Techno-economic Analysis and Comparative Study for the Sustainability of Private Motor Vehicles in China

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Abstract. This article discusses the life cycle energy consumption and cost of three new energy vehicles (NEVs) through life cycle analysis (LCA) and techno-economic analysis, and compares them with a conventional vehicle (CV). In ideal, average, and extreme scenarios, new energy vehicles are more sustainable than CV, especially in terms of greenhouse gas emissions, but are not as economical as CV. To be concise, electric vehicles have the best environmental sustainability, but the total cost is higher than CVs. The total cost of hybrid electric vehicles is slightly lower than conventional vehicles, but the environmental sustainability is poor.

1. Introduction

1.1. Emission and pollution

With the continuous tightening of environmental protection policies, the government has implemented strict regulations on the emission of private passenger cars. With that, in recent years, many new energy vehicles have been utilised, such as plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), as well as hybrid electric vehicle (HEV). BEVs are completely driven by rechargeable batteries, such as lead-acid batteries, nickel-cadmium batteries, nickel-hydrogen batteries or lithium-ion battery. Both the internal combustion engine (ICE) and the electric motor are used for HEV, where the source of electrical energy is the engine. Compared with general hybrid vehicles, PHEV is characterized with its rechargeable battery that can be charged by a generator driven by the internal combustion engine on the vehicle as well as an external power source.

A study of three electric vehicles in the United Kingdom, the United States and France showed that electric vehicles can reduce well-to-wheel carbon dioxide emissions by 90% compared to existing traditional vehicles [1]. This research also indicated that the increased dependence on nuclear power and renewable energy will decrease the carbon dioxide emissions produced by electric vehicles. For gasoline vehicles, the energy consumption and carbon emissions of the entire life cycle include oil exploration, extraction, storage and transportation, smelting, transportation to gas stations, and finally consumption during vehicle operation. This is collectively referred to as "mine to wheel" [2]. Another research shows that EVs produce less pollution than traditional cars, but the process of production and usage requires more energy than traditional cars [3].

Before depending on new energy vehicles, a detailed and comprehensive life cycle analysis must be carried out. The definition of "full life cycle" is the input, output, and potential environmental impact of a product system from the raw materials obtained from nature till the final disposal. It is more representative to use this concept to evaluate the emissions of various energy vehicles rather than focusing on only one part of the production process.
At the moment, thermal power generation accounts for a large part of China's total power generation, making it difficult to replace it in the short term. Thermal generation in China is significantly dependent on fossil fuels (85%), especially coal which constitutes 90% of the total fossil fuels used [3]. Unfortunately, coal is not a clean source of energy, meaning that an electric vehicle using the electricity currently generated in China will not be as effective in reducing emissions as hoped. On the other hand, coal is a cheap source of energy, making it an affordable and widely used fuel across China. Such a dilemma necessitates a life cycle and techno-economic analysis for electric vehicle usage in China to find the optimum trade-offs between sustainability and affordability.

By 2030, CO2 emissions from China are predicted to surpass 15 billion tons [2]. After 2030, the emissions are expected to decrease due to policies that encourage the deployment of new energy vehicles (NEVs), including battery electric vehicles (BEVs), PHEVs, and fuel cell vehicles (FCVs). In addition to the source of electricity used for the electric vehicle, life cycle analysis also considers the emissions produced during automobiles production. As mentioned before, the emissions of NEV production is considerably high, and it will be required to reduce it to decrease the overall emissions of an EV. Several ways have been devised to decrease the emissions of EV production, including the use of magnesium and aluminium to replace steel which will also lead to better performance [4]. Moreover, such materials will lead to EVs with lighter weight, causing a decrease in emissions during car operation.

1.2. Policy and demand

Consumer demand for private cars is majorly affected by government policies. It is predicted that by the end of 2020, car owners will reach 280 million, which will definitely cause severe air pollution and traffic congestion [5]. Energy security might also be negatively affected, if all of these cars depended on conventional fuel, such as petrol, which is not widely produced in China [6]. New policies aim to restrain the rapid growth of car ownership. Recently, there is a new tight restriction on owning conventional cars in big cities in China, such as Beijing, Shanghai, and Guangzhou to limit air pollution and traffic congestion [7]. The two possible ways to have governmental permission to own a conventional car is either to apply for the low-probability lottery or through auction. In Beijing's lotteries, for example, the probability of winning a qualification license for a conventional car is only 0.8% [5]. Under this rather strict policy limiting people's ownership of conventional cars, what followed was a generous subsidy for buyers of new energy vehicles. However, the sales of private new energy cars have been poor, with only 0.1% of the 17600 new energy cars are owned privately [5]. This is understandable given the currently incomplete infrastructure of charging facilities in China [3]. In the early phase of deploying the policies of new energy vehicles, many battery manufacturers in China maintained a cautious and hesitant attitude towards battery production for such cars. The reason is that battery production for EVs is more complicated and expensive compared to conventional cars, due to the higher energy density and more reliable properties required for a NEV [5]. This still holds to be a challenge that should be resolved for more effective deployment of the policies for new cars in China. Due to the recent progress of China's new energy vehicle and internet industry, new energy vehicles have shown signs of significant development. By the end of 2018, 330 thousand public charging piles were built, 6 times more compared to 2015. Beijing, Shanghai, Shenzhen have built large-scale charging service networks. It is anticipated that this trend will continue in the next years [8].

1.3. Techno-economic

Technological advancements significantly improved the performance of new energy vehicles, yet Chinese people still need to consider the cost when buying private cars for household use. Therefore, a techno-economic analysis is essential for finding the optimum solutions for the energy vehicles market in China. Research shows that using hybrid cars reduces fuel consumption and CO2 emissions by 34-47% and 89-103g CO2, respectively. However, a hybrid car costs €5000-10000 more than a traditional combustion engine car [9]. Overall, the total costs of a hybrid car were significantly higher compared to a conventional one.
It has been reported that the industry of car manufacturing in China still lacks key aspects with respect to the development of new energy vehicles, rendering the cost of use high [8]. Although many large cities in China have begun to encourage the use of NEVs, most of these vehicles are used for public transportation with only a few electric vehicles privately owned. Most people are still opting for the time consuming and low-probability traditional car lottery unless they have an urgent need for a car, forcing them to purchase an electric vehicle. Despite the governmental subsidies and diversity of EV manufacturers, the cost of use is still high compared to traditional vehicles [10]. In short, major advancements are still required in the Chinese EV industry to be able to replace conventional combustion engine vehicles.

2. Life cycle analysis

2.1. Analysis boundary

After reviewing the Chinese car market, three NEVs and one conventional vehicle (CV) were chosen to be the basis of comparative analysis. The three types of NEVs were BEV, HEV and PHEV. The selected models with their vehicle characteristics are shown in Table 1.

It can be observed that the fuel consumption is the largest, despite its relatively lightweight compared to the other models. This is followed by the fuel consumption trends of HEV and PHEV. In contrast, BEV does not consume any fuel as expected. The fuel consumption of the electric motor is also slightly lower than that of the engine on the internal combustion engine (ICE) [11] but this does not mean that new energy vehicles do not produce emissions. Despite the relatively low fuel consumption exhibited by NEVs during their operation, such vehicles still produce considerable emissions across their lifetime. Such emissions are generated during the manufacture of the vehicle, along with the production of electricity necessary for vehicle operation. Such emissions can only be quantified through a life cycle analysis (LCA). LCA was conducted to compare the energy spent and emissions produced by the chosen four models. The analysis boundary encompasses the production phase and operation phase, as shown in Figure 1. The production phase includes vehicle manufacturing, power generation, and fuel production, while the operation phase includes operation and maintenance.

| Parameters          | BEV Tesla model 3 | HEV Levin Hybrid | PHEV BMW 5 PHEV | CV Nissan Sylphy |
|---------------------|-------------------|-----------------|-----------------|-----------------|
| Consumption         | 13.5kwh/hKm       | 4.1 L/hKm       | 18 kwh/hKm      | 8.7 L/hKm      |
|                     | 3.6kwh/hKm        | 3.6kwh/hKm      | 1.5 L/hKm       |                 |
| Fuel/Battery Type   | Li-ion battery    | Ni-MH battery/ICE | Li(NiCoMn)O₂/ICE | ICE            |
| Life cycle Endurance (× 10^4 Km) |          |                 |                 |                 |
|                     | 24                | 24              | 24              | 24             |
| Total weight (Kg)   | 1731              | 1535            | 2145            | 1271           |

The data in the above table comes from the sales data of China’s largest auto consumer website Autohome.com.cn up to July 2020. (Data resource: Autohome.com.cn)
Figure 1. Boundaries of life cycle analysis (LCA)

The car production chain focuses on manufacturing and assembling the different parts of the vehicle including chassis, frame, gearbox and more importantly, the battery in case of a NEV. The electricity chain is concerned with electricity generation in China, while fuel chain, which is essential for CVs, focuses on the mining, refining and distribution of ICE fuels. The emissions of NEVs are mainly concentrated in vehicle manufacturing and electricity production. China's electricity production mainly relies on conventional non-sustainable energy sources such as oil and coal [5]. The expected emissions from such processes are listed in Appendix. The contaminants are classified by greenhouse gases, acid rain contaminant, particle matters, and VOC, and CO. Vehicle emission policies in China takes into account carbon monoxide, nitrogen oxides, particulate pollutants in addition to the recently added nitrous [2].

2.2. Method

2.2.1. Software and model. GREET software was used to conduct LCA for the four chosen vehicle models, with the main boundary is well-to-wheel (WTW). GREET, which stands for greenhouse gases, regulated emissions, and energy use in transportation, is a full life-cycle software sponsored by the Argonne National Laboratory (US). This study is based on the data simulation of GREET 2019. The electricity consumption of NEVs is based on the consumption trends in China, which can already be found in the software. On the other hand, the software does not have any China-specific data for urban emissions, so data based on the United States was used instead. Due to the stricter pollution standards of the United States compared to China, the calculated emissions in this study are lower than expected [12]. For a fair comparison, the energy of CV (gasoline and electricity) is based on "Distributed China mix" in GREET software. All scenarios assume a NEV whose battery needs to be replaced once, and other parts of the body, such as the chassis, transmission system (gearbox, controller), body (aluminum), etc. are included in consumption and emissions.

2.2.2. Analysis based on different scenario. The study projects the simulation results till 2030. GREET preset models were adjusted according to the vehicle specifications of the chosen models. Different vehicle operation trends, in terms of fuel consumption and emissions, can be observed depending on vehicle status. In other words, an HPEV will produce lower emissions and spend less energy when it is being operated with higher charging efficiency. Therefore, a scenario analysis was deemed necessary to account for all the possible operation trends across the lifetime of the vehicle. Three scenarios were chosen in this study: (i) ideal (ii) average (iii) extreme. In the ideal scenario, the calculations were based on the condition when all models can possibly produce the least amount of emissions. This corresponds to the highest charging and gasoline combustion efficiencies. For PHEV, two main operating modes are being utilized, namely charge-depleting operating conditions
(CD) and charge-consuming (CS). During PHEV operation under CD condition, the battery can perform deeper work, usually when the battery power is high, and the value of state of charge in this state is usually between 0.2 and 0.9 (i.e. 0 when the power is exhausted and 1 when the battery is full). The electric energy in the battery during the CS operation phase is converted from the mechanical energy output by the ICE through the power generation of the drive motor. At this time, the ICE is responsible for the main power output. The CS mode is usually turned on when the battery power is low. For NEVs, the emissions predominantly depend on the charging efficiency, while for CVs the emissions and energy consumption depend on load capacity.

2.3. Data and information

2.3.1. Scenario 1. In this scenario, parameters of the 4 cars are set by an ideal state hypothesis, the charging efficiency (η) was calculated as:

\[
\eta = \frac{\text{Discharging Current} \times \text{Cut off time}}{\text{Charging Current} \times \text{Charging time}} \tag{1}
\]

η of BEV and PHEV was assumed to be 85%, the ICE of PHEV and CV is driven by the gasoline and 100% CD working condition with a 100 kg payload in CV.

Table 2. Comparison of energy consumption (MJ/100 km) between CV and NEV (Ideal State Hypothesis)

| Energy Catagories       | BEV          | HEV          | PHEV         | CV            |
|-------------------------|--------------|--------------|--------------|---------------|
|                         | Tesla model3 | Toyota levin | BMW 5 PHEV   | Nissan Sylphy |
| Total Energy            | 438.8        | 867.5        | 476.1        | 483.3         |
| Fossil Fuel             | 189.0        | 397.0        | 214.0        | 240.0         |
| Coal Fuel               | 146.0        | 197.0        | 97.0         | 1.7           |
| Natural Gas Fuel        | 35.0         | 48.0         | 82.0         | 25.0          |
| Petroleum Fuel          | 8.2          | 152.0        | 35.0         | 214.0         |
| Renewable               | 25.0         | 30.0         | 19.0         | 0.7           |
| Biomass                 | 2.7          | 3.7          | 1.8          | 0.4           |
| Nuclear                 | 3.9          | 4.9          | 4.3          | 0.4           |
| Non-Fossil Fuel         | 29.0         | 35.0         | 23.0         | 1.1           |

Figure 2. Comparison of energy consumption between CV and NEV (Ideal State Hypothesis)
According to Table 2 and Figure 2, it can be found that the total consumption of BEV is the lowest. Compared with HEV, consumption is reduced by nearly 50%. The same trend is also reflected in fossil fuel consumption. The reduction in energy consumption is more obvious for BEV than other types of NEV. For a country like China that mainly relies on coal for power generation, coal fuel consumption of BEV, HEV and PHEV is significant. This also affects the overall emissions from these vehicles since coal contains a considerable amount of sulfur, as shown in Table 3. In terms of total emissions, BEV emits the least among all vehicles in terms of greenhouse gas (GHG) emissions. Compared with CV, the GHG emissions are reduced by 78% when using BEV. On the contrary, NEVs emit more PM10 and PM2.5 particulate than CV. This is also linked to the high coal consumption for electricity generation in China. For BEV, VOC and CO emissions are all concentrated in the well to pump (WTP) phase. For HEV, VOC and CO emissions are mainly concentrated in the Pump to well (PTW) stage, which is the operation phase. It is worth noting that the emissions produced by BEVs in the operation phase are all zero, and the "fuel" of electric vehicles is the electricity provided by batteries. It can be seen that the emissions of BEVs and other EVs are mainly related to China’s energy mix. If the emission is to be significantly curbed, the energy mix must include more clean energy.

Table 3. Comparison of total emission between CV and NEV (Ideal State Hypothesis)

| Emission Type | BEV (Tesla model3) | HEV (Toyota Levin) | PHEV (BMW 5 PHEV) | CV (Nissan Sylphy) |
|---------------|--------------------|--------------------|-------------------|-------------------|
| VOC (g/100Km) | 18.00              | 34.96              | 4.27              | 8.63              |
| CO (g/100Km)  | 9.95               | 86.83              | 28.10             | 87.74             |
| NOx (g/100Km) | 6.32               | 9.62               | 19.70             | 6.86              |
| PM10 (g/100Km)| 3.17               | 3.95               | 2.75              | 0.45              |
| PM2.5 (g/100Km)| 1.03              | 1.59               | 1.18              | 0.40              |
| SOx (g/100Km) | 43.31              | 53.00              | 39.05             | 1.14              |
| CH4 (g/100Km) | 0.28               | 0.48               | 2.84              | 22.67             |
| CO2 (Kg/100Km)| 15.47              | 30.32              | 36.57             | 13.25             |
| N2O (g/100Km) | 0.28               | 0.24               | 0.11              | 0.08              |
| GHG (Kg/100Km)| 16.25              | 32.34              | 28.00             | 11.40             |

2.3.2. Scenario 2. This scenario is based on the average cases. The charging efficiency of EV is about 40%, which is also the charging efficiency of most domestic charging piles in China. The operating conditions of the PHEV are set at 50% CD and 50% CS. Furthermore, the loading in CV is set to 250 kg. The other settings are the same as in scenario 1.

As shown in Table 4, the main fuel consumed are fossil energy and coal, but unlike scenario 1, the consumption expectedly increased. It is worth noting that although the total energy consumption of BEV has increased significantly, it is all concentrated in the WTP phase. This further highlights the importance of adapting China’s energy mix. This is in line with the results from literature. In fact, countries with fossil energy as their main energy sources such as China and the United States need to optimize their energy structure to maximize the sustainability and effectiveness of electric vehicles [12]. According to the simulated data, for these countries, the energy consumed (Figure 3) by NEV is greater than the total energy consumed by CV. The GHG emission (Table 5) in this specific scenario differs from NEVs and CVs, indicating a potential to reduce the greenhouse effect.
Table 4. Comparison of energy consumption (MJ /100 km) between CV and NEV (Average State Hypothesis)

| Energy Categories | BEV | HEV | PHEV | CV |
|-------------------|-----|-----|------|----|
|                   | Tesla model3 | Toyota levin | BMW 5 PHEV | Nissan Sylphy |
| Total Energy      | 720.7 | 893.9 | 911.6 | 715.1 |
| Fossil Fuel       | 310.0 | 408.0 | 431.0 | 354.0 |
| Coal Fuel         | 262.0 | 207.0 | 98.0  | 6.2 |
| Natural Gas Fuel  | 39.0  | 49.0  | 105.0 | 43.0 |
| Petroleum Fuel    | 10.0  | 152.0 | 227.0 | 305.0 |
| Renewable         | 42.0  | 32.0  | 20.0  | 2.3 |
| Biomass           | 5.0   | 3.9   | 1.9   | 0.1 |
| Nuclear           | 5.7   | 5.1   | 4.7   | 1.1 |
| Non-Fossil Fuel   | 47.0  | 37.0  | 24.0  | 3.4 |

Figure 3. Comparison of energy consumption between CV and NEVs (Average State Hypothesis)

Table 5. Comparison of total emission between CV and NEVs (Average State Hypothesis)

| Emission Type         | BEV | HEV | PHEV | CV |
|-----------------------|-----|-----|------|----|
|                       | Tesla model3 | Toyota Levin | BMW 5 PHEV | Nissan Sylphy |
| VOC(g/100Km)          | 18.85 | 36.02 | 8.64 | 7.84 |
| CO(g/100Km)           | 11.26 | 86.03 | 53.00 | 50.00 |
| NOx(g/100Km)          | 8.95  | 9.93  | 37.30 | 20.10 |
| PM10(g/100Km)         | 4.33  | 4.11  | 3.15  | 1.18 |
| PM2.5(g/100Km)        | 1.36  | 1.64  | 1.54  | 0.94 |
| SOx(g/100Km)          | 68.48 | 55.31 | 40.27 | 4.01 |
| CH4(g/100Km)          | 0.45  | 0.50  | 5.36  | 5.03 |
| CO2(Kg/100Km)         | 26.34 | 31.30 | 68.00 | 69.14 |
| N2O(Kg/100Km)         | 0.46  | 0.24  | 0.22  | 0.35 |
| GHG(Kg/100Km)         | 27.48 | 33.37 | 38.41 | 74.00 |
2.3.3. Scenario 3. This scenario is set based on some extreme conditions. For example, under certain circumstances, BEV owners can only charge the vehicle through a domestic 220V power supply in China. This is a relatively inefficient charging mode, and the charging time usually reaches more than 10 hours, the charging efficiency is set at 25%. In this particular scenario, due to the low power of the battery, PHEV models can only run through the internal combustion engine when operating. For CV, set a maximum loading of 500kg. (Table 6)

Table 6. Comparison of energy consumption (MJ /100 km) between CV and NEV (Extreme State Hypothesis)

| Energy Categories     | BEV Tesla model3 | HEV Toyota levin | PHEV BMW 5 PHEV | CV Nissan Sylphy |
|-----------------------|------------------|------------------|-----------------|-----------------|
| Total Energy          | 1022.0           | 1741.0           | 1690.1          | 1284.8          |
| Fossil Fuel           | 440.0            | 772.0            | 794.0           | 606.0           |
| Coal Fuel             | 385.0            | 554.0            | 245.0           | 5.6             |
| Natural Gas Fuel      | 42.0             | 59.0             | 131.0           | 70.0            |
| Petroleum Fuel        | 12.0             | 158.0            | 418.0           | 530.0           |
| Renewable             | 60.0             | 83.0             | 41.0            | 24.0            |
| Biomass               | 7.3              | 11.0             | 4.7             | 22.0            |
| Nuclear               | 7.7              | 11.0             | 7.4             | 1.2             |
| Non Fossil Fuel       | 68.0             | 93.0             | 49.0            | 26.0            |

By comparing the data in Table 7, we can observe that the total energy consumption of NEVs is higher than that of CV. Therefore, in extreme cases, NEV may not be more energy-efficient than CV. Similar to other scenarios, the energy consumed by BEVs is majority in the WTP phase. According to the data in Figure 4, HEV consumes significant amounts of coal in this scenario. Therefore, in terms of policies, NEV cannot be promoted in all cases. However, such promotion should be considered within a specific range under specific user needs and conditions.

In terms of emissions, it can be seen that BEV’s performance in GHG emissions is better than the other three vehicles. This means that under any of the three scenarios, the use of BEV will lead to a reduction in GHG emissions. Another noteworthy result is that PHEV emissions are higher in this scenario. This is because, in CS mode, PHEV cannot rely on electric motors and internal combustion engines as the power source, and can only be driven by internal combustion engines with relatively small displacement. PHEV models are usually equipped with heavier batteries, resulting in heavier body weight, so PHEV can be regarded as a kind of CV in this scenario.

![Consumption of different fuel in scenario 3](image)

**Figure 4.** Comparison of energy consumption between CV and NEVs (Extreme State Hypothesis)
Table 7. Comparison of total emission between CV and NEV (Extreme State Hypothesis)

| Emission Type | BEV Tesla model3 | HEV Toyota Levin | PHEV BMW 5 PHEV | CV Nissan Sylphy |
|---------------|------------------|------------------|-----------------|-----------------|
| VOC(g/100Km)  | 19.76            | 38.58            | 13.98           | 8.01            |
| CO(g/100Km)   | 12.63            | 89.88            | 77.6            | 91.41           |
| NOx(g/100Km)  | 11.75            | 17.81            | 24.5            | 39.42           |
| PM10(g/100Km) | 5.74             | 8.07             | 5.19            | 6.88            |
| PM2.5(g/100Km)| 1.7              | 2.59             | 2.29            | 5.01            |
| SOx(g/100Km)  | 89.06            | 110              | 65.57           | 4.15            |
| CH4(g/100Km)  | 0.62             | 1                | 0.78            | 13.52           |
| CO2(Kg/100Km) | 37.9             | 63.9             | 86.3            | 75.63           |
| PM10(Kg/100Km)| 0.65             | 0.294            | 0.31            | 1.55            |
| PM2.5(Kg/100Km)| 39.43           | 67.01            | 83.37           | 78              |

3. Techno-economic analysis

The previous LCA assessment analysed the consumption and emissions of four car models based on different driving technologies. This section will combine vehicle costs and environmental costs to construct a comprehensive evaluation system for NEVs and CVs. Few studies regarding economic analysis concluded that CV has better economic benefits [12]. The following techno-economic analysis focuses on total cost, including measurement of the cost of environmental pollution and the measurement of the economic costs.

3.1. Environmental pollution cost

The total cost of emitted pollutants (\(C_p\)) was calculated based on the unit cost of pollutants and the amount of pollutants discharged with 10% the discount rate [14][15].

\[
C_p = \Sigma e_i d_i \times (1 + 10\%)^t \quad (2)
\]

where \(e_i\) stands for the total amount of emitted contaminant (kg); \(d_i\) stands for the unit cost of certain contaminant. Table 8 shows the predicted cost (\(€/ton\)) of a certain contaminant in 2000 [16]. Such outdated data can be corrected as follows [12]:

\[
d_i = d'_i R \times \frac{Cost(\frac{e_i}{1000})_{2000 \ China CPI}}{Cost(\frac{e_i}{1000})_{2000 \ China CPI}} \quad (3)
\]

Where \(d'_i\) stands for the unit cost before correction and \(R\) stands for the RMB to Euro exchange rate, up to Oct, 2020, (\(€ = ¥ 7.96\)). CPI (consumer price index) is a macroeconomic indicator that reflects the changes in the price level of consumer goods and services generally purchased by urban and rural households. The CPI in China for Aug 2020 is 104 and for 2000 was 100, respectively.

Table 8. Unit cost of specific air contaminants (Maibach et al., 2008)

| Contaminant | Cost (€/ton) | Cost (¥/Kg) |
|------------|-------------|-------------|
| Nox        | 12594.0     | 100.0       |
| CO2        | 58.0        | 0.5         |
| VOC        | 700.0       | 5.6         |
| PM         | 32570.0     | 259.2       |
| Sox        | 11581.0     | 92.1        |
| CO         | 132.0       | 1.1         |
| N2O        | 6200.0      | 51.3        |
| CH4        | 480.0       | 4.0         |
3.2. Operation cost

The economic cost mainly concentrates on the tangible cost of the proprietor and is an evaluation of consumers buying, using and disposing of cars. This article assumes that private car owners will start using them in 2020 and the cycle will be 10 years, that is, until 2030. In the economic cost calculation, only the cost difference due to the type of car is included in the accounting, so as to compare the difference in the total cost of traditional cars and three types of new energy vehicles. The following model is recommended:

\[ TC = AC + nOC - DC \] (4)

TC: Total Cost stands for the total economic cost of NEVs and CVs in the whole life cycle stage; AC: Acquisition Cost stands for the all one-off costs that consumer used when purchasing the car. nOC: Operation Cost stands for the combination of energy cost, maintenance cost, operating cost, tax and insurance cost, etc. DC: Disposition cost stands for the resale or disposal cost of vehicles.

3.2.1. Acquisition cost. The acquisition cost includes manufacturer's retail price (MRP) and license fee (LF), as well as purchase tax (PT):

\[ AC = MRP + LC + PT \] (5)

\[ PT = \frac{MRP}{1 + 13\%} \times r \] (6)

The manufacturer’s retail price refers to the cost paid to the car manufacturer when purchasing a car. The cost mainly includes the price of auto parts, processing and assembly costs, and design costs. The license fee is mainly the cost of car license, which was assumed to be ¥500. The purchase tax is related to the price of the car. If the consumer buys a domestic private car, the taxable price is the full price paid to the dealer and the extra-price expenses, excluding value-added tax (tax rate 13%), measured in r (10%).

3.2.2. Operation cost. Operation Cost refers to the cost of energy, maintenance, insurance and taxes paid by the owner of the private car when using the car [12][17]:

\[ OC = \sum_{i=1}^{n} \frac{EC + TIC}{(1 + k)^{i-1}} + \sum_{i=1}^{n} MC_i \] (7)

EC: Energy Cost per year; TIC: vehicle and vessel tax and insurance cost, MC: Maintenance Cost.

k: Discount rate (5% in this article)

Energy cost is calculated differently as:

\[ EC(CV) = Oil Price(\frac{¥}{L}) \times Oil Consumption(\frac{L}{hkm}) \times Service life(\frac{hkm}{year}) \times \frac{1}{Efficiency} \] (8)

\[ EC(BEV) = Service life(\frac{hkm}{year}) \times electricity Consumption(\frac{kwh}{hkm}) \times Price(\frac{¥}{kwh}) \times \frac{1}{Efficiency} \] (9)

\[ EC(PHEV and HEV) = Oil Price(\frac{¥}{L}) \times Oil Consumption(\frac{L}{hkm}) \times Service life(\frac{hkm}{year}) + Service life(\frac{hkm}{year}) \times electricity Consumption(\frac{kwh}{hkm}) \times Price(\frac{¥}{kwh}) \times \frac{1}{Efficiency} \] (10)

For tax and insurance in China, On August 1, 2018, the Chinese government required that new energy vehicles and ships that meet the standards be exempted from the vehicle and vessel tax, and that energy-saving vehicles that meet the standards should be levied in half. Total TIC was assumed to be ¥1000 per year. The average service life of a private car in China is calculated to be 239/100km per year [18]. Electricity price from a charging pile in China is ¥1.5 [8].

Maintenance cost due to battery replacement of those NEVs, MC is calculated as:
Battery price is assumed to be ¥50000 each. Gearbox and engine maintenance price is assumed to be ¥50000. Assume the maintenance price start with ¥2000 in the first year, due to the aging of car parts, assume the price increases by 5% every year:

\[ \text{Basic Maintenance Price} = 2000 \times (1 + 5\%)^t \quad (12) \]

### 3.2.3. Disposition Cost

The last stage of the car life cycle is recycling. Assuming that some parts that still have certain value can be resold, the article assumes a depreciation rate of 20%, and a total of 10 years of car life. In China, the resale price of the battery is around ¥8000 [19]. The disposition cost (DC) was calculated as:

\[ DC = \frac{(1 - 20\%)^t \times MRP + 8000}{(1 + k)^t} \quad (13) \]

### 3.3. Results

According to the three scenario assumptions, the environmental pollution cost under the extreme state assumption is the highest (Figure 5), and the social cost of PHEV is the highest regardless of the situation. The cost of BEV is higher (73%) than that of CV under the assumption of Scenario 1, which is the Ideal state. In all other cases, the cost of BEV is the lowest, 84% lower than PHEV (Scenario 1) and 93% respectively. (Scenario 2), 77% (Scenario 3). Compared with CV, the environmental pollution cost of BEV is 69% (Scenario 2) and 51% (Scenario 3) lower respectively. The emission cost of HEV is not much different in the assumptions of Scenario 1 and Scenario 2, but under relatively low charging efficiency, such as 25% set in Scenario 3, the emission cost will increase greatly. Another point is that the environmental pollution cost regarding CV is proportional to the overall emission, which is related to the loading on it.
The disposition cost (DC) shows a downward trend, and the residual value of the four models after 10 years of use (239000km, the car life cycle assumed for this study) has fallen. Among them, the price of battery recycling is relatively low compared to the price of NEVs, so they depreciate more.

![Figure 6. Operation cost among the 4 chosen vehicle models](image)

Meanwhile, it is clearly reported that the total cost (TC) term shows huge differences (Figure 7) among the selected models. One of the reasons among is that the retailing prices of the 4 cars vary within a great difference. Another reason is that the OC differs from model to models. The immature power system technology of NEVs and the high manufacturing cost have caused the high price of electric vehicles. Coupled with the limited range of pure electric vehicles, long charging time, and safety factors in use, electric vehicles have not been widely used. Various reasons make the life cycle cost of NEVs higher than the more mature CV. However, the current research on NEVs advanced power batteries is ongoing, and the manufacturing cost of automotive batteries will gradually decrease with the development of mass manufacturing and technology. [17]. It can be predicted that if the Cp increases, probably the TC of CV will overtake that of NEVs. However, the main pollution caused by NEVs is based on the electricity generation chain, which is highly related to the distribution of China's energy mix. The main point of addressing the issue of vehicle pollution, it is more than important to optimize the energy mix pathway the original source of energy.

![Figure 7. Total cost of the 4 models](image)
4. Discussion
The techno-economic analysis in the previous section shows that HEV has the lowest total cost in the 3 suggested scenarios throughout the lifecycle within the research boundary. Yet, the energy consumptions in 3 scenarios of the HEV are not the lowest. Conversely, in the ideal scenario total consumption of the HEV is the highest, which leads to a significant higher emission of specific gases such as GHG and CO than BEV. This indicates a not sustainable but economical choices of purchasing a HEV. An opposite result can be observed when it comes to BEV, in the average case, the OC of BEV is the second highest after CV. However, it is rather environmentally friendly when evaluating the total energy consumption. The advantage of the BEV’s energy consumption is distinct especially in extreme scenarios, with 40% less consumption comparing with the other two NEV models. The emissions of VOC and CO in the average scenario are much smaller than the other three models, which has a good environmental significance to the air. The PHEV model has the highest TC. This is because the purchase price of the selected model is more expensive, but the OC value of PHEV is not high during the operation phase. However, during the whole life cycle the total energy consumption is high, also, compare with the other 2 NEV models the NOx emission of PHEV is the highest in the 3 scenarios which may cause contaminations. CV produces the most GHG in both ideal scenario and average scenario, indicating the most significant influence on global warming. Meanwhile the OC of the CV is also high compare to HEV which is the most economical one.

5. Conclusions
Under the same energy structure, from the perspective of full life cycle emissions, NEV has the potential and significance for sustainable development in terms of greenhouse gas emissions compared to CV. However, in terms of energy consumption, NEV does not necessarily have a clear advantage over CV. The total energy consumption of PHEV and HEV is assumed to be about 35% higher than CV in the extreme case. It can be estimated that NEV is a potential choice to solve the current global warming caused by excessive greenhouse gas emissions.

In terms of techno-economic analysis, NEV does not have obvious advantages over CV. Only under the assumption of ideal conditions, the total cost of BEV is close to that of CV. In other cases, BEV has a higher total cost than CV. Among NEVs, the total cost of PHEV is higher than CV in all cases. Only the total cost of HEV is lower than CV, but it is not objectively sustainable.

It is believed that the energy structure affects the types and amounts of pollutants emitted. China should actively develop new energy power generation, improve its own energy structure, and enhance NEV’s environmental advantages. Also, the government should introduce relevant support policies to support BEV automakers to improve the charging efficiency and reduce prices; at the consumer level, if budgets are sufficient. In general, PHEV and BEV will be the preferred EV choices because both are (i) more environmentally friendly than HEV and CV, and (ii) their operating costs are comparable to CV.

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7. Appendix

| Categories          | Emission | Categories of contaminate gas Detriments                                                                 | Source                                      |
|---------------------|----------|--------------------------------------------------------------------------------------------------------|---------------------------------------------|
| GHGs                | CO₂      | Global warming contribution approximately 63.7%                                                      | Complete combustion of carbon               |
|                     | Hydrocarbon | Global warming contribution approximately 19.2%                                                      | Incomplete combustion of Fuel               |
|                     | N₂O      | Global warming contribution approximately 5.7%                                                      |                                              |
| Acid Rain Contaminant | NOₓ      | Destroy lung tissue and aggravate respiratory diseases; acid precipitation                            | Nitrogen gas and Oxygen in the cylinder     |
|                     | SOₓ      | Cause lung and cardiovascular diseases, serious harm to plants and water organisms                    | Sulfur-containing organics in gasoline      |
| Particle matter     | PM₂.₅/₁₀ | Exacerbate respiratory diseases and cause bronchitis                                                  |                                              |
| Other Contaminant   | VOC, CO  | Toxicity and carcinogenicity                                                                          |                                              |