proportion of coal consumption, thereby optimizing the energy structure [9]. This study is guided by the macro development goals of domestic clean energy and analyzes the mutual impact between EVs integration into the power grid and carbon emissions based on the content shown in the "energy structure module" in Figure 1.

C. The Impact of the Development of Vehicle-to-Grid (V2G) Technology on Carbon Emissions

V2G technology enables electric vehicles (EVs) to interact with the grid in both directions. It allows EVs not only to charge from the grid but also to supply excess energy back to the grid [10]. Considering the dominant position of thermal power generation in current demand response and its high carbon emissions, this study proposes integrating V2G technology into the demand response mechanism, utilizing EVs to replace a portion of thermal power generation in response, thus significantly reducing carbon emissions. The charging and discharging behavior of EVs in the demand response process is illustrated in the "charging and discharging response module" shown in Figure 1.

III. Dynamic Model of Vehicle to Grid Integration Under Dual Carbon Goals

A. System Dynamics Model

System dynamics is a system simulation method based on systems theory, combining control theory and information theory, to identify the root causes of problems by studying the internal structure of a system. The modeling process of system dynamics, as shown in Figure 2.

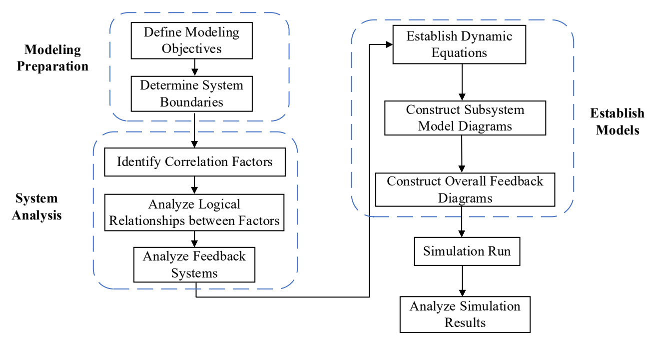

Figure 2. System dynamics modeling process diagram.

B. Submodule modeling

In the context of dual carbon goals, this paper uses system dynamics method to model and analyze the impact of EVs' integration into the grid on carbon emissions. Specifically, the factors influencing the change in carbon emissions curve are divided into four submodules: EV development module, charging and discharging response module, energy structure module, and carbon emissions module. These four submodules are interconnected and together form a complete framework for analyzing the impact of EVs' integration into the grid on carbon emissions[11].

1) EV development module:

With the rapid growth of national GDP and the gradual increase in personal consumption levels, the demand for cars has been increasing. EVs have experienced rapid development. This article mainly constructs a dynamic evolution model of the conversion between EVs and CVs based on social, economic, and EVs development factors, as shown in Figure 3.

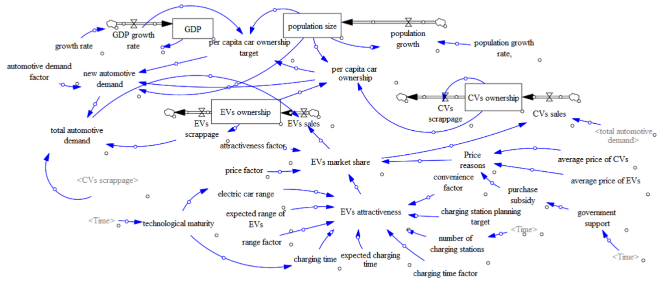

Figure 3. EVs development module Vensim diagram.

The scale of EVs is mainly influenced by the purchase volume $B_{EV}(t)$, scrappage volume $D_{EV}(t)$, and initial ownership volume $E_V(t_0)$:

$$E_V(t) = \sum_0^T [B_{EV}(t) - D_{EV}(t)] + E_V(t_0) \tag{1}$$

$$B_{EV}(t) = Z_V(t) \cdot E_V^{sp}(t) \tag{2}$$

$$D_{EV}(t) = E_V(t) \cdot d_{EV} \tag{3}$$

where, $Z_V(t)$ is the total demand for cars, $E_V^{sp}(t)$ is the market share of EVs, d_{EV} is the monthly scrappage rate of EVs.

Due to the constraints of relevant factors in the development process of EVs, the calculation formulas for the purchase volume and scrappage rate of EVs are given by (2) and (3) respectively. Similarly, for the development scale of CVs, the purchase volume $B_{CV}(t)$, scrappage volume $D_{CV}(t)$, and initial ownership volume $C_V(t_0)$ can be determined separately.

$$C_V(t) = \sum_0^T [B_{CV}(t) - D_{CV}(t)] + C_V(t_0) \tag{4}$$

$$B_{CV}(t) = Z_V(t) \cdot [1 - E_V^{sp}(t)] \tag{5}$$

$$D_{CV}(t) = C_V(t) \cdot d_{CV} \tag{6}$$

where, d_{CV} is the scrappage rate of CVs per month.

The purchase share of EVs $E_V^{sp}(t)$ is influenced by the price factor $E_V^{PF}(t)$ and the attractiveness of EVs products $E_V^{ATT}(t)$.

$$\begin{aligned} E_V^{sp}(t) &= E_V^{ATT}(t) / [E_V^{ATT}(t) + E_V^{PF}(t)] \cdot \eta_1 \\ &+ E_V^{PF}(t) / [E_V^{ATT}(t) + E_V^{PF}(t)] \cdot \eta_2 \end{aligned} \tag{7}$$

$$E_V^{PF}(t) = E_V^{\text{Price}}(t) - C_V^{\text{Price}}(t) - A_P(t) \tag{8}$$

$$A_P(t) = \alpha_1 \cdot S_{ub}(t) \tag{9}$$

$$S_{ub}(t) = e^{0.01t} \tag{10}$$

where, η_1 is attraction factor, η_2 is price factor, $E_V^{\text{Price}}(t)$ is the selling price of EVs, $C_V^{\text{Price}}(t)$ is the selling price of CVs, $A_P(t)$ is the purchase subsidy of EVs, $S_{ub}(t)$ is government support efforts, α_1 is purchase subsidy coefficient of EVs.

The calculation form of EVs attractiveness is as follows:

$$\begin{aligned} E_V^{ATT}(t) &= [E_V^R(t) / E_V^{RE}(t)]\eta_3 + \\ & [E_V^T(t) / E_V^{TE}(t)]\eta_4 + [E_V^{CS}(t) / E_V^{CSE}(t)]\eta_5 \end{aligned} \tag{11}$$

$$E_V^R(t) = c_1 \cdot e^{T_M(t)} \tag{12}$$

$$E_V^T(t) = c_2 \cdot e^{-T_M(t)} \tag{13}$$

$$E_V^{CS}(t) = c_3 + c_4 \cdot t \tag{14}$$

where, $E_V^R(t)$ is the range of EVs, $E_V^T(t)$ is the expected range of EVs; E_V^{RE} is charging time for EVs, $E_V^{CS}(t)$ is the number of charging stations, $E_V^{CSE}(t)$ is the expected number of charging stations, η_3 is range factor, η_4 is charging factor, η_5 is convenience factor. c_1, c_2, c_3, c_4 is average range of EVs, average charging time of EVs, current number of charging stations, and monthly construction of charging stations; $T_M(t)$ is technological maturity.

The demand for car scale is influenced by factors such as urban social development, economic conditions, and population growth. The total demand for existing cars can be obtained through the scrapping of EVs, the scrapping of CVs, and the demand for new cars $\Delta V(t)$.

$$Z_V(t) = D_{EV}(t) + D_{CV}(t) + \Delta V(t) \tag{15}$$

$$\Delta V(t) = [V_{PE}(t) - V_P(t)] * \alpha_2 * P_{OP}(t) \tag{16}$$

$$V_P(t) = [E_V(t) + C_V(t)] / P_{OP}(t) \tag{17}$$

$$V_{PE}(t) = V_P(t) + G_{GDP}(t) * c_5 / P_{OP}(t) \tag{18}$$

where, $V_P(t)$ is Per capita car ownership, $V_{PE}(t)$ is target for per capita car ownership, $P_{OP}(t)$ is population size, $G_{GDP}(t)$ is GDP growth, c_5 is The constant of the impact rate of GDP and population on EVs.

$$C_{GDP}(t) = \sum_0^T G_{GDP}(t) + C_{GDP}(t_0) \tag{19}$$

$$G_{GDP}(t) = C_{GDP}(t) * g_r^{GDP} \tag{20}$$

$$P_{OP}(t) = \sum_0^T G_P(t) + P_{OP}(t_0) \tag{21}$$

$$G_P(t) = P_{OP}(t) * g_r^P \tag{22}$$

where, $C_{GDP}(t_0)$ is initial value of urban GDP, g_r^{GDP} is GDP growth rate, $G_P(t)$ is monthly average population growth, $P_{OP}(t_0)$ is initial population value, g_r^P is growth rate of population.

2) Charging and discharging response module:

EV charging and discharging facilities are mainly provided by charging operators. As an independent enterprise, the operator needs to bear the construction $C_{str}(t)$ and operation costs of charging facilities $M_{an}(t)$, and the source of income is the charging service fees paid by customers $B_{en}(t)$.

$$B_{en}(t) = [(P_{cha}(t) - p_{pur}) \cdot L_{cha}(t)] + [C_{dis} \cdot L_{dis}(t)] \quad (23)$$

$$M_{an}(t) = C_{man} \cdot E_V^{CS}(t) \quad (24)$$

$$C_{str}(t) = E_V^{CS}(t) \cdot (C_{str}^{per} - S_{ub}^{str}) \quad (25)$$

$$S_{ub}^{str} = \alpha_3 \cdot S_{ub} \quad (26)$$

where, $P_{cha}(t)$ is the charging unit price, p_{pur} is the operator's electricity purchase unit price, $L_{cha}(t)$ is the monthly average charging capacity, C_{dis} is the discharge service fee, $L_{dis}(t)$ is the monthly average discharge capacity, C_{man} is the basic operation and maintenance costs for each charging station, C_{str}^{per} is the basic construction cost of each charging station, S_{ub}^{str} is the subsidy for charging facility construction, α_3 is subsidy coefficient for charging station construction.

Therefore, the total revenue of charging operators is:

$$B_{OP} = \sum_{0}^{T} [B_{en}(t) - M_{an}(t) - C_{str}(t)] + B_{OP}(t_0) \quad (27)$$

where, $B_{OP}(t_0)$ is the initial value of revenue for charging operators.

The average monthly discharge capacity of the user is:

$$L_{dis}(t) = L_{cha}(t) \cdot \alpha_4 \quad (33)$$

where, α_4 is charge discharge conversion coefficient.

The average monthly discharge revenue for users is:

$$P_{user}^{dis}(t) = p_{ri}^{dis} \cdot L_{dis}(t) \quad (34)$$

where, p_{ri}^{dis} is the discharge subsidy.

Based on the above, the total charging expenditure of EVs users can be obtained, which is mainly determined by the combined monthly average charging cost and monthly average discharge income.

$$C_{user}^{total}(t) = \sum_{0}^{T} [C_{user}(t) - P_{user}^{dis}(t)] \quad (35)$$

The feedback subsystem of the charge discharge response module is shown in Figure 4.

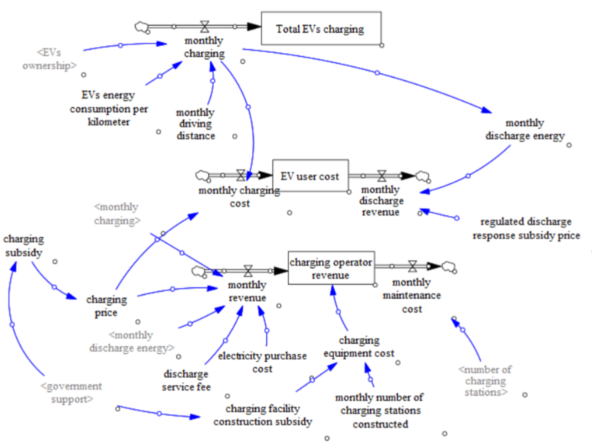

Figure 4. Vensim diagram of the charging and discharging response module.

3) Energy structure module:

With the continuous deepening of the sustainable energy development strategy, the proportion of renewable clean energy in the energy structure is expected to continue to expand. This paper constructs a system dynamics feedback model to simulate different scenarios of clean energy development, and then studies the impact of changes in the proportion of clean energy on carbon emissions in the regional energy network. A corresponding feedback flowchart is shown in Figure 5.

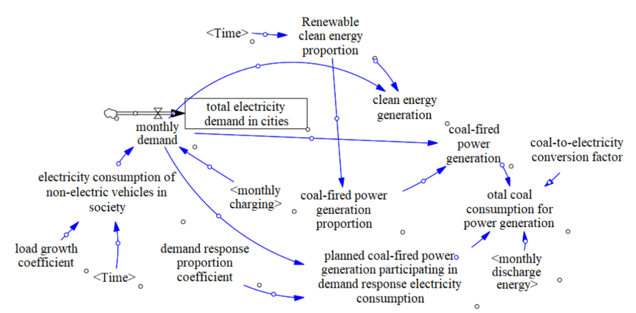

Figure 5. Vensim diagram of the energy structure module.

For the average monthly electricity demand of the whole society, this article defines it as the combination of non EVs demand and charging demand, that is:

$$D_e^{total}(t) = D_e^{s}(t) + L_{cha}(t) \quad (36)$$

The average monthly demand for non EVs in society is:

$$D_e^{s}(t) = (\omega)^t \cdot D_e^{s}(t_0) \quad (37)$$

where, ω is load growth coefficient, $D_e^{s}(t_0)$ is the initial value of monthly average demand for non EVs in society.

The monthly renewable energy generation capacity is:

$$E_{le}^{re}(t) = p_{er}^{re}(t) \cdot D_e^{total}(t) \quad (38)$$

where, $p_{er}^{re}(t)$ is the proportion of clean energy.

The calculation method for the monthly average coal-fired thermal power generation $E_{le}^{coal}(t)$ and the monthly average coal-fired consumption caused by thermal power generation $Q_{coal}(t)$ is as follows:

$$E_{le}^{coal}(t) = [1 - p_{er}^{re}(t)] \cdot D_e^{total}(t) \tag{39}$$

$$Q_{coal}(t) = [E_{le}^{coal}(t) + D_R(t) - L_{dis}(t)] \cdot \alpha^{e-c} \tag{40}$$

$$D_R(t) = D_e^{total}(t) \cdot \tau \tag{41}$$

where, $D_R(t)$ is the thermal power generation participating in monthly demand response, α^{e-c} is coal electricity conversion factor, τ is demand response proportion coefficient.

4) Carbon emission module:

This paper mainly explores how the development path of the energy structure and the entry of EVs into the grid affect the process of achieving China's "carbon neutrality" and "carbon peak" goals, especially quantitatively analyzing the specific impact of EVs on carbon emissions. To achieve this goal, we mainly conduct a comprehensive and in-depth analysis of carbon emissions by coupling the three sub-feedback systems constructed in the previous text. Figure 6 shows the coupling relationship between these systems.

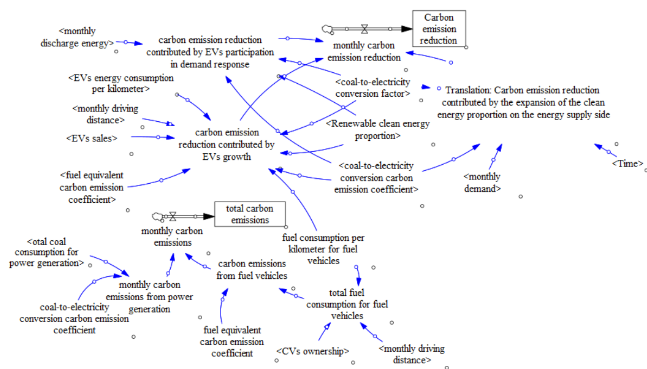

Figure 6. Vensim diagram of the carbon emission module.

The monthly average carbon flow emissions $C_{ar}(t)$ caused by EVs entering the grid and the energy supply side are mainly composed of two parts: the carbon emissions from the power generation side $G_{en}(t)$ and the carbon emissions from the CVs exhaust $F_{uel}(t)$, that is:

$$C_{ar}(t) = G_{en}(t) + F_{uel}(t) \tag{42}$$

$$C_{ar}^{total}(t) = \sum_{0}^{T} C_{ar}(t) + C_{ar}^{total}(t_0) \tag{43}$$

$$G_{en}(t) = Q_{coal}(t) \cdot \alpha_{carbon}^{e-c} \tag{44}$$

$$F_{uel}(t) = Q_{fuel}(t) \cdot \alpha_{carbon}^{f-c} \tag{45}$$

$$Q_{fuel}(t) = P_{krf}(t) \cdot E_{mil} \cdot C_V(t) \tag{46}$$

where, $C_{ar}^{total}(t)$ is the monthly average carbon emissions, $C_{ar}^{total}(t_0)$ is the initial value of monthly average carbon emissions, α_{carbon}^{e-c} is coal electricity conversion carbon emission coefficient, $Q_{fuel}(t)$ is the monthly average carbon emissions of CVs, α_{carbon}^{f-c} is equivalent carbon emission coefficient of fuel, $P_{krf}(t)$ is the fuel consumption per unit kilometer of CVs.

Therefore, the specific value of monthly carbon reduction is:

$$R_{carbon}(t) = R_{carbon}^{EV-CV}(t) + R_{carbon}^{der}(t) + R_{carbon}^{energy}(t) \tag{47}$$

$$\begin{aligned} R_{carbon}^{EV-CV} &= [P_{krf}(t) \cdot \alpha_{carbon}^{f-c} - P_{krc}(t) \cdot (1 - p_{er}^{re}(t)) \\ &\cdot \alpha^{e-c} \cdot \alpha_{carbon}^{e-c}] \cdot E_{mil} \cdot B_{EV}(t) \end{aligned} \tag{48}$$

$$R_{carbon}^{der}(t) = L_{dis}(t) \cdot p_{er}^{re}(t) \cdot \alpha^{e-c} \cdot \alpha_{carbon}^{e-c} \tag{49}$$

$$R_{carbon}^{energy}(t) = \frac{d(p_{er}^{re}(t))}{dt} \cdot D_e^{total}(t) \cdot \alpha^{e-c} \cdot \alpha_{carbon}^{e-c} \tag{50}$$

where, $R_{carbon}^{EV-CV}(t)$ is the monthly average carbon reduction contribution of EVs growth, $R_{carbon}^{der}(t)$ is the monthly average carbon reduction contribution of EVs participating in demand response, $R_{carbon}^{energy}(t)$ is the monthly average carbon emissions reduction due to the expansion of the proportion of clean energy on the energy side.

IV. Example Analysis

A. Example Basic Data

This article selects a city in southwest China as the research object and conducts in-depth simulation analysis. Using Vensim software, a dynamic feedback system model was constructed to explore the impact of EV scale development and changes in energy structure on regional carbon emissions through simulation analysis. The simulation time was set from January 2024 to January 2034, with a total of 121 months, and a time step of 1 month was used in the study.

This study makes the following assumptions about the development of clean energy: the proportion of clean energy remains constant at the beginning and end of the simulation, and three different scenarios are planned for the development of clean energy, namely, the normal scenario, the pessimistic scenario, and the optimistic scenario. In the normal scenario, the proportion of clean energy increases linearly; in the pessimistic scenario, the growth rate is slow at first and then fast; in the optimistic scenario, the growth rate is fast at first and then slow.

B. Analysis of Simulation Result

1) Electric vehicle development forecast analysis:

In the simulation experiment, the development forecast of EVs and CVs is shown in Figure 7. From this graph, it can be seen that the number of EVs has grown from 435,700 to 2,760,490, showing a strong and significant growth rate. In comparison, although the number of CVs has increased from 5,434,400 to 6,4747,600, the growth rate is slowing down. Over time, EVs have become more and more attractive to consumers due to improvements in key technologies such as range and charging efficiency, as well as the gradual improvement of charging infrastructure. According to predictions, the market share of EVs is expected to exceed 50% by 2025, and by the end of the simulation period, the market share of EVs will exceed 70%, with the number of EVs approaching 30% of the total number of vehicles. This trend indicates that the gradual replacement of CVs by EVs has become the mainstream trend.

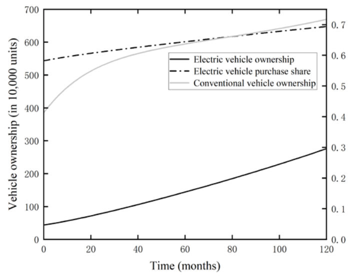

Figure 7. EV and CV ownership and EV purchase share.

2) Prediction and analysis of carbon emissions:

According to the development trend of clean energy, this paper simulates the development paths of three different rates of clean energy. The monthly electricity demand and the monthly carbon emissions under these three scenarios are shown in Figure 8.

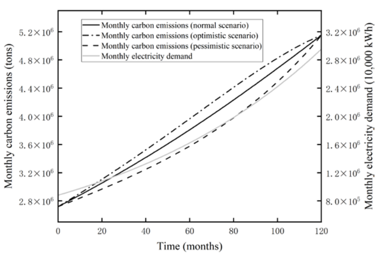

Figure 8. Monthly electricity demand and monthly carbon emissions under three scenarios.

As shown in Figure 8, the monthly electricity demand has been increasing steadily over the simulated ten years, from 8.8 billion kWh to 29.5 billion kWh. However, it is reassuring to see that the growth rate of monthly carbon emissions has remained relatively stable, despite the significant increase in electricity demand. The emissions have increased from 2.72 million tons to 5.15 million tons. This trend demonstrates the important role of EVs and the increasing share of clean energy in reducing carbon emissions.

The carbon emissions generated by EVs and CVs per 100 kilometers of travel are shown in Figure 9. From the graph, it can be seen that as the proportion of clean energy increases, the carbon emissions per unit distance traveled by EVs are gradually decreasing, from 3.2 kilograms to 1.9 kilograms. In comparison, CVs rely on fossil fuel power generation and do not use clean energy, resulting in their carbon emissions remaining relatively stable at 4.536 kilograms. Considering the high number of CVs in circulation, their carbon emissions are quite significant and put considerable pressure on the environment.

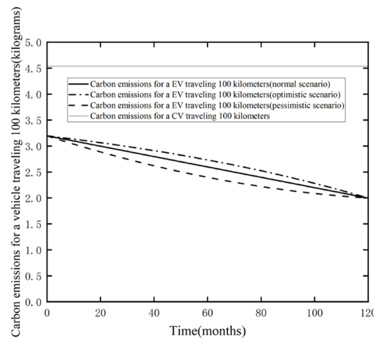

Figure 9. The change in carbon emissions produced by EV and CV traveling 100 kilometers.

3) The impact of electric vehicle integration and changes in energy structure on carbon emissions:

To explore the actual impact of EVs integration on carbon emissions, this study adopts a quantitative research method to analyze the effects of EVs participating in demand response, EVs growth, and the expansion of clean energy proportion on reducing carbon emissions.

The carbon emissions reduction contributed by EVs participating in demand response is shown in Figure 10(a). The carbon emissions reduction contributed by the growth of EVs is shown in Figure 10(b). The carbon emissions reduction contributed by the expansion of clean energy proportion on the energy side is shown in Figure 11.

From Figures 10 and 11, it can be seen that the carbon emission reduction contributed by EVs participating in demand response is the most significant in terms of monthly carbon emission reduction. The monthly carbon emission reduction in the initial simulation period is 6964.02 tons, and in the final simulation period, it is 110306 tons, which fully demonstrates the significant positive effect of EVs participating in demand response on carbon emission reduction. The next significant contribution is the carbon emission reduction contributed by the expansion of clean energy proportion on the energy side. Taking the steady green energy development scenario as an example, the monthly carbon emission reduction in the initial simulation period is 6284.8 tons, and in the final simulation period, it is 21072.5 tons. Lastly, the carbon emission reduction contributed by the growth of EVs itself is considered. In the initial simulation period, the monthly carbon emission reduction is 424.45 tons, and in the final simulation period, it is 2019.32 tons.

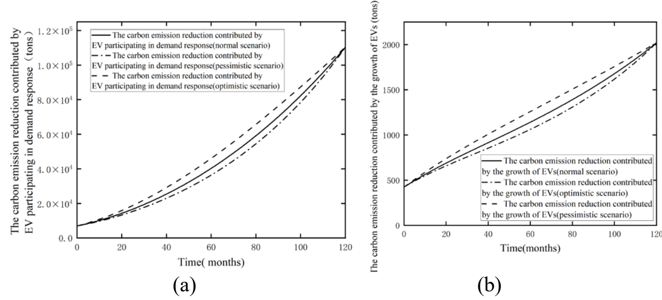

Figure 10. EV participation in demand response and changes in carbon emissions reduction brought about by EV growth.

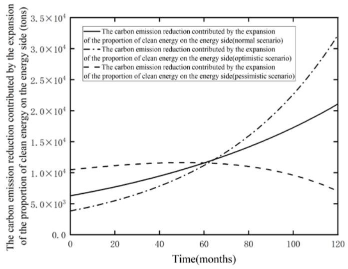

Figure 11. The change in carbon emission reduction contributed by the expansion of clean energy proportion on the energy side.

V. Conclusions

This paper explores the interaction between EVs integration and carbon emission reduction in depth. Based on system dynamics, a dynamic carbon emission impact model of EVs integration and clean energy development is constructed to simulate the effects of EVs integration and changes in energy structure on carbon emissions under different clean energy development paths. Through detailed simulation analysis, the following important conclusions can be drawn:

- With the development of clean energy, the number of EVs has increased from 435,700 to 2,760,490. During this process, the continuous expansion of EVs will have a significant effect on carbon emissions reduction.
- If EVs can replace some of the coal-fired power plants in demand response, the reduction in carbon emissions will be further enhanced.
- The vigorous development of clean energy is of great significance for achieving carbon reduction goals.

In the future, it is possible to deepen the modeling research on user participation in V2G technology and incorporate important national policies as significant variables into the optimized model for the impact of EVs to grid on reducing carbon emissions.

Acknowledgment

This work was supported in part by the China Southern Power Grid Corporation Technology Project (GZKJXM20222151).

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