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Synergistic Air Pollutants and GHG Reduction Effect of Commercial Vehicle Electrification in Guangdong's Public Service Sector

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Abstract: This paper aims to analyze the associated environment and climate benefits of electrification by comparing the air pollutant and CO_2 emissions from the fuel cycle of battery electric commercial vehicles (BECVs) and internal combustion engine commercial vehicles (ICECVs) through a case study in Guangzhou Province. Five types of vehicles (i.e., electric buses, coaches, light-duty trucks, dump trucks, and waste haulers) used in the public service sector were selected for analysis, taking into account six development scenarios based on the prevalent ownership trends of electric vehicles and the energy system optimization process. The results reveal that an increase in commercial vehicle electrification in the public service sector will cause reductions of 19.3×10^3 tons, 0.5×10^3 tons, 9.5×10^3 tons, and 8.5×10^6 tons for NO_x, $PM_{2.5}$, VOCs, and CO_2, respectively, from the base 2030 case (CS_II, the electrification rates of buses, coaches, light-duty trucks, dump trucks, and waste haulers will reach 100%, 26.5%, 15.4%, 24.0%, and 33.1%, and their power needs will be met by 24% coal, 18.4% gas, and 13.2% renewable power), but with a slight increase in SO_2 emissions. With the further penetration of BECVs into the market, the emission reduction benefits for NO_x, $PM_{2.5}$, VOCs, and CO_2 could be even more remarkable. Moreover, the benefit obtained from the optimization of the share of renewable energy is more noticeable for CO_2 reduction than for air pollutant reduction. Prioritizing the electrification of light-duty trucks after completing bus electrification could be a potential solution for achieving ozone pollution control and lowering carbon emissions in Guangdong. In addition, these results can provide scientific support for the formulation or adjustment of advanced pollution mitigation and peaking carbon policies in Guangdong, as well as other regions of China.

Keywords: electric commercial vehicles; fuel cycle; air pollutants emission reductions; peaking carbon emission; Guangdong Province

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1. Introduction

Owing to their high fuel consumption and high pollution emissions, commercial vehicles (CVs), including all trucks and passenger vehicles more than nine seats, are one of the major contributors to ambient air pollution and global warming. According to the China Mobile Source Environmental Management Annual Report (2020) [1], diesel trucks accounted for 78% of the NO_x emissions and 89.9% of the $PM_{2.5}$ emissions of the automobile sector in 2019. Considering their high energy efficiency and low emissions, battery electric commercial vehicles (BECVs) have been identified as a possible solution for the energy crisis, for improving air quality, and for tackling global warming in China.

In recent years, the Chinese government has implemented incentive policies for the development of new energy vehicle technologies in order to create a clean and sustainable transportation system. The use of BECVs in public sectors, such as the commuting, municipal, and logistics sectors, has been under rapid development [2,3]. Having achieved an over 90% electrification rate for buses, Guangdong, one of the most urbanized regions in China, is a pioneer in the area of electric vehicle development. Moreover, light-duty electric goodsdelivery vehicles, medium- and heavy-duty electric coaches, as well as electric waste haulers have also been widely adopted in Guangdong, especially in the Pearl River Delta Region.

Their lack of air pollutants and CO_2 emissions during the use phase make battery electric vehicles (BEVs) one of the most straightforward and effective means for the reduction in ambient air pollutants and CO_2 in the transportation sector [4,5]. While several studies have highlighted the synergistic effects of the emission mitigation of air pollutants and greenhouse gas (GHG) from the promotion of BEVs in China using a life cycle impact assessment approach [4–7], some researchers have indicated that there might be an increase in the emissions of air pollutants when considering the whole life cycle [8–10], or even an increase in CO_2 emissions [11]. Hence, it is meaningful to conduct a study on the fuel cycle in order to analyze the emission characteristics of BECVs, since most emissions from BECVs are produced from the power production stage in the fuel cycle indirectly [12–14]. In addition, many domestic studies only focus on electric buses or electric taxis [15,16]; some include electric passenger cars [4,17], but very few pay attention to the environmental or climate impacts of BECVs on the public services sector [18]. It is therefore essential to study the environment and climate benefits BECVs have in terms of the fuel cycle on the public services sector.

Therefore, the purpose of this study is to analyze the associated environment and climate benefits brought about by the substitution of internal combustion engine commercial vehicles (ICECVs) with BECVs in the public services sector (i.e., electric buses, coaches, light-duty trucks, dump trucks, and waste haulers) in 2025 and 2030. The China VI Emission Standard is adopted for diesel commercial vehicles here to further investigate the benefits of electrification and to evaluate the scale of emissions of CO_2 and other relevant air pollutants (i.e., SO_2, NO_x, $PM_{2.5}$, VOCs). In addition, the research boundary is the air pollutants and CO_2 emissions during the fuel cycle for both BECVs and ICECVs (i.e., energy production, storage, and transportation, as well as any other process required by power marketing and diesel marketing, while excluding the air pollutants and CO_2 emissions caused during the extraction and transportation of raw materials). The results of this study provide scientific support to clarify the environmental and climate benefits brought about by the promotion of BECVs, as well as providing development strategies relating to BECVs for policy makers.

2. Methods and Data

2.1. Overview of the Study Area

Guangdong Province is located in the southernmost part of mainland China (20°09′∼25°31′ N, 109°45′∼117°20′ E), with Fujian to the east, Jiangxi and Hunan to the north, Guangxi to the west, and the South China Sea to the south. Guangdong is the largest province in terms of population and economy in China. It achieved a GDP of 107,671.1 million yuan in 2019 and its number of motor vehicles has been rapidly increasing with the development of the province's economy and society. From 2010 to 2019, the number of motor vehicles in Guangdong increased from 8.0 million to 23.3 million, with an average annual growth rate exceeded 12.5%. At the end of 2019, the number of motor vehicles in Guangdong Province reached 23.3 million, of which 2.4 million were trucks. On the one hand, motor vehicle pollution has become a serious source of air pollution in Guangdong. On the other hand, its shortage of energy and mineral resources and enormous demand for fossil fuels cause Guangdong to rely heavily on coal and natural gas imports, causing concerns regarding local energy safety for policy makers in this region.

2.2. Scenario Analysis

Two key factors are analyzed in this study: the prevalent ownership trends of electric vehicles and the energy system optimization process in Guangdong.

2.2.1. Factor 1: Share of BECVs Ownership

The penetration of BECVs into the market in Guangdong by 2025 and 2030 will directly affect the environment and climate benefits brought about by commercial vehicle electrification. Hence, different shares under different policy promotion efforts are studied, including one where an increase in the ownership of BECVs is brought about under the scenario of substantial known policy promotion, as established the basic scenario of BECVs ownership (OECVBS). Following the usual policy orientation in Guangdong, the OECVBS assumes that all updated or newly registered buses and coaches will be electric vehicles and that in OECVBS2025 the market shares of newly registered electric light-duty trucks, dump trucks, and waste haulers will exceed 1/3, 1/2, and 1/2, respectively, during the 14th Five-Year Plan period (2021–2025). By OECVBS2030, it is calculated that the share of newly registered BECVs ownership, as mentioned above, will be no less than 100%, 100%, 50%, 100%, and 100% during the 15th Five-Year Plan period (2026–2030), respectively. In the other scenario, we model an aggressive increment in BECVs ownership due to the urgent needs of the peaking carbon emissions (OECVPS). In OECVPS, a further BECVs promotion policy will be published on the basis of OECVBS, with the assumption that not only will the share of newly registered BECVs ownership reach the level of OECVBS, but also that old ICECVs will be substituted by BECVs. It is assumed that in OECVPS2025 no less than 100%, 6%, 6%, 10%, and 20% diesel buses, coaches, light-duty trucks, dump trucks, and waste haulers will be replaced by electric models between 2021 and 2025, respectively. Additionally, in OECVPS2030 the replacement rates of the other four types mentioned will increase to 10.5%, 9%, 20%, and 40% between 2026 and 2030, respectively. In addition, it is expected that bus electrification will be 100% completed no later than 2025.

2.2.2. Factor 2: Optimization of Installed Power Capacity

The installed power capacity in 2025 and 2030 were estimated by integrating the Guangdong Province Action Plan for Cultivating New Energy Strategic Emerging Industrial Clusters (2021–2025), the Guangdong Province Onshore Wind Power Development Plan (2016–2030), the Guangdong Province Offshore Wind Power Development Plan (2017–2030), and other policy documents that relate to the installed capacity of renewable energy power generation, as well as the results of previous studies [19]. On the basis of the predicted installed power capacity, different degrees of installed clean power capacity for 2025 and 2030 are presented. The usual power structure circumstance in 2025 (PSBS2025) will consist of 30.1% coal, 16.7% gas, and 8.1% renewable power. Additionally, it will consist of 24% coal, 18.4% gas, and 13.2% renewable power supply by 2030 (PSBS2030), respectively. A more proactive case (PSOS2030) is considered as well, which assumes that the installed capacity of renewable energy power generation will be increased by 20% and the installed capacity of power transmission from west to east will be increased by 10% compared with PSBS2030, while the share of thermal power remains the same as that in 2025. In PSOS2030, the rates of use of coal power, gas power, and renewable energy power generation will be adjusted to 23.6%, 13.1%, and 16.0%, respectively.

2.2.3. Scenario Descriptions

Based on the different assumptions of ownership of BECVs and installed power structure in the target year, this research integrates the two influencing factors and forms a total of six development scenarios for analysis, as listed in Table 1.

Table 1. Description of different scenarios.

Combined Scenario	Ownership of BECVs	Power Structure
CS_I	OECVBS2025	PSBS2025
CS_II	OECVBS2030	PSBS2030
CS_III	OECVBS2030	PSOS2030
CS_IV	OECVPS2025	PSBS2025
CS_V	OECVPS2030	PSBS2030
CS_VI	OECVPS2030	PSOS2030

2.3. Energy Consumption of Vehicles in the Use Stage

In order to further analyze the energy consumption of commercial vehicles in the use stage, two equations are proposed as follows:

2.3.1. Unit Energy Consumption of BEVs and Internal Combustion Engine Vehicles (ICEVs) in the Use Stage

$$F_i = P_i \times EC_i \times VKT_i \tag{1}$$

Here, F_i is the electricity or fossil fuel consumption of vehicle i each year, in kWh/a or g/a; P_i is the number of vehicles i. EC_i is the unit distance electric energy or fuel consumption for vehicle i, as shown in Table S1 (Supplementary Materials), which is calculated based on the commercial vehicle energy consumption certification and electric vehicle battery capacity and range in the real world. VKT_i is the average annual mileage of vehicle i, in km/a, and its value is displayed in Table 2 [20].

Table 2. Average mileage of commercial vehicles (unit: km/year).

Vehicles	Bus	Coach	Light-Duty Truck	Dump Truck	Waste Hauler
Mileage	60,000	58,000	36,000	48,000	54,000

2.3.2. Ownership of Commercial Vehicles

Several characteristic factors are used in the multiple linear regression model to predict the trends of ownership of commercial vehicles, including urban population, urbanization rate, gross domestic product, regional industrial output value, and fixed asset investment. The formula is as follows:

$$P = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot x_3 + \beta_4 \cdot x_4 + \beta_5 \cdot x_5 \tag{2}$$

where P_i is the number of vehicles I used that year, x denotes the factor influencing the commercial vehicle ownership, and β_i is the regression coefficient.

Data from Statistical Yearbook of Guangdong Province were used for this analysis. The R-squared and adjusted R-squared values of the multiple regression models used for predicting the ownership of commercial vehicles were 0.908 $\sim$ 0.989 and 0.893 $\sim$ 0.987. The models were also to be found significant at a 99% confidence level (significance values, named p-values, <0.01). p-values associated with F-statistic and t-statistic indicate that the predictor variables have a significant relationship with the ownership of commercial vehicles. Additionally, it is noted that the predicted ownership of commercial vehicles in the target year is calibrated based on the analysis of historical performances by the trend extrapolation method. The stocks of BECVs in the target year are determined based on the current newly registered BECVs stocks and the proportions of newly registered BECVs out of the total.

2.4. Air Pollutants and CO_2 Emission of Vehicles in Fuel Cycle

2.4.1. Emission from Energy Production and Storage, Transportation, and Marketing Stage

The annual emissions of air pollutants and CO_2 from power production and fossil fuel production are calculated by the following equations:

$$E_{ei} = L_i \times EF_{ei} \tag{3}$$

$$E_{oi} = F_i \times EF_{oi} \tag{4}$$

where E_{ei} is the annual emissions of air pollutants and CO_2 for the approach i to power production, g/a; L_i is the annual power generation of the power production approach i, kWh/a; EF_{ei} is the unit emission factor of air pollutants and CO_2 for approach i, obtained from the actual emissions and fossil fuel consumption levels of coal-fired power plants after ultra-low emission transformation and gas-fired power plants after denitrification transformation and treatment in Guangdong, g/kWh (as shown in Figure S1). E_{oi} is the annual emissions of air pollutants and CO_2 throughout the whole process of diesel production, storage, transportation, and marketing, g/a; F_i is the fossil fuel consumption of vehicle i each year, referring specifically to the annual usage of diesel here, g/a; EF_{oi} is the air pollutants and CO_2 emission factors for the use of diesel in production, storage, transportation, and marketing, which was selected according to the actual emission levels of major refineries in Guangdong Province, with reference to the Technical Manual for the Preparation of Urban Air Pollutant Emission Inventories, as well as the results of Wang T. et al. [21], g air pollutants/g diesel or g CO_2/g diesel (as shown in Figure S2).

In addition, the comprehensive conversion rate of electric energy from the power plant to the electric vehicle is taken as 90%, due to the impacts of the loss rate of the grid transmission line and the charging efficiency of the on-board charger.

2.4.2. Emissions from ICECVs during the Use Stage

The annual emissions of NO_x, $PM_{2.5}$, and VOCs from ICECVs during the use stage are calculated as follows:

$$E_{vi} = P_i \times EF_{vi} \times VKT_i \tag{5}$$

$$EF_{vi} = EF_{vi-V} \times \delta_i \times \rho_i \tag{6}$$

where E_{vi} denotes the annual emissions of NO_x, $PM_{2.5}$, or VOCs during the use of vehicle i, g/a; P_i is the number of vehicles i. EF_{vi} is the unit emission factor of air pollutants per unit distance of the vehicle i, g/km (as shown in Table S2), and is calculated based on the revision of the China V Standard vehicles, Liu X. et al. and Liu Y. et al. [22,23]. VKT_i is the average annual mileage of vehicle i, km/a. EF_{vi-V} is an emission factor of the China V Standard vehicle, g/km. δ_i is the ratio of the China VI emission standard value to the China V emission standard value. ρ_i is the correction factor.

The annual emissions of SO_2 and CO_2 from ICECVs during the use stage are calculated using the following equations [20]:

$$E_{SO_2\_vi} = 2.0 \times F_i \times \alpha_i \tag{7}$$

$$E_{CO_2\_vi} = F_i \times \gamma_i \tag{8}$$

$E_{SO_2\_vi}$ is the annual SO_2 emissions during the use of vehicle i, g/a. F_i is the annual fuel consumption of vehicle i, g/a. α_i is fixed as a parameter representing the average sulfur content of the fuel; the value of10 ppm was used in this study. $E_{CO_2\_vi}$ is the annual CO_2 emissions caused during the use of vehicle i, g/a. F_i is the annual fuel consumption of vehicle i, g/a. γ_i is fixed as a parameter representing the CO_2 emissions emitted per unit fuel used; the value of 3.17g CO_2/g diesel was used in this study.

3. Results

3.1. Ownership and Energy Consumption of CVs

Based on the provincial and national socio-economic development forecast and predictions of the market share of electric vehicles, the ownership scale of commercial vehicles in Guangdong in 2025 and 2030 were calculated and are displayed in Figure 1. This figure shows that electrification rates under OECVBS2025 are expected to reach 100%, 18.0%, 11.7%, 18.1%, and 24.3% for buses, coaches, light-duty trucks, dump trucks. and waste haulers, respectively. By 2030, it is anticipated that buses will be fully electrified, while the electrification rates of coaches, light-duty trucks, dump trucks, and waste haulers will achieve values of 26.5%, 15.4%, 24.0%, and 33.1% under OECVBS2030, respectively. The electrification ratios of buses, coaches, light-duty trucks, dump trucks, and waste haulers are expected to reach 100%, 23%, 16.2%, 25.5%, and 38.1% in OECVPS2025, while these are 100%, 35.5%, 21.5%, 37.7%, and 57.5% in OECVPS2030, respectively. Furthermore, the electrification rates in the peaking CO_2 emission scenario of the remaining four vehicles apart from buses are all higher than those in the base scenario, along with an increase in the ownership of BECVs by 31.2% and 34.1% in the public service sector of OECVPS2025 and OECVPS2030, respectively.

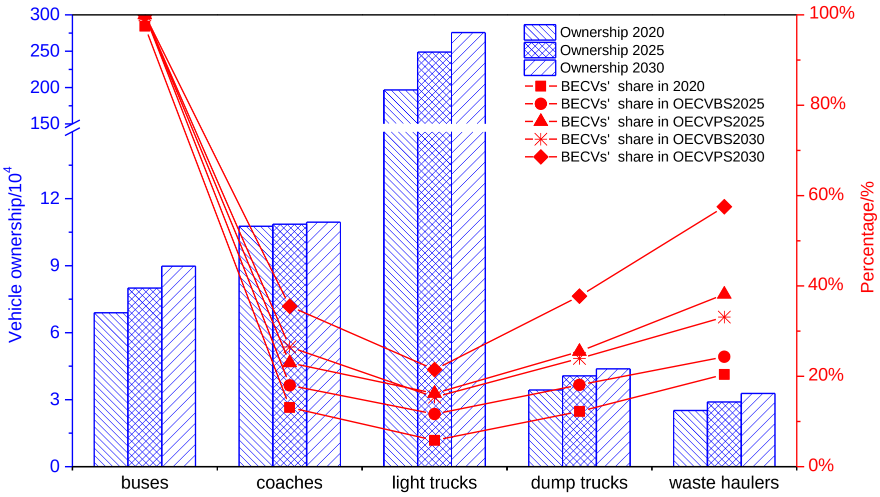

Figure 1. Forecast results of the progress of commercial vehicle electrification.

Figure 2 demonstrates that the energy consumption changes before and after the electrification of commercial vehicles in Guangdong in 2025 and 2030 under OECVBS and OECVPS. The electrification of commercial vehicles in Guangdong would sharply increase the demand for electricity to 8.7 $\times$ 10^9 kWh/a and greatly reduce the fossil fuel consumption by 2.6 $\times$ 10^6 tons diesel/a in OECVBS2025; meanwhile, 3.5 $\times$ 10^6 tons/a diesel consumption reduction together with 11.7 $\times$ 10^9 kWh/a additional electricity demand in OECVBS2030. Furthermore, under the peaking CO_2 emissions condition, extra electric power would be required to fulfill the demand for electrification, representing a value of 10.8 $\times$ 10^9 kWh/a in OECVPS2025 and a value of 15.1 $\times$ 10^9 kWh/a in OECVPS2030, respectively. Meanwhile, a great amount of diesel could be saved annually, with values of 3.2 $\times$ 10^6 tons/a and 4.5 $\times$ 10^6 tons/a for OECVPS2025 and OECVPS2030, respectively. As a result, the electrification of buses and light-duty trucks under these two scenarios requires the largest power consumption and makes the greatest contribution to saving fuel compared to the electrification of other commercial vehicles.

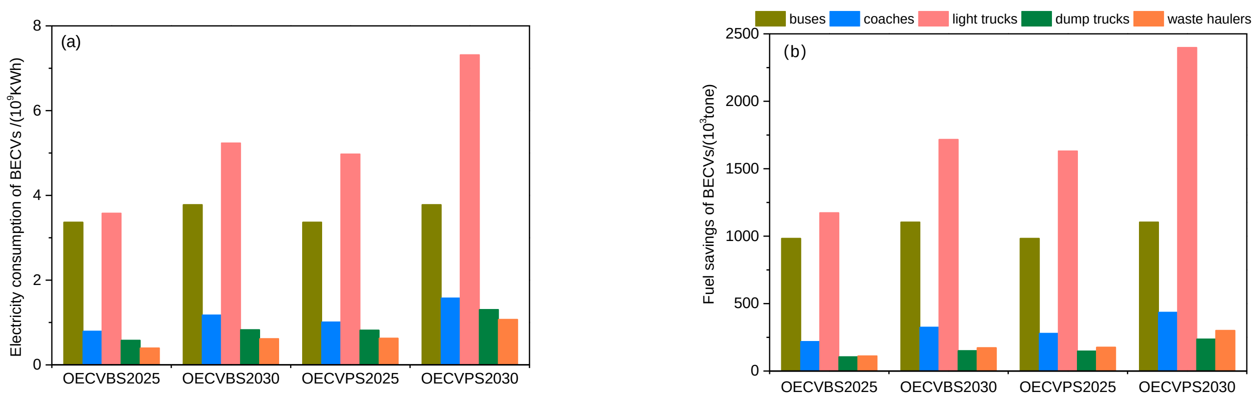

Figure 2. Electricity consumption and fuel savings brought about by BECVs. In the picture, (**a**) Electricity consumption increased by BECVs. (**b**) Fuel consumption saved by BECVs.

3.2. *Unit Emission Level for Air Pollutants and* CO_2

According to the China VI, the unit-vehicle emission levels of air pollutants from ICECVs and BECVs in Guangdong are displayed in Figure 3. Compared with conventional ICECVs, BECVs' unit-vehicle emissions of NO_x, $PM_{2.5}$, or VOCs drop dramatically. In detail, the reduction in VOCs for all vehicles effected by electrification seemed to be the most remarkable, with a depletion of more than 93% found. The reduction in NO_x is also impressive, with a more than 90% NO_x reduction found after the electrification of all commercial vehicles under different scenarios, except for dump trucks. It was found that there are great variations between different vehicles for the unit emission reduction in $PM_{2.5}$. The emission reductions in $PM_{2.5}$ for buses and coaches can reach the best amelioration effects, with more than 90% reductions achieved, but lower mitigation impacts appeared for dump trucks ($\leq$36.4%). However, it is worth noting that electrification has some negative impacts on the environment. An increase in SO_2 emission is inevitable after electrification, with a critical increase of 4.4 times brought about by dump truck electrification in PSOS2030 compared to ICECVs. An increase in SO_2 is attributed to the fact that using coals for power generation might contain a higher sulfur content than the deep-desulfurized diesel circulating in Guangdong. In general, commercial vehicle electrification in Guangdong can lead to appreciable air pollutant emission mitigation effects, which is attributed to the fact that Guangdong has much a cleaner power structure due to the benefits of the West to East Power Transmission.

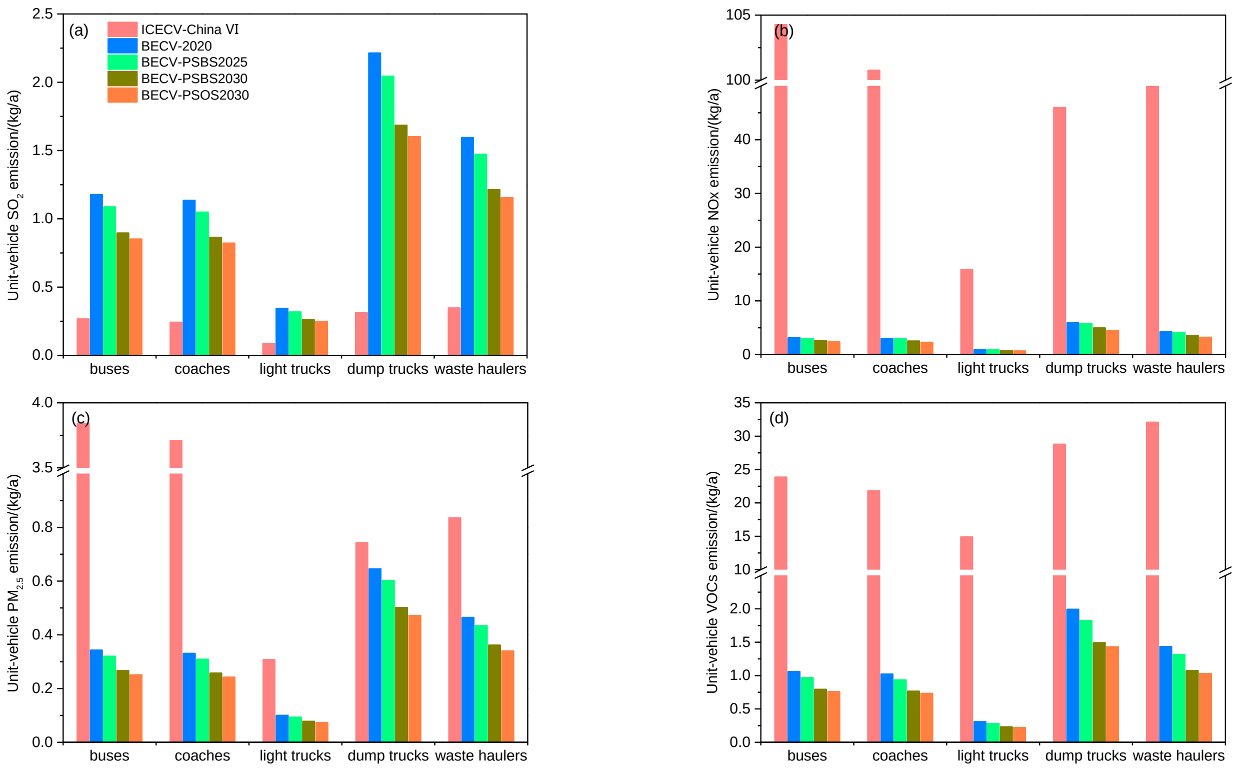

Figure 3. The unit-vehicle air pollutant emission levels of fuel and electric vehicles. In the pictures (**a**–**d**), unit-vehicle SO_2, NO_x, $PM_{2.5}$, and VOCs emission levels of China VI ICECVs and BECVs.

The unit-vehicle emission levels of CO_2 from ICECVs and BECVs in Guangdong are shown in Figure 4. From the picture, it can be seen that the CO_2 emissions display obviously declining features. The highest reduction rate will be 75% from light-duty truck electrification, while the lowest reduction rate from dump truck electrification will be larger than 50%. The CO_2 emission reduction in electrification here performs more effectively than studies on other regions [12,24,25], which is explained by the fact that the share of coal-fired power in Guangdong is much lower than the average coal-fired power proportion in China.

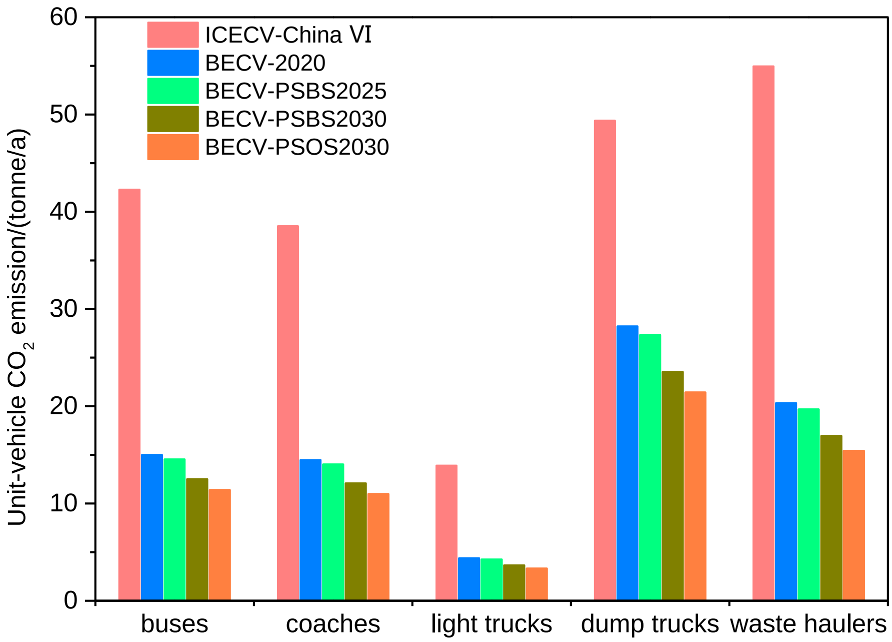

Figure 4. The unit-vehicle CO_2 emission levels of fuel and electric vehicles.

3.3. Emission Amelioration Benefit of Commercial Vehicle Electrification in Fuel Cycle

Figure 5 illustrates the comparison of emissions of air pollutants before and after the implementation of electrification in Guangdong in 2025 and 2030. Throughout the fuel cycle, the implementation of BECVs can significantly reduce NO_x, $PM_{2.5}$, and VOCs, but may slightly increase the SO_2 emissions. In CS_II, the implementation of commercial vehicle electrification is expected to annually reduce air pollutant emissions, with values of 19.3×10^3 tons/a, 0.5×10^3 tons/a, and 9.5×10^3 tons/a for NO_x, $PM_{2.5}$, and VOCs, respectively. Similarly, in CS_III, the air pollutant emission reductions for NO_x, $PM_{2.5}$, and VOCs present great reductions benefits after the implementation of commercial vehicle electrification; these are 19.4×10^3 tons/a, 0.5×10^3 tons/a, and 9.6×10^3 tons/a, respectively. Compared with CS_II and CS_III, the emission reduction benefits of NO_x, $PM_{2.5}$, and VOCs for CS_V increased by 21.4%, 14.8%, and 32.4%, while the emission reductions effects for CS_VI increased by 21.5%, 14.9%, and 32.4%, which generally match the growth level of ownership, respectively.

Remarkable reduction benefits for NO_x and $PM_{2.5}$ are shown; they are equivalent to 4.6% and 10.2% in CS_II and 5.6% and 11.5% in CS_V for the total NO_x and $PM_{2.5}$ from mobile sources in Guangdong in 2019, respectively [26]. These results are consistent with the research conclusions of Tan R. et al., Yu X. et al., and Shafique M. et al. [27–29], indicating that the promotion of electric commercial vehicles is an important way for Guangdong to achieve the goals of pollutant mitigation and air quality improvement in the future. Moreover, it is highlighted that continuously optimizing the electric energy structure in Guangdong could further enhance the emission reduction benefits of vehicle electrification, despite the amelioration impacts from power structure optimization not being as large as those from electrification.

In addition, the CO_2 emission reduction effects before and after the implementation of electrification in Guangdong are also calculated, as shown in Figure 6. It can be seen that the promotion of commercial vehicle electrification can bring about significant CO_2 emission reduction benefits throughout the entire fuel cycle. In 2025, the ratio of CO_2 emission reduction in BECVs to ICECVs could reach more than 65%. The emission reduction ratios of the four different scenarios in 2030 further increased to more than 70%. Comparing CS_III with CS_II, as well as comparing CS_VI with CS_V, it can be seen that a substantial power structure optimization will cause an approximately 3.7% CO_2 emission reduction. Based on these results, persistent power structure optimization will also play a positive and significant role in promoting commercial vehicle electrification and bringing benefits to CO_2 emission reduction.

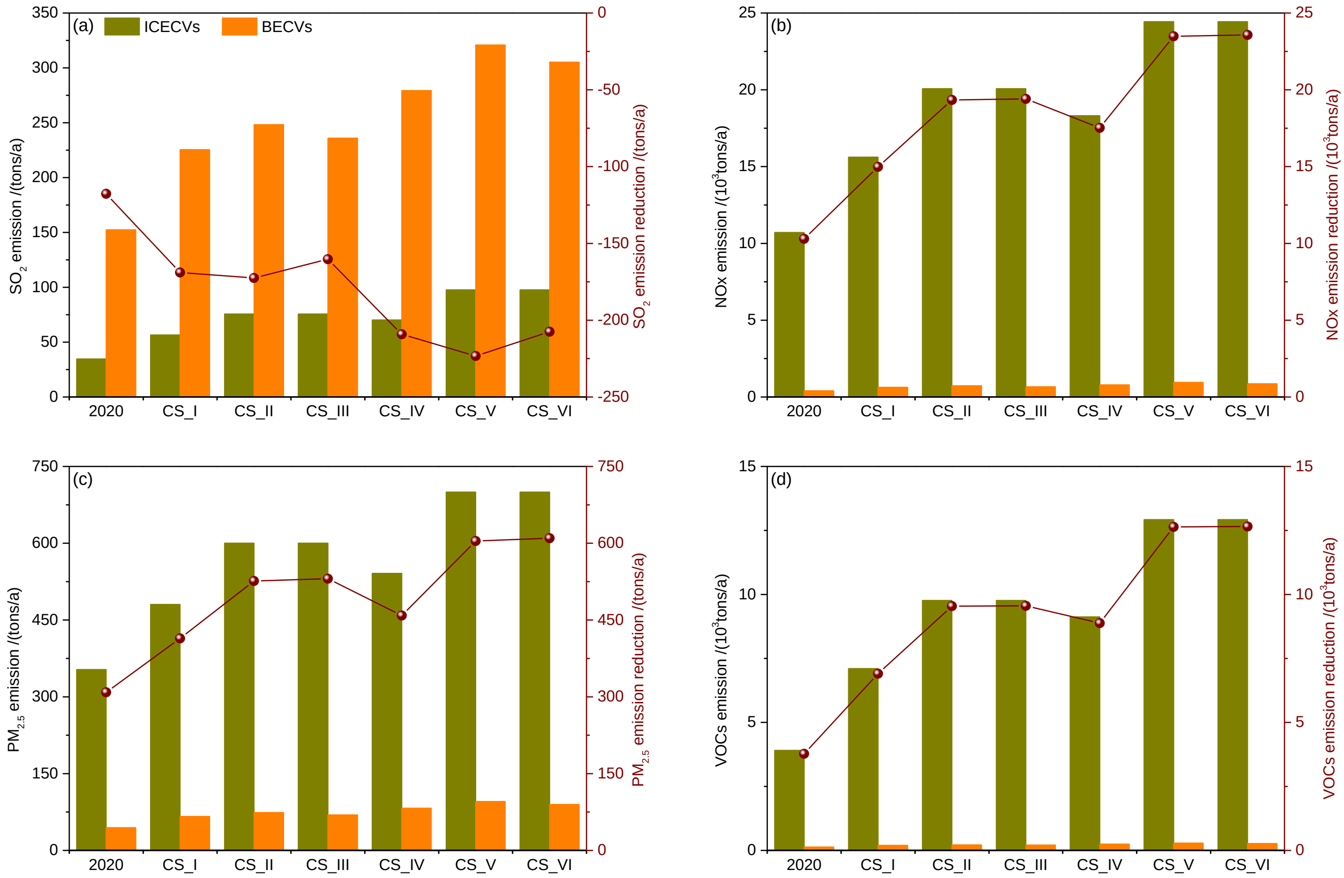

Figure 5. Comparison of air pollutant emissions before and after the electrification of commercial vehicles. In picture (**a**), negative emission reductions in SO_2 denote the slight increase in SO_2 emissions after the implementation of electrification. In the pictures (**b**–**d**), the emission reductions for NO_x, $PM_{2.5}$, and VOCs come from the implementation of electrification.

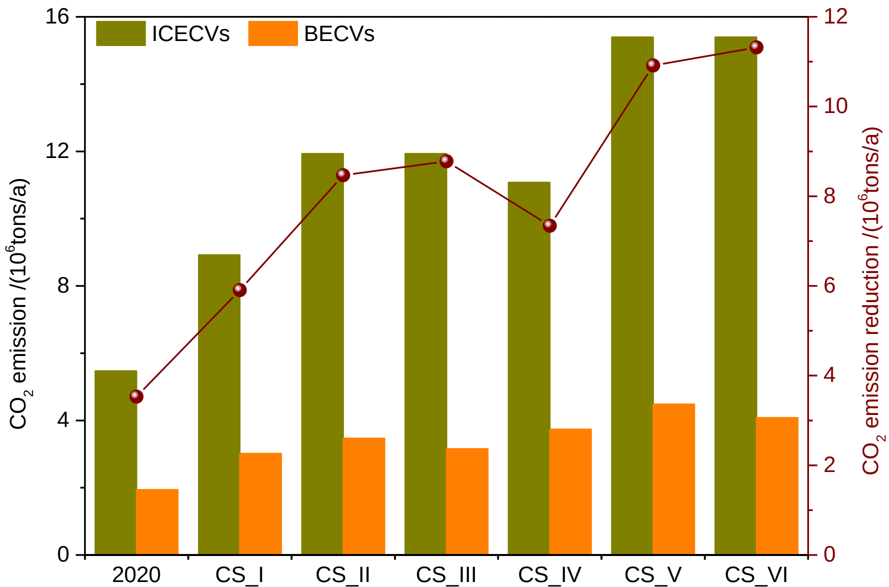

Figure 6. Comparison of CO_2 emissions before and after the electrification of commercial vehicles (note: the emission reductions in CO_2 come from the implementation of electrification).

The air pollutant and CO_2 emission reductions' amounts and proportions for commercial vehicle electrification in the public service sector in Guangdong are pictured in Figures 7 and 8. It can be observed that there are differences between the emission reduction benefits of different vehicles in either scenario. Light-duty trucks obtain the most remarkable reduction potential among all, as a sharp emission depletion can be seen from 2020 to 2030. Overall, the electrification of buses and light-duty trucks contributes the most to the emission reduction in NO_x, $PM_{2.5}$, and VOCs, and CO_2. In CS_V and CS_VI, the electrification of these two types of vehicles account for more than 75% of the NO_x, $PM_{2.5}$, and VOCs reduction. However, the increase in SO_2 from the electrification of these two types of vehicles is concerning, accounting for more than 70% of the increase in SO_2 emissions in 2030. Dump truck electrification contributes to the lowest fractions of the emission reduction in air pollutants. Even in CS_VI, it contributes no more than 4% to the reduction in NO_x, $PM_{2.5}$, and VOCs, and contributes no more than 4.1% to the CO_2 reduction. Figures 7 and 8 reaffirm that optimizing only the power structure will not have a significant impact on the reduction in NO_x, $PM_{2.5}$, and VOCs and will only benefit CO_2 reduction and slow the increase in SO_2.

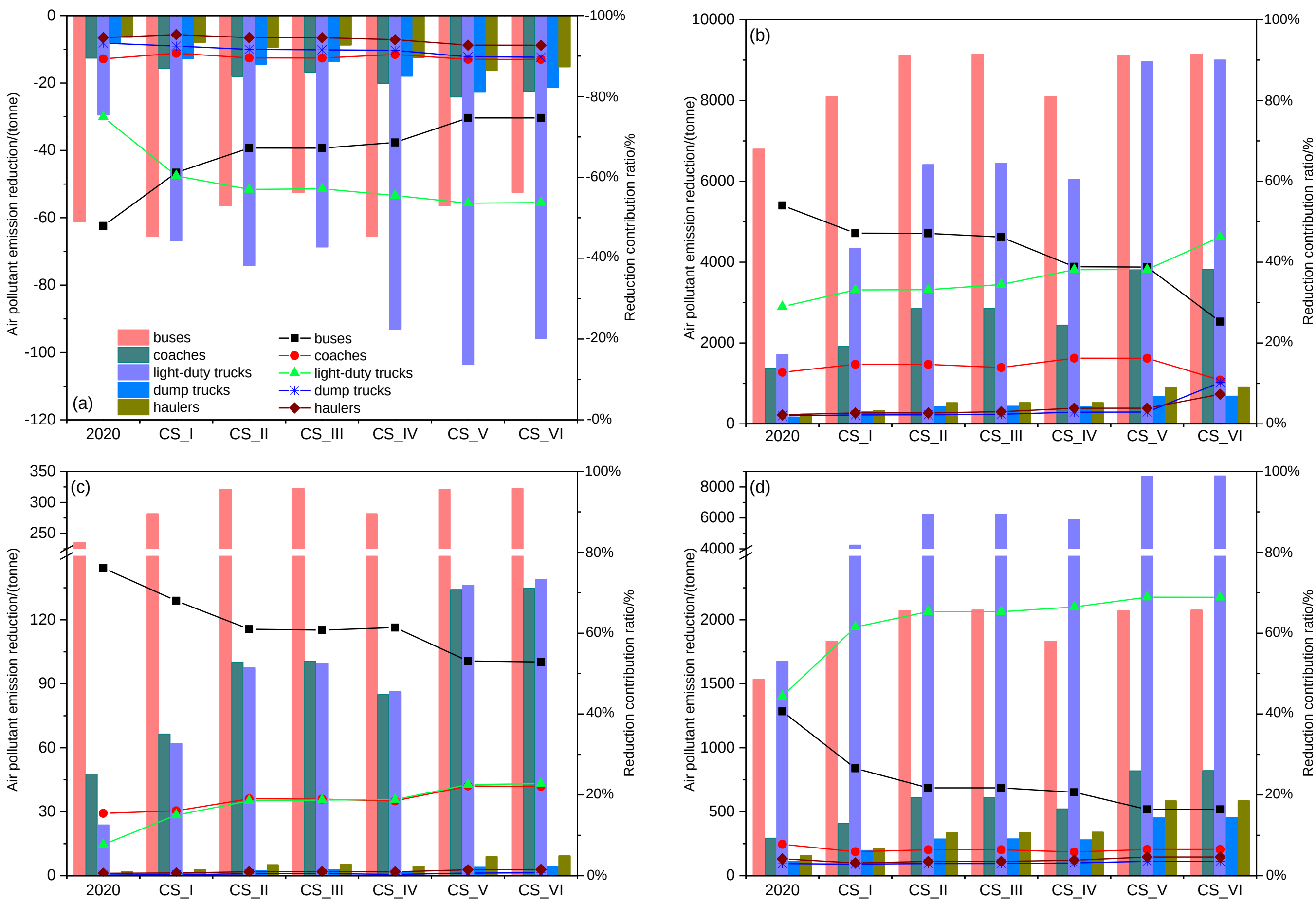

Figure 7. The proportion of air pollutant emission reduction brought about by the electrification of different vehicles. In the pictures, (**a**–**d**) are the emission reductions for SO_2, NO_x, $PM_{2.5}$, and VOCs, respectively. Additionally, it should be noted that the negative emission of SO_2 denotes that no emission reduction has occurred.

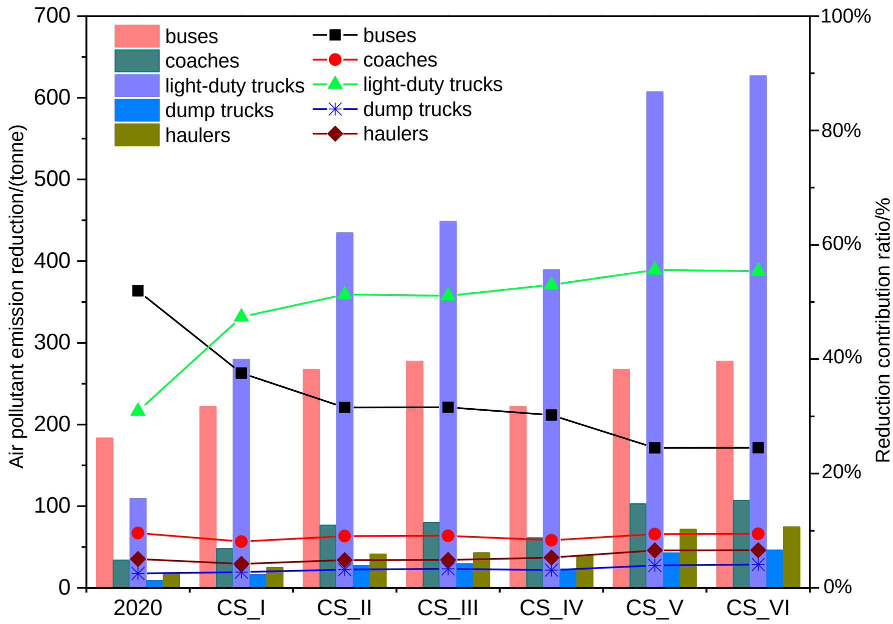

Figure 8. The proportion of CO_2 emission reduction brought about by the electrification of different vehicles.

4. Discussion

4.1. Sensitivity Analysis of BECVs Emission to Power Structure

Compared to ICECVs, the air pollutants (i.e., NO_x, $PM_{2.5}$, and VOCs) and GHG (i.e., CO_2) emissions from the fuel cycle of BECVs show obvious declines, consistent with previous results [30–33]. However, the optimization of the power structure in 2030 cannot have significant emission reduction effects of BECVs. The sensitivity of BECVs emissions to the optimization of the power structure refers to the impact on the emission level of BECVs when a certain component of the power structure changes by a certain proportion. This sensitivity is expressed by the ratio of the change rate of pollutant emissions to the change rate of the power generation mode. The greater the absolute value of the ratio is, the higher the sensitivity will be. This can be attributed to the fact that the main way to optimize the power energy structure is to increase the proportion of renewable energy power generation and reduce the use of coal power. Therefore, in order to further analyze the sensitivity of the emissions in the fuel cycle of BECVs to optimizing the power structure, the proportion of renewable energy power generation and coal power generation are taken as sensitive factors affecting the emissions of BECVs in the paper; these are listed in Figure 9. The main factor affecting the fuel cycle emissions of BECVs is the proportion of coal-fired power generation in the power structure. This explains our finding that the optimization of the power structure in 2030 will not bring significant emission reduction effects for BECVs. Therefore, in order to achieve greater emission reduction benefits for commercial vehicle electrification, it is necessary to accelerate the alternative process of coal-fired power.

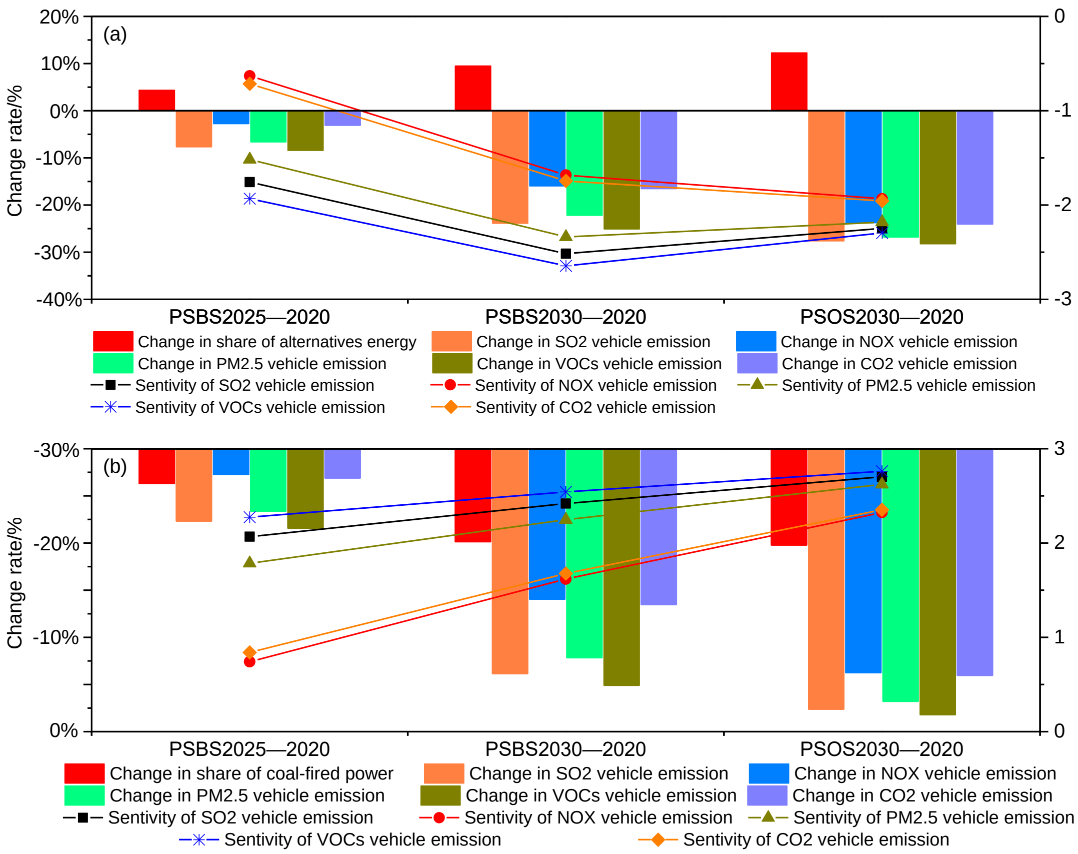

Figure 9. The sensitivity of electric bus emissions to the proportion of renewable energy power generation and coal power generation. (**a**) The sensitivity of electric bus emissions to the proportion of renewable energy power generation. (**b**) The sensitivity of electric bus emissions to the proportion of coal power generation.

4.2. Uncertainty Analysis of Emission Estimation of CVs

In this study, the benefits of reductions in air pollutants and GHG emissions brought about by the substitution of ICECVs with BECVs in the public service sector (i.e., electric buses, coaches, light-duty trucks, dump trucks, and waste haulers) are calculated based on reasonable estimations. However, the air pollutant and GHG emission reductions obtained for ICECVs and BECVs are influenced by many sophisticated factors, such as vehicle type, motor vehicle emission standards, power generation, and electric power structure. Any uncertainties due to these factors could severely restrict the accuracy and validity of the benefits of air pollutant and GHG emission reductions. First of all, the uncertainty surrounding the predicted ownership of commercial vehicles and the number of BECVs replacing ICECVs has introduced great uncertainty into the results for air pollutants and GHG emissions. Secondly, the China VI emission standards for heavy-duty diesel vehicles have only just begun to be implemented in China, and currently there are few studies on the actual emission levels of China VI diesel commercial vehicles. Hence, the uncertainties regarding the emission factors of the China VI diesel commercial vehicles used in this study are based on calibrations of the emission factor of the corresponding China V model. Moreover, the research and formulation of China VII motor vehicle emission standards have been put on the agenda, and it is possible that they will be implemented after 2025. These drawbacks could cause the proposed results to deviate from the actual values for the target years. In addition, constant energy consumption levels are used to measure the fuel consumption and power consumption of various commercial vehicles in the target year, ignoring the energy-saving and emission-reduction benefits that could be gained from technological progress. Additionally, these might lead to some errors occurring in the calculation of the emission reduction benefits of BECVs in the fuel cycle. Therefore, in the future efforts should be made to further identify the effects of various factors on the benefits of air pollutant and GHG emission reductions for ICECVs and BECVs. This would help us to obtain more detailed information on the air pollutant and CO_2 emission reduction benefits brought about by the electrification of commercial vehicles.

4.3. Promotion Strategies of Commercial Vehicle Electrification

Despite uncertainties existing in the calculation of the emission reduction benefits, it is vital to promote the use of BECVs in the future. This research distinguishes the emission reduction differences brought about by the use of various BECVs. This could be beneficial in helping us to identify the management priority for pollutant and CO_2 emission reductions. The importance of air quality amelioration and peaking carbon emissions is indisputable for Guangdong Province [34], as well as for the whole of China [35,36]. Therefore, further attention should be paid to the electrification of buses and light-duty trucks, which could provide a potential solution for Guangdong regarding controlling the emissions of ozone precursors (i.e., NO_x and VOCs) and the emissions of CO_2. In general, it is recommended that decision-makers should give higher priority to bus and light-duty truck electrification, which will bring enormous benefits to air quality amelioration and peaking carbon emissions in Guangdong Province, as well as in other regions.

5. Conclusions

The reductions in the emissions of air pollutants and CO_2 in the fuel cycle brought about by commercial vehicle electrification in the public service sector were calculated under six different combination scenarios. Additionally, the fossil fuel consumption reduction brought about by the electrification of commercial vehicles was also evaluated in the paper. Our results indicate that by 2030 the electrification of the five commercial vehicles mentioned here in OECVBS2030 could save 3.5×10^6 tons fossil fuel, with an annual emission reduction of 19.3×10^3 tons NO_x, 0.5×10^3 tons $PM_{2.5}$, 9.5×10^3 tons VOCs, and 8.5×10^6 tons CO_2 in CS_II. The outcomes for OECVPS are consistent with those for OECVBS, as well as with better energy conservation and emission reduction effects. Moreover, this study also indicates that unless the proportion of coal power generation can be reduced effectively while increasing the proportion of renewable energy power, the air quality amelioration benefits of the electrification of commercial vehicle might be ambiguous, yet electrification will still help in CO_2 reduction.

The environmental and climate benefits achieved by the promotion of BECVs will play a key role in local air quality improvement and help us to meet the peaking carbon emissions target for Guangdong. Under the premise of realizing a 100% electrification of buses, higher priority should be given to the electrification of light-duty trucks, which would provides a potential solution to Guangdong for controlling the emissions of ozone precursors (i.e., NO_x and VOCs) and CO_2. In addition, these results could stimulate the introduction of advanced pollution mitigation and peaking carbon policies by policy makers in Guangdong, as well as those of other regions of China.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su131911098/s1, Figure S1: Air pollutants and CO_2 emission factors of power production, Figure S2: Air pollutants and CO_2 emission factors of diesel in production, storage, transportation and marketing, Table S1: Average energy consumption of commercial vehicles, Table S2: Air pollutants emission factors of China VI commercial vehicles.

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