

# The Environmental Impacts and Economic Benefits on Comprehensively Promoting Alternative Fuel Buses in China: Life-Cycle and Scenario Analysis Based on LEAP Model

Siting Xie

College of Economics, Jinan University, Guangzhou, China

Email: xiesiting1993@163.com

**How to cite this paper:** Xie, S. T. (2019). The Environmental Impacts and Economic Benefits on Comprehensively Promoting Alternative Fuel Buses in China: Life-Cycle and Scenario Analysis Based on LEAP Model. *Journal of Geoscience and Environment Protection*, 7, 99-121.

<https://doi.org/10.4236/gep.2019.74007>

**Received:** February 19, 2019

**Accepted:** April 15, 2019

**Published:** April 18, 2019

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## Abstract

With the continuous development of urban public transportation, the harmful GHG emissions and pollutants generated by itself and the consequent issues such as the losses of residents' health, economic value and residents' welfare have become the focus of social attention. In order to study the impacts of promoting new energy vehicles on public transportation pollution mitigation and residents' health benefits, this paper adopts the LEAP model to build some scenarios that fulfill different development needs to quantitatively analyze the ownership of new energy buses, the reduction of pollutants and the losses of residents' health welfare. It is concluded that promoting new energy buses comprehensively can significantly reduce the emissions of atmospheric pollutants and the economic losses of residents' health, but cannot fully realize the targets of greenhouse gas reduction under Life Cycle Analysis.

## Keywords

New Energy Buses, Emission Mitigation, Economic Benefits, Life-Cycle Analysis, Scenario Analysis

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## 1. Introduction

### 1.1. Fast-Growing of and Pollutant Emissions from China's Road Transport Sector

Facing the severe challenges of the global resource crisis and environmental pollution, all the countries are actively seeking countermeasures to achieve the dual mandate of environmental protection and social economic development. At

present, exhaust emission of transport sector has become an important source of air pollution in China, especially in the first-tier cities such as Beijing, Shanghai, and eastern densely populated areas. The contribution of mobile sources to fine particulate matter (PM<sub>2.5</sub>) concentrations is as high as 20% to 40%. In 2016, China's motor vehicles exhaust emission was initially approved at 44.725 million tons, including carbon monoxide (CO) of 34.393 million tons, nitrogen oxides (NO<sub>x</sub>) of 5.778 million tons, and particulate matter (PM) of 0.534 million tons<sup>1</sup>. In recent years, in order to alleviate the road-transport sector's environmental pollution problems, China has adopted a two-pronged approach. On the one hand, the government adopts restrictive measures, such as some of first-tier cities to adopt "traffic restriction" and "restricted purchase" measures; on the other hand, it adopts encouraging measures, such as implementing public transport priority polices, and vigorously developing large-capacity public transport like BRT and rail transit<sup>2</sup>. The total length of public steam tram lines in 2017 reached 559,000 kilometers, an increase of 30,000 kilometers compared with 2016, which is four times the total mileage of highways nationwide<sup>3</sup>. The rapid development of urban road public transportation can fulfill the increasing traffic demand, and mitigate somewhat the overall pollution problem of the road traffic department compared with private transportation.

However, road transport, including urban public transportation, mainly uses the traditional fossil energy at this stage (such as gasoline and diesel). According to the official website of the Ministry of Transport of China<sup>4</sup>, in 2015, the number of public standard operating buses was 561,800 units, including new energy buses that account for about 20%. Fossil energy consumption in internal combustion engines is the major cause of air pollution, haze and photochemical smog. Since urban public transportation is mostly distributed in densely populated areas, PM<sub>2.5</sub>, NO<sub>x</sub> and other polluting gases in the exhaust emissions would immediately affect human health and quality of life that could negatively influence economic growth and residents' welfare. With the continuous development of urban public transportation, the harmful GHG (Greenhouse Gas, GHG) emissions and pollutants generated by itself and the consequent issues such as the losses of residents' health, economic value and residents' welfare have become the focus of social attention.

In order to curb harmful GHG emissions and pollutants in the road transport sector, improve the ecological environment, and realize the sustainable development, China has vigorously supported the technology research and marketing promotion of new energy vehicles in recent years, which has made great progress. Especially in the aspect of urban buses, China proposed the "863-plan"

<sup>1</sup>Data Sources: *China Vehicle Environmental Management Annual Report 2017*, Ministry of Environmental Protection of The People's Republic of China.

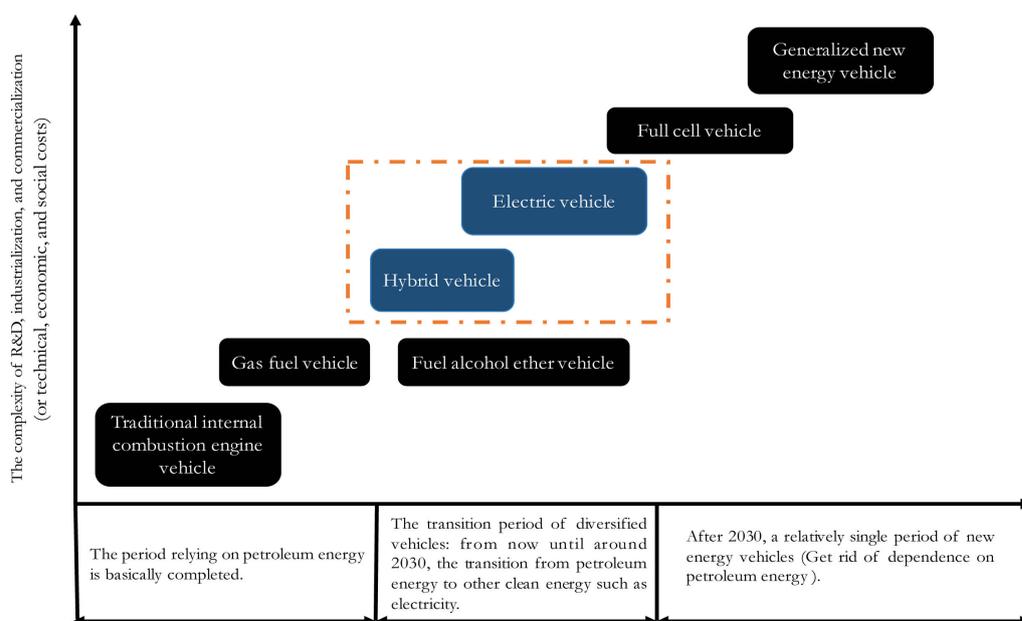
<sup>2</sup>Source: *The 13th Five-Year Development Outline of Urban Public Transportation*, Ministry of Transport of the People's Republic of China.

<sup>3</sup>Data Sources: *Public Transport Big Data Analysis Report of China's Major Cities (the first half of 2017)*, amap.com.

<sup>4</sup>URL: <http://zizhan.mot.gov.cn>, Ministry of Transport of China.

in the 1990s, which suggested to step up efforts to develop urban environmental-friendly buses. At the beginning of the century, the “10th Five-Year Plan” dedicated electric buses incentive project. The “11th Five-Year Plan” proposed increasing technology research and development of alternative fuel buses, and further promote the industrialization process of electric vehicles. In 2009, electric vehicle demonstration and application project that named the “Ten Cities and Thousand Vehicles” was launched. At present, from the perspective of technology research, industrialization and commercialization, China’s new energy vehicles are mainly concentrated on hybrid vehicles and pure electric vehicles (as shown in **Figure 1**), which both have high feasibility and economy in energy saving and environmental protection and application. Hybrid vehicles and electric vehicles were expected to be the mainstream of new energy vehicles in the next stage<sup>5</sup>.

Therefore, the urban public transportation sector, especially the new energy buses, is an important demonstration of promoting new energy vehicles in China. In order to study the impacts of promoting new energy vehicles on public transportation pollution mitigation and residents’ health benefits, this paper adopt the LEAP model<sup>6</sup> (Long Range Energy Alternatives Planning System) to build some scenarios that fulfil different development needs to quantitatively analyze the ownership of new energy buses, the reduction of pollutants and the losses of residents’ health welfare. It is an urgent and critically important to comprehensively describe the opportunities and impacts of actively seeking energy security and achieving emission mitigation of pollutants.



**Figure 1.** Panorama of China’s new energy vehicle industry development route.

<sup>5</sup>URL: <http://auto.gasgoo.com/topic/newenergy/>, Current status and prospects of new energy vehicles.

<sup>6</sup>Official website: <http://www.energycommunity.org/> or <http://www.sei-us.org/>.

## 1.2. Literature Review

The rapid development of public transportation in various countries has generated sharp-increasing energy consumption, ever-growing pollutant emissions, and substantial losses to residents' health welfare. Therefore, several scholars have conducted a large number of studies on the analysis of energy saving and emission mitigation potential of public transportation, the evaluation and optimization of transport sector policy and the assessment of residents' health welfare. In the term of pollution measurement and policy evaluation and optimization, many earlier studies used the LEAP model to analyze the energy conservation and emission mitigation policies formulated by the highway and railway passenger transport departments in different cities and concluded that controlling private cars, fuel economy management and fuel taxation are the three most effective measures to achieve the reduction goal (Bose & Srinivasachary, 1997; Yan & Crookes, 2009). Some studies used scenario analysis to assess the impact of pollutant emissions from China's transport sector on air quality under different emission standards, and found that various pollutant emissions will be reduced more than 50% in the context of implementing strict emission standards by 2020, which will greatly improve the air quality of China and even East Asia (Saikawa et al., 2011). Moreover, many studies focus on the vehicle emission factor and establishing pollution emission inventories for specific technology pathways, in order to quantitatively estimate the CO, HC, NO<sub>x</sub> and PM<sub>2.5</sub> emissions (He, 2015; Fan et al., 2016).

Promoting energy-saving vehicles as one of the important methods of energy conservation and emission mitigation in the public transport sector is an inevitable trend in the future development. Domestic and foreign scholars carried out in-depth studies on upgrading energy-saving vehicles, improving energy-using efficiency and exploring emission mitigation potentials. Researches indicated that considering the various factors such as oil prices, subsidy policies, alternative energy vehicles technology and prospective vehicles ownership, widespread use of alternative energy vehicles in urban transportation can effectively reduce CO<sub>2</sub> and other pollutant emissions, and the road transport sector should increase the implementation to simultaneously promote pure electric vehicles (EVs) and hybrid (HEVs) vehicles in the future (Brady & O'Mahony, 2011; Pasoglu et al., 2012; Chen & He, 2013). However, some scholars are skeptical about the mitigation efficiency of alternative energy vehicles. From the perspective of the Life Cycle Analysis, alternative energy vehicles instead of fossil energy vehicles cannot fully achieve the goal of energy saving and emission mitigation based on China's current coal-fired power generation ratio (Kong et al., 2012). As alternative energy buses are the main targets of promoting new energy vehicles, scholars also conduct in-depth research on the economical efficiency of them. Research suggests that combining with ownership costs, energy consumption during the whole life cycle and losses caused by pollutant emissions, higher financial subsidies can make up for the difference in the social costs between conventional diesel buses (CDBs) and hybrid buses (HEVs), and after entering the regionalization promotion stage, the costs during the whole life cycle of

HEVs will be lower than CDBs (Ou et al., 2009).

Increasing traffic demand not only leads to a rapid increase in pollutant emissions from the transportation sector, but also a serious threat to economic development and residents' health. Therefore, residents' health levels would be one of important indicators to assess the effects of transport policy measures. In general, the comprehensive analysis framework of health benefits includes three steps: calculating the air quality concentration, estimating the physical losses of residents' health caused by air pollutants, and evaluating economic losses of residents' health. Firstly, the models of estimating the pollutant emissions from various policy paths has evolved from a simple first-generation to a complex third-generation model. Scholar had used Model-3/CMAQ (Community Multi-Scale Air Quality model) to study the effects of five kinds of vehicle emission control measures on air quality in the Pearl River Delta region in China. Results point out that multiple pollutants mixed and specific regional pollution control strategies are necessary (Che et al., 2011). Secondly, literature in the field of epidemiology has confirmed that air pollution can increase the risk of lung cancer, respiratory diseases, and cardiovascular disease. In view of the debate about the existence of threshold, most of the literature uses linear exposure-response functions and zero threshold hypothesis to estimate the physical losses of residents' health, which are widely used in health risk assessment research. Several studies quantify the impact of major atmospheric pollutants on residents' total mortality, respiratory diseases daily mortality and cardiovascular disease daily mortality etc. (Quah & Boon, 2003; Chen, 2013; Liu et al., 2014). Finally, based on the economic perspective, the amount of physical loss is converted into monetized loss. In the field of health statistics, the existing assessment methods mainly include cost of illness method (COI) and willingness to pay method (WTP). Study uses synthesized evaluation method to estimate the health impacts and economic costs of China's road transport. The results show that total health losses of air pollution caused by Beijing transportation during 2004-2008 are about 0.58% of Beijing's GDP (Guo et al., 2010).

In summary, the existing literature only focuses on the research of energy saving and carbon mitigation in public transportation, and ignore to do a comprehensive research on the main pollutant emissions of vehicle exhaust. At the same time, it is lack to do a systematic research on the transmission mechanism from pollutant emission mitigation of alternative energy vehicles to residents' health benefits. This paper analyzes the future trends of alternative energy bus ownership and pollutant emissions under different scenarios in China's development plan. Meanwhile, study simultaneously calculates the economic benefits of promoting alternative energy buses on residents' health benefits.

## 2. Methodology

### 2.1. Model Structure

#### 2.1.1. Pollutant Emissions Accounting of Buses

##### 1) Pollutant emissions accounting during driving

The LEAP model, a bottom-up energy-environment accounting tool based on scenario analysis, is mainly used to evaluate the effects of energy technologies, alternative energy programs and energy initiatives plans. The central concept of the LEAP model is the end-use-driven scenario analysis. It includes an integrated energy system accounting framework that can considers both demand-side and supply-side technologies and simultaneously assesses the overall impact on the system.

This model sets 2014 as the base year, and the main classification of bus vehicles is shown in **Table 1**. The ethanol gasoline for vehicles is determined according to *Ethanol Gasoline for Motor Vehicles (E10) (GB 18351-2017)*. The ratio of fuel to gasoline is determined by reference to the existing research (Thomas, 2009).

In the model, the direct energy consumption of the buses is determined by several factors:

$$EC_t = \sum stock_{i,j,t} \times FE_{i,j,t} \times DT_{i,j,t} \quad (1)$$

where  $EC_t$  is the energy consumption for the given year  $t$ ;  $i$  is the type of bus;  $j$  is the fuel type used by the bus;  $stock_{i,j,t}$  is bus inventory of bus type  $i$  using fuel type  $j$  in the given year  $t$ ;  $FE_{i,j,t}$  is the average on-road fuel economy of bus type  $i$  using fuel type  $j$  in the given year  $t$ ;  $DT_{i,j,t}$  is the average annual traveled mileage of bus type  $i$  using fuel type  $j$  in the given year  $t$ .

Among them, the bus inventory is determined by the following factors:

$$stock_{i,j,t} = \sum stock_{i,j,t-1} \times SurRat_{v,i} + Sale_{i,j,t} \quad (2)$$

$$Allstock_t = \sum stock_{i,j,t} \quad (3)$$

where  $v$  indicates the year when the bus is put into use;  $SurRat_{v,i}$  is the retention rate of bus type  $i$  after  $v$  years;  $Sale_{i,j,t}$  is the sales volume of bus type  $i$  using fuel type  $j$  in the given year  $t$ ;  $Allstock_t$  is the bus possession for the given year  $t$ .

## 2) Pollutant emissions accounting under Life Cycle Analysis

New energy buses discharge less pollutants or even can achieve zero emissions during driving. But as China's power industry is still dominated by coal-fired

**Table 1.** China's bus vehicles classification.

Vehicle Technology	Model	Fuel type
Conventional energy	Gasoline buses	Gasoline
	Diesel buses	Diesel
	Bioethanol-gasoline buses	10% Bioethanol + 90% Gasoline
Saving energy	LPG	Liquefied petroleum gas
	LNG/CNG	Natural gas
New energy	Hybrid buses	70% Gasoline + 30% Electricity
	Battery electric buses	Electricity

CNG-Compressed Natural Gas; LPG-Liquefied Petroleum Gas; LNG-Liquefied Natural Gas.

units, emission mitigation effect of new energy buses is still disputed. This study used Life Cycle Analysis (LCA) to assess the potential impact of products' whole life cycle. The main life cycle of fuel mainly consists of two parts: the one is from well to pump (WTP), involving the extraction and transportation of raw materials, production and transportation of fuel etc.; and another one is from pump to wheel (PTW), which is related to fuel consumption and emissions. Limited by data sources, this study only conducts a full life cycle assessment of conventional buses and new energy buses.

The pollutant emissions of the buses can be calculated by the following formula:

$$Emission_{i,j,k,t} = EC_t \times EmiRat_{i,j,k} + EC_t \times \mu_j \times Emifac_{j,k} \quad (4)$$

where  $k$  is the type of pollutant emissions, which includes greenhouse gas carbon dioxide  $CO_2$  and pollutants such as carbon monoxide  $CO$ , nitrogen oxides  $NO_x$  and particulate matter  $PM_{10}$ ;  $EmiRat_{i,j,k}$  is the emission factor of pollutant  $k$  by the bus type  $i$  using fuel type  $j$ ;  $\mu_j$  is the energy consumption caused by unit fuel type  $j$ ;  $Emifac_{j,k}$  is the emission factor of pollutant  $k$  discharged by fuel type  $j$ .

### 2.1.2. Relationship between Buses Pollutant Emissions and Air Quality

This study uses Box Model to establish the connection between buses pollutant emissions and air quality. The Box Model assumes that the simulated environment has uniform atmospheric conditions, and the chemical reaction mechanism of the pollutants is simplified. The pollutants in each period are completely purified in the current issue, which means that there are no cumulative pollutant emissions. The current air pollutant concentration can be calculated using the following formula:

$$c = b + \frac{S \times L}{u \times H} \quad (5)$$

where  $c$  is the atmospheric pollutants concentration ( $\mu\text{g}/\text{m}^3$ );  $b$  is the background concentration of pollutants ( $\mu\text{g}/\text{m}^3$ ), that is, there is natural gas concentration without any human activities;  $S$  is the emission rate of pollutants ( $\mu\text{g}/\text{s}\cdot\text{m}^2$ );  $L$  is the length (m);  $u$  is the average wind speed (m/s);  $H$  is the height of the box (m).

$$\frac{S_2}{S_1} = \frac{C_2 - b}{C_1 - b} \quad (6)$$

where  $S_1$  and  $S_2$  respectively represent the reference emission rate and the future emission rate of pollutants ( $\mu\text{g}/\text{s}\cdot\text{m}^2$ );  $Emission_1/Emission_2$  means the ratio of the reference emission to the future emission under the assumption of uniform discharge of pollutants, which can be equated with  $S_1/S_2$ .  $C_1$  and  $C_2$  respectively represent the reference concentration and the future concentration of air pollutants ( $\mu\text{g}/\text{m}^3$ ).

### 2.1.3. Impact of Air Pollutants on Residents' Health Losses

When the air pollution concentration is determined, the physical quantity of the

resident's health losses can be quantified by the epidemiological exposure-response function. The resident's health losses are determined by three factors: the concentration of pollutants, the exposure-response coefficients between health outcome and pollutants, and the exposed population:

$$Case_{i,j}^{Morb} = ER_{i,j} \times C_j \times P \quad (7)$$

where  $ER_{i,j}$  stand for the exposure-response coefficients between health outcome and the pollutant;  $C_j$  is the pollutant concentration;  $P$  is the exposed population. After obtaining the physical quantity of residents' health losses, we use three assessment methods: WTP (Willingness to Pay), COI (Cost of Illness) and VSL (Value of Statistical Life) to calculate the economic losses of unit resident, and thus evaluates the economic value of promoting new energy buses.

## 2.2. Data

### 2.2.1. Stock and Sales Volume of Buses in China

This study selected 2014 as the basic year. Since there is no official data on the annual sales volume of buses, the sales growth rate in this study varies according to the scenario (as shown in [Table 2](#)).

### 2.2.2. Fuel Economy, Annual Mileage and Vehicle Survival Rate

The fuel economy standard of heavy-duty diesel vehicles in China is relatively late, and the related research is relatively rare. This study cites the average fuel economy of 29 China IV diesel buses, 34 L/100 km as the benchmark of diesel buses in the basic year. For natural gas buses, the actual testing results of 9 CNG buses show that the fuel economy of the natural gas buses is 15% lower than that of the diesel buses. Also according to the available testing data under the conservative setting, the fuel economy of battery electric buses and hybrid buses is 180% and 20% higher than that of diesel buses, respectively. The fuel economy of ethanol gasoline is 90% of gasoline ([Wang, 2015](#)) (as shown in [Table 3](#)).

Due to the lack of official statistics, the annual mileage of basic year is determined by existing research ([Guo et al., 2007](#); [He et al., 2005](#); [Wang et al., 2007a](#); [Yan, 2008](#)). We select 35,000 kilometers as the bench mark. Each bus has a service age of 17 years. To make the data closer to reality, we assume that each bus

**Table 2.** Fuel economy, annual mileage and vehicle survival rate.

Vehicle type	Fuel economy (L/100 km)	Annual mileage (km)	Age (years)
Gasoline buses	35.02	35,000	17
Diesel buses	34	35,000	17
LNG/CNG	44.2	35,000	17
Bioethanol-gasoline buses	31.52	35,000	17
Hybrid buses	28.33	35,000	17
Battery electric buses	12.14	35,000	17

Source: The data of fuel economy and annual mileage is quoted from the earlier studies and obtained by proportional conversion ([Wang, 2015](#); [Ou et al., 2010](#)).

**Table 3.** Stocks of buses in China (2010-2014).

Vehicle type/Year	2010	2011	2012	2013	2014
Gasoline buses	33,917	27,959	23,778	17,183	13,294
Diesel buses	290,271	304,215	306,465	302,428	279,927
Bioethanol-gasoline buses	13,920	12,549	9735	7978	4600
LPG	7535	9500	8884	8385	8408
LNG/CNG	69,943	89,432	110,907	149,531	183,953
Hybrid buses	1970	6613	11,704	19,186	29,320
Battery electric buses	957	1218	1722	3050	7297
Other	2007	1680	1696	1888	2004
Total	420,520	453,266	474,891	509,629	528,803

Source: China Communications Statistical Yearbook (2010-2014). Ministry of Transport of the People's Republic of China. Since the statistics of the dual fuel vehicles are not classified, and the application is less. At present, the dual-fuel buses mainly used in China mainly use CNG as an alternative fuel, so the dual-fuel vehicles are classified into LNG vehicles. Considering that LNG and CNG energy consumption and emissions are basically the same, no distinction is made here.

must adhere to the degradation rate, which follows an exponential function:  $S_t = S_{t-1}e^{pt}$  (where  $p$  is the parameter.  $t$  is the usage time). According to the age of different buses, we set the mileage for the last year to be 0. Therefore, the exponential function in the degradation profile is:

$$S_t = S_{t-1} \cdot e^{-0.045t} \quad (8)$$

where  $S$  represents the share of the buses;  $t$  represents the age of the buses.

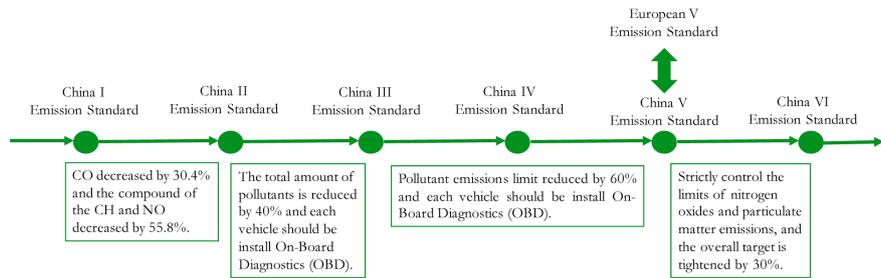
In the LEAP model, the survival profile is used to describe the survival rate of the different life cycle stages. Once the bus has reached the end of useful age or mileage limit, it must be scrapped. If the bus has reached the end of useful age and does not reach the mileage limit, the maximum length of age may be allowed to extend, provided that it successfully passes all technical standards (Jiang and Yi, 1997; Ministry of Commerce of the PRC (MCC), 2000). Therefore, the survival rate follows an exponential function:

$$S_t = S_{t-1} \cdot e^{-0.02t} \quad (9)$$

where  $S$  represents the share of the buses;  $t$  represents the age of the buses.

### 2.2.3. Direct Emission Factors

There are no official emission factor data available in China. This study cites national vehicle emission standards data and some literature data. From China I emission standard to China V, its automobile exhaust emission standards have been gradually benchmarking the standards of European. The target of China V emission standard is more inclined to the diesel vehicles with serious pollution, and the indicators of that have increased by a large margin. The particles concentration of China V emission standard is even stricter by 82%. Since 2017, China has focused on tightening the limits of nitrogen oxides and particulate matter emissions (Figure 2). The emission factors draw on the research results of previous scholars (Table 4).



**Figure 2.** The evolution of China’s emission standards.

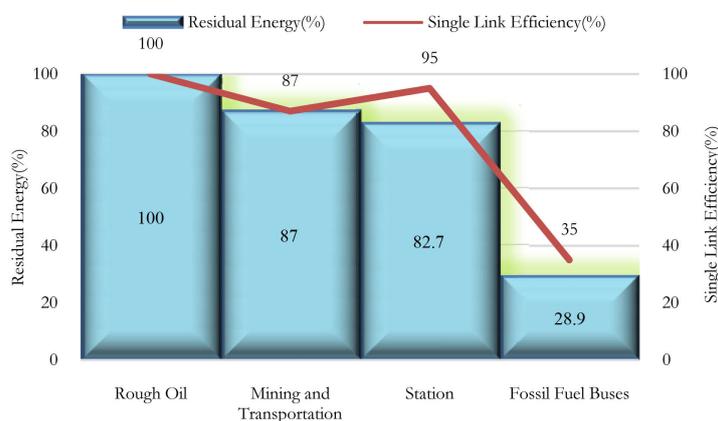
**Table 4.** Direct emission factors for each bustype.

Vehicle type	Source	CO <sub>2</sub> (g/km)	CO (g/km)	NO <sub>x</sub> (g/km)	PM <sub>10</sub> (g/km)
Gasoline buses	Hu et al. (2006)	1400	93.92	8.51	0.816
	Hu et al. (2006)	1171.32	7.2	21.33	0.126
	Euro I (2002)	1125.9	3.3	11.6	0.6
Diesel buses	Euro II (2005)	1082.5	3.0	12.4	0.3
	Euro IV (2010)	1072.8	0.3	6.4	0.1
	Euro V (2016)	1072.8	0.3	3.6	0.1
	Euro VI (2050)	1072.8	0.3	0.7	0.1
	Hu et al. (2006)	1072.4	79.96	8.79	0.071
	Euro I (2002)	1530.6	8.4	16.5	0.1
CNG	Euro II (2005)	1420.3	2.7	15.0	0.1
	Euro IV (2010)	1254.8	1.0	10.0	0.1
	Euro VI (2016)	1254.8	1.0	10.0	0.1
	Euro VI (2050)	1072.8	0.3	0.7	0.1
LPG	Hu et al. (2006)	1254.4	87.13	6.93	0.083
Bioethanol-gasoline buses	Clairotte et al. (2013)	1362.2	0.28	0.014	0.0005
Hybrid buses	Chen & He (2013)	77	95	0	21.6
Battery electric buses	-	-	-	-	-

Source: European emission standard is quoted from the earlier study (Cai & Xie, 2010).

**2.2.4. Efficiency Parameters and Emission Factors of Life-Cycle Analysis**

To simplify, we refer to existing research parameters. Ignoring the impact of bus types and vehicle weight on energy consumption, the efficiency of diesel and gasoline buses from crude oil extraction to refined fuel is about 87%, and from refinery transportation to the gas station consumes 5%. Then the fuel efficiency of diesel and gasoline engine is about 35% and 20%, respectively. Finally, the cycle energy efficiency of diesel and gasoline buses is 28.9% and 16.5%, respectively (Figure 3). Diesel bus requires 45 L diesel fuel for 100 km. The fuel consumption is the filling amount of the fuel station to the fuel tank. According to the diesel density 0.84 g/ml, diesel bus requires 55.1 kg standard coal for 100 km,



**Figure 3.** Energy efficiency of fossil fuel buses under Life Cycle Analysis (Sun et al., 2012).

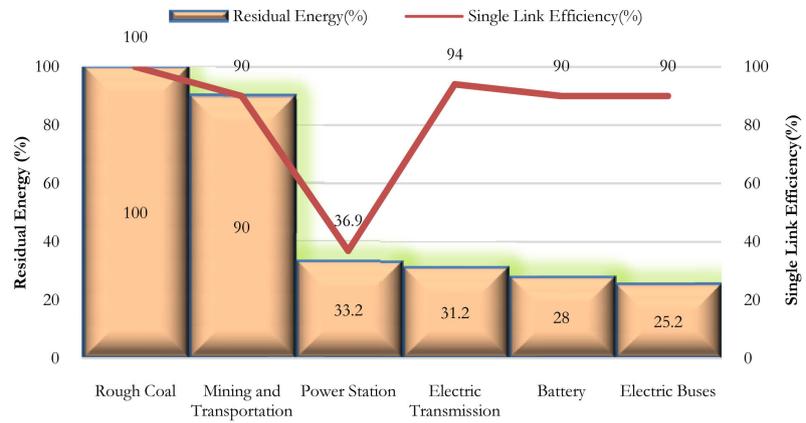
which can be converted into 66.6 kg rough oil. Likewise, gasoline bus requires 55 L gasoline fuel for 100 km. According to the gasoline density 0.72 g/ml, gasoline bus requires 58.3 kg standard coal for 100 km, which can be converted into 70.5 kg rough oil (Kong et al., 2012).

In the China's power generation industry, electricity generating from coal-fired units account for about 76% of total generation, that is, electricity mainly comes from coal. According to the statistics of the China Electricity Council, in 2010, the net coal consumption rate of thermal power plants above 6000 kW is 333 g/(kWh). The power supply efficiency is about 36.9%, and the national average power line loss rate was 6.5%. Assume that the efficiency of coal mining, transportation, washing and other processes before coal-fired power generation is 90%, and we find that the full-cycle energy efficiency of electric buses under coal-fired power generation is about 25.2% (Figure 3). The electric bus requires 150 kWh electricity for 100 km. This consumption is the amount of electricity charged by the power grid to the battery. Of this, the coal-fired unit supplies 114 kW electricity, and the thermal power plants consume 40.4 kg standard coal, which can be converted into 44.9 kg rough coal (Figure 4).

According to *China Statistical Yearbook 2011* and *China Energy Statistical Yearbook 2011*, one-ton standard coal for power generation will equally discharge 1.74 kg particulate matter PM and 6.6 kg nitrogen oxides  $\text{NO}_x$  in 2010. If one electric bus requires 150 kWh electricity for 100 km, it will discharge 70.5 g pollutant particles PM and 265.5 g nitrogen oxides  $\text{NO}_x$  (as shown in Table 5).

### 2.2.5. Exposure-Response Coefficients

Existing epidemiological research of the exposure-response function can quantify the physical volume of residents' health hazards at certain air pollutant levels. To simplicity, this study treats China as a whole without any distinction between geography condition and other details. Considering the availability of exposure-response coefficients, this study selected health outcome closely related to bus pollutant emissions includes respiratory mortality, cardiovascular mortality, respiratory hospitalizations, cardiovascular hospitalization, asthma visit and acute bronchitis visit (Table 6).



**Figure 4.** Energy efficiency of electric buses under life cycle analysis (Kong et al., 2012).

**Table 5.** Energy consumption and pollutant emissions (100 km).

	Fuel consumption (Physical volume) <sup>1</sup>	Material consumption (Standard coal) (kg)	CO <sub>2</sub> (kg)	CO (kg)	NO <sub>x</sub> (kg)	PM (kg)
Gasoline buses	55 L gasoline	70.5 kg rough oil	134.57	1.112	1.497	0.794
Diesel buses	45 L diesel	66.6 kg rough oil	110.10	0.910	1.225	0.065
Hybrid buses	38.5 L gasoline + 45 kWh electricity	46.6 kg rough oil + 13.5 kg rough coal	109.89	0.637	0.937	0.069
Battery electric buses	150 kWh electricity	44.9 kg rough coal	109.28	-	0.265	0.071

Source: the data of Fuel consumption and pollutant emissions is quoted from the earlier study (Ou et al., 2008; Kong et al., 2012).

**Table 6.** Exposure-response coefficients of health outcome.

Health outcome	Pollutants	Exposure-response coefficient	References
Respiratory mortality	NO <sub>x</sub>	1.62	Shang et al. (2013)
	PM <sub>10</sub>	0.32	Shang et al. (2013)
Cardiovascular mortality	NO <sub>x</sub>	1.46	Shang et al. (2013)
	PM <sub>10</sub>	0.43	Shang et al. (2013)
Respiratory hospitalizations	NO <sub>x</sub>	2.57	Zhang et al. (2015)
	PM <sub>10</sub>	1.72	Zhang et al. (2015)
Cardiovascular hospitalization	NO <sub>x</sub>	1.18	Zhang et al. (2015)
	PM <sub>10</sub>	1.39	Zhang et al. (2015)
Asthma visit	NO <sub>x</sub>	1.46	Halonen et al. (2008)
	PM <sub>10</sub>	1.50	Guo et al. (2018)
Acute bronchitis visit	NO <sub>x</sub>	1.19	Guo et al. (2018)
	PM <sub>10</sub>	0.31	Guo et al. (2018)

Exposure-response coefficients indicate the percentage of health outcome increases when pollutant concentration increases 10 µg/m<sup>3</sup>.

### 2.2.6. The Economic Losses of Residents

This study uses the VSL, WTP and COI as assessment methods to convert the physical volume of residents' health hazards caused by bus pollutants emissions into economic losses (as shown in **Table 7**).

## 3. Scenario Design

In 2015, the National Development and Reform Commission ("NDRC") has promulgated the *Opinions on Giving Better Play to the Role of Transportation in Supporting and Leading Economic and Social Development at Present*, which is called "China's Transportation 2050". The Opinions points out that it is necessary to vigorously develop various forms of large-capacity public transportation, and build green transport system based on public transportation. The important issues of the Opinions are encouraging the application of new energy vehicles and speeding up the elimination of old vehicles. Therefore, this study will regard the year 2050 as the future scenario period.

In the first step, the business as usual (BAU) assumes that government to do nothing to influence the long-term development trend of public transportation. As China has implemented the Euro VI emission standard since 2018, we set that the current emission standard is Euro VI and the sales growth rate of buses is 3.05% according to the growth rate in 2010-2014.

In the second step, we make policy interventions. The development trend of public transportation mainly needs to meet the following two needs:

1) To meet the urban modernization construction, that is, to meet the goal of urban public transportation construction. In 2014, China had a population of 1.37 billion, which will reach 1.44 billion in 2030 and fall to 1.36 billion in 2050 according to The United Nations Outlook. The state regulation is that bus equipped with 7 and 12 sets per 10,000 people in small and medium-sized cities and the national civilized Class A cities, which is estimated 0.955 million and 1.673 million buses, respectively.

2) To meet the alternative requirements of public transportation, that is, to meet the goal of prioritizing public transportation. In 2013, the State Council of

**Table 7.** The economic losses of health outcome (RMB).

Health outcome	Methods	Unit cost	References
Respiratory mortality	VSL	933,841.2	Xie (2011)
Cardiovascular mortality	VSL	933,841.2	Xie (2011)
Respiratory hospitalizations	COI	5080.8	<i>China Health and Family Planning Statistical Yearbook 2013</i>
Cardiovascular hospitalization	COI	7147.9	<i>China Health and Family Planning Statistical Yearbook 2013</i>
Asthma visit	WTP	78.18	Kan & Chen (2004)
Acute bronchitis visit	WTP	124.60	Kan & Chen (2004)

The parameters of asthma visit and acute bronchitis visit are based on the ratio of per capita disposable income of the specific city and nation in basic year.

China deployed ten measures to control air pollution. The measures explicitly proposed the priority of public transportation development to ensure that the concentration of atmospheric pollutants in key industries fell by 30% by the end of 2017. We draw on the setting of existing study. According to BAU of the existing study, the total annual mileage traveled by buses is 27.42 billion kilometers, and the annual mileage of each bus is 35,000 kilometers, which is estimated 783,400 buses in 2050. In the scenario three, it assumes that 20% of the increased mileage of private and commercial vehicles will be transferred to buses. It means that the total annual mileage traveled by buses is 62.65 billion kilometers, which is estimated 1.79 million buses in 2050. In the scenario four, it assumes that 30% of the increased mileage of private and commercial vehicles will be transferred to buses. It means that the total annual mileage traveled by buses is 80.27 billion kilometers, which is estimated 2.39 million buses in 2050 (He & Qiu, 2016).

In the third step, we set up the scenario of promoting new energy buses under different growth rates of public transportation. In 2018, the State Council of China issued *the Development Plan of Modern Comprehensive Transportation System (the 13th Five-Year Plan)*, which mentioned that the convenient, efficient, and green transportation system will be built in 2020 and some regions will take the lead in achieving modernization of transportation. Therefore, we set that the sales rate of new energy buses will reach 80% by 2020, and new energy buses will be fully promoted by 2030. Within the new energy buses, the sales rate of battery electric buses will reach 60% and 80% by 2020 and 2030, respectively. In 2050, it fully promoted battery electric buses (Table 8).

**Table 8.** Scenario and definition.

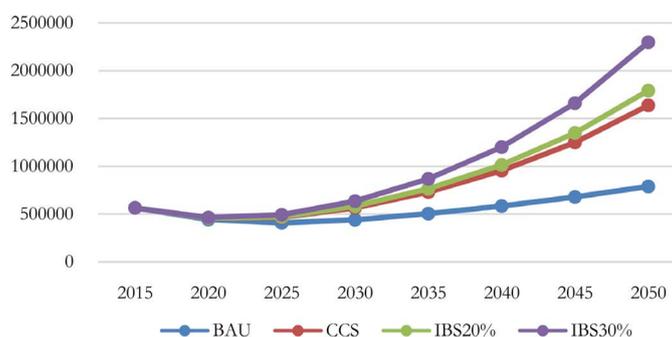
Hypothesis	Scenario	Abbreviation	Definition
Baseline reference	Business As Usual	BAU	The sales growth rate is 3.05%; Euro VI emission standard
Meet the urban modernization construction	Achieve the standard of he national civilized Class A cities	CCS	The sales growth rate is 5.55%; Euro VI emission standard
Meet the alternative requirements of public transportation	20% of the increased mileage of private and commercial vehicles will be transferred to buses	IBS20%	The sales growth rate is 5.86%; Euro VI emission standard
	30% of the increased mileage of private and commercial vehicles will be transferred to buses	IBS30%	The sales growth rate is 6.5%; Euro VI emission standard
Promoting new energy buses	All of Above	INEV INEVccs INEV20% INEV30%	The sales rate of new energy buses will reach 80% and 100% by 2020 and 2030, respectively; Within the new energy buses, the sales rate of battery electric buses will reach 60% and 80% by 2020 and 2030, respectively; In 2050, it fully promoted battery electric buses

## 4. Results

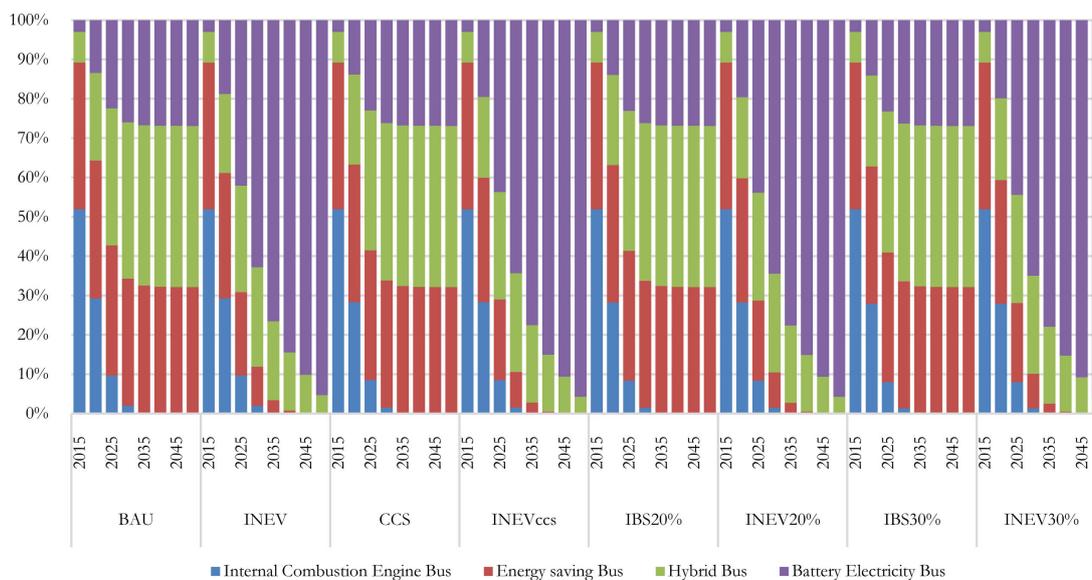
### 4.1. Buses Inventory Estimation

With the help of LEAP model, we estimate the inventory of buses using different fuel types (2015-2050) under different scenarios.

The results of the simulation show that: 1) With the sales rate set by the scenario, whether it meets which hypothesis, the total amount will decrease first and then slowly rise from 2020 to 2030 (As shown in **Figure 5** and **Figure 6**). That is, at the early stage, the vehicle growth rate is less than the elimination rate, which indicates that this period is the transition period of update from the traditional energy buses to the energy-saving buses or the new energy buses. 2) Comparing the growth trends of different buses types respectively, we will find that traditional energy buses will gradually withdraw from the market, and the growth rate of energy-saving buses will slow down in the later period. Under the scenario of promoting new energy buses, the inventory of energy-saving buses has dropped sharply (As shown in **Figure 7**). Promoting new energy buses has replaced the growth of energy-saving buses to a certain extent.



**Figure 5.** Estimating trends of inventory under different scenarios.



**Figure 6.** Estimating trends of inventory under different scenarios (Area chart).

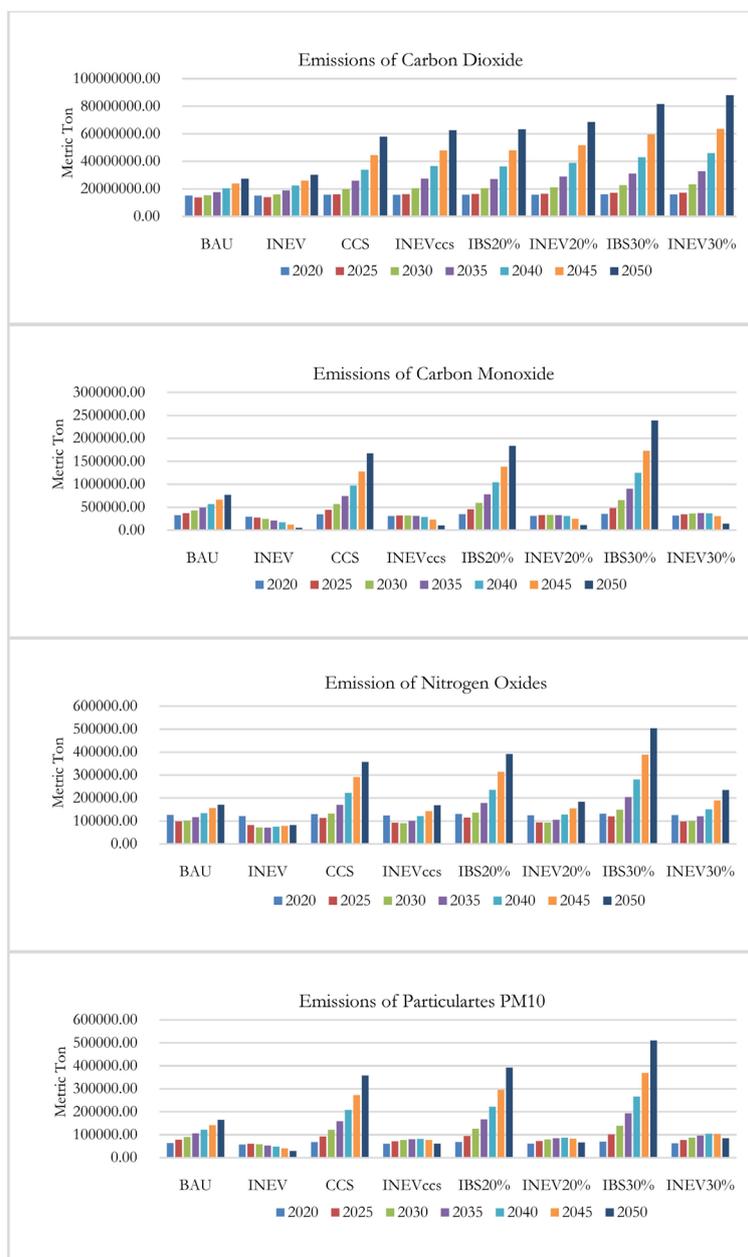


**Figure 7.** Estimating trends of inventory using different fuel under different scenarios.

#### 4.2. The Emission Reduction of Promoting New Energy Buses

The estimating trends of greenhouse gases and pollutants emission under different scenarios show that: 1) In the setting scenario CCS, IBS 20% and IBS 30%, greenhouse gas CO<sub>2</sub>, atmospheric pollutant CO, NO<sub>x</sub> and particulate matter PM10 emitted by buses exhaust have been a year-on-year rise. 2) Comparing the

setting scenarios BAU and INEV, CCS and INEV<sub>ccs</sub>, IBS20% and INEV20%, IBS30% and INEV30% respectively, we will find that promoting new energy buses have a significant effect of pollutant reduction, but under the case of life cycle analysis, the greenhouse gas is surging rather than falling (As shown in **Figure 8**). The main reason for the negative effect of greenhouse gas reduction is that China's current coal-fired power generation accounts for a large proportion. The greenhouse gas reduction of new energy buses in the terminal are not enough to offset the greenhouse gas generated by power generation and transportation.



**Figure 8.** Estimating trends of emission of greenhouse gases and pollutants under different scenarios.

The test results of emission reduction under different scenarios show that the greenhouse gas reduction effect of promoting new energy buses is negative under the condition of life cycle analysis, but the efficiency of atmospheric pollutants reduction is remarkable. In 2030, the emission reduction ratios of atmospheric pollutants CO, NO<sub>x</sub> and particulate matter PM<sub>10</sub> are 40%, 30% and 35% respectively; in 2050, the atmospheric pollutant CO emission reduction ratio is over 90%. The emission reduction efficiency of NO<sub>x</sub> is about 52%, and PM<sub>10</sub> is about 83% (As shown in **Table 9**).

### 4.3. The Estimating Results of Residents' Health Losses

The United Nations estimates that China's population will reach 1.3645 billion in 2050. We assume that one-third of the population will be exposed to harsh conditions by 2050. At the same time, in order to do a quantitative study of economic losses caused by pollutants, we will set two scenarios. One is the background concentration, that is, there is no natural state of pollutants caused by human activities. We set that the annual average concentrations of NO<sub>x</sub> and PM10 are 21 µg/m<sup>3</sup> (Chen & He, 2013) and 10 µg/m<sup>3</sup> (Wu et al., 2010) respectively. The other is the air pollutant concentration value of the baseline scenario. We set that the annual average concentration of NO<sub>x</sub> and PM<sub>10</sub> are 37.25 µg/m<sup>3</sup> and 28.9 µg/m<sup>3</sup> (iFinD database) in 2020 respectively. According to the model described in 3.1.2, we calculate the air pollutant concentration values for 2030 and 2050 (as shown in **Table 10**).

**Table 9.** The emission reduction of promoting new energy buses under different scenarios (%).

Pollutant	Scenario	2020	2025	2030	2035	2040	2045	2050
Carbon Dioxide	BAU-INEV	0.36	-0.76	-3.61	-6.96	-8.83	-9.16	-9.81
	CCS-INEV <sub>ccs</sub>	0.39	-0.60	-3.12	-6.07	-7.61	-7.80	-8.47
	IBS20%-INEV20%	0.39	-0.58	-3.06	-5.96	-7.47	-7.64	-8.31
	IBS30%-INEV30%	0.41	-0.53	-2.89	-5.68	-7.08	-7.22	-7.90
Carbon Monoxide	BAU-INEV	10.52	26.56	42.98	57.70	69.90	81.67	93.39
	CCS-INEV <sub>ccs</sub>	10.89	27.13	43.57	58.17	70.30	82.05	93.77
	IBS20%-INEV20%	10.94	27.19	43.63	58.22	70.35	82.10	93.82
	IBS30%-INEV30%	11.06	27.38	43.82	58.37	70.47	82.22	93.94
Nitrogen Oxides	BAU-INEV	4.31	16.77	30.46	39.24	44.59	49.66	52.08
	CCS-INEV <sub>ccs</sub>	4.60	17.80	31.78	40.46	45.73	50.74	52.88
	IBS20%-INEV20%	4.64	17.93	31.94	40.60	45.86	50.86	52.96
	IBS30%-INEV30%	10.94	27.19	43.63	58.22	70.35	82.10	93.82
Particulates PM10	BAU-INEV	10.27	23.18	36.22	48.82	60.02	71.15	82.32
	CCS-INEV <sub>ccs</sub>	10.56	23.61	36.78	49.44	60.69	71.88	83.09
	IBS20%-INEV20%	10.60	23.66	36.85	49.51	60.77	71.96	83.18
	IBS30%-INEV30%	10.70	23.80	37.03	49.70	60.98	72.18	83.41

**Table 10.** Air pollutant concentration in the future scenarios.

Year	Pollutant concentration	BAU	CCS	IBS20%	IBS30%	INEV	INEV <sub>ccs</sub>	INEV20%	INEV30%
2030	NO <sub>x</sub>	32.02	37.75	38.56	40.92	26.01	29.84	30.38	31.96
	PM <sub>10</sub>	32.35	35.25	35.65	36.83	29.07	31.07	31.35	32.16
2050	NO <sub>x</sub>	46.88	85.01	91.85	114.17	28.47	47.06	50.37	61.18
	PM <sub>10</sub>	41.67	62.94	66.73	79.09	25.07	28.93	29.61	31.79

The results of the economic losses of residents' health caused by buses exhaust show that: 1) Under the baseline scenario BAU, the economic losses of residents' health caused by atmospheric pollutants NO<sub>x</sub> and PM<sub>10</sub> emitted by bus exhausts in China in 2030 and 2050 are 859.062 billion RMB and 1200.276 billion RMB, which are equivalent to 1.04% and 1.45% of the national GDP in 2017, respectively. Among them, the economic losses caused by respiratory diseases are the largest, which are accounting for 59.46% of total value. The second one is cardiovascular disease. 2) In the setting scenario CCS, IBS 20% and IBS 30%, the economic losses of residents' health caused by exhaust pollutants NO<sub>x</sub> and PM<sub>10</sub> are increasing whether in 2030 or 2050. Without planning and intervention, the economic losses of residents' health caused by the bus industry in adapting to the urban modernization construction and the replacement demand of the public transportation system are gradually increasing. It means that while the public transport system is slowing down the negative externalities brought about by private transportation, there is also room for optimization. 3) Comparing the setting scenario BAU and INEV, CCS and INEV<sub>ccs</sub>, IBS 20% and INEV20%, IBS 30% and INEV30% respectively, the results show that promoting new energy buses vigorously can make the economic losses of residents' health reduced significantly. Especially in the future scenario 2050, when the traditional energy buses are completely replaced by the new energy buses, the economic losses of residents' health will be reduced by 39.31% to 50.31%, and the effect on the residents' welfare is considerable (as shown in **Table 11**).

## 5. Discussion

### 5.1. Summary

We set up four scenarios which based on two basic assumptions of meeting urban modernization and the requirements of public transportation replacement to promote the environmental impact and economic effects of new energy buses from the whole life cycle analysis. Then, we set the further scenarios that comprehensively promote new energy in the basic situation to calculate the impact on residents' health benefits and the economic benefits of carbon and pollutant reduction in different situations.

We find that the emissions of atmospheric pollutants such as carbon monoxide CO, nitrogen oxides NO<sub>x</sub> and particulate matter PM will be significantly reduced after the promoting new energy buses comprehensively, which will help

**Table 11.** Economic losses caused by air pollutant under different scenarios.

Scenario	2030 (Billion RMB)	2050 (Billion RMB)	Proportion of GDP in 2017 (2030)	Proportion of GDP in 2017 (2050)
BAU	859.0692	1200.2716	1.04%	1.45%
INEV	725.7780	726.5445	0.88%	0.88%
CCS	983.5360	2049.4718	1.19%	2.48%
INEV <sub>ccs</sub>	809.8200	1074.9299	0.98%	1.30%
IBS20%	1001.0604	2201.5955	1.21%	2.66%
INEV20%	821.6079	1136.9945	0.99%	1.37%
IBS30%	1052.3492	2697.7591	1.27%	3.26%
INEV30%	856.0808	1338.9348	1.04%	1.62%

China achieve the goal of reducing pollution, improving urban air quality and reducing expenditure of residents' disease effectively, thereby improving residents' welfare. However, because coal-fired power generation still accounts for a dominant position in China, the emissions of greenhouse gas CO<sub>2</sub> are surging rather than falling after promoting new energy buses comprehensively. The targets of greenhouse gas reduction cannot be fully realized. The economic losses of residents' health after promoting new energy buses comprehensively will be reduced by 39.31% to 50.31%, which indicates that the effect on the residents' welfare is considerable.

In summary, new energy buses have obvious advantages in energy conservation and pollution mitigation. In the future, it will bring good environmental impact and huge economic benefits to China in terms of environmental protection and energy conservation with the premise of ensuring grid security, the improvement of China's energy structure, breakthroughs in battery technology and the full deployment of infrastructure.

## 5.2. Policy Suggestion

The first suggestion is to increase the technology of new energy buses and optimize the policy environment of promoting new energy buses. According to the results of future scenario, while under the full life cycle assessment method, the promoting new energy buses can achieve the goal of reducing polluting gas emissions, thereby reducing the health economic losses and improving the welfare of residents. Therefore, promoting new energy buses is one of the important measures to deal with the energy crisis and environmental pollution. At present, the commercialization process of new energy buses is still in its infancy. In the future, it is necessary to increase the research of batteries and the improvement of endurance. At the same time, it is important to optimize the policy environment for promoting new energy buses. We must do a good job in the comprehensive construction of infrastructure such as giving priority to the land for charging stations or incorporating charging pile facilities into the overall urban planning.

The second is suggestion to optimize the power generation structure and improve the electricity efficiency of new energy buses. Comparing the efficiency of driving process and the whole life cycle assessment method, it can be seen that a large amount of polluting gasemits during the process of raw material mining, producing and transporting. New energy buses are the general trend of road transportation industry in the next 50 years. To order to achieve energy conservation and emission reduction targets, it is necessary to speed up the technical transformation of coal-fired power plants and increase the proportion of clean energy power generation.

### Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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