Electric vehicle transformation in Beijing and the comparative eco-environmental impacts: A case study of electric and gasoline powered taxis

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Abstract

Tailpipe emissions of gasoline vehicles are one of a main cause of atmospheric environmental problems such as global warming and haze. The substitution of electric vehicles for conventional gasoline vehicles is a promising new way to reduce urban air pollution in many countries such as America, Japan, the EU countries and China. In 2011, Beijing launched a plan that was the substitution of electric vehicles (such as Midi taxis) for gasoline vehicles (such as Hyundai taxis) to low carbon transformations. Our study used local data and LCA based analysis to compare environmental impacts of the transition from Hyundai gasoline vehicles to Midi electric vehicles. We established a life cycle analysis (LCA) model with GaBi6 software and a life cycle assessment integrated model by CML2001 (Problem oriented) and EI99 (Damage oriented) models, which evaluated the comparative environmental impacts of the full life cycle, production stage, use stage and end of life. Finally, we analyzed the key haze-induced factors, key life cycle processes and the sensitivities of lifetime and electric power mix.

Our results indicated that in light of the full life cycle assessment, electric vehicles could play significant role in decreasing the potential of Global Warming, Abiotic Depletion and Ozone Layer Depletion; whereas, electric vehicles also exhibited the impacts for increases in the potential of Acidification, Eutrophication, Human Toxicity and Eco-toxicity (marine aquatic and terrestrial). On the basis of inventory data analysis and 2010 Beijing electricity mix, the comparative results of haze-induced pollutants emissions showed that the full life cycle emission of VOCs from a Midi electric vehicle was lower than a Hyundai gasoline vehicle, but the emissions of PM2.5, NOx, SOx of a Midi electric vehicle were higher than a Hyundai gasoline vehicle. These differences are mainly the result of different emissions during the use stages. In addition, the results of sensitivity analysis indicated that the decreased rate of Green House Gas per kilometer (Midi relative to Hyundai) gradually improved with the increase of lifetime and use of cleaner energy; haze-induced pollutants and carbon emissions from EVs could be reduced significantly with the increased use of cleaner energy.

1. Introduction

Road transportation is one of the essential conditions of economic development for all countries in the world. However, it has also become one of the main air pollution sources in many cities since the 1970s. In many developed countries, vehicle emissions cause 30%–60% of total air pollution (Guo, 2008). Recently, the percentage of air pollutants from vehicle emissions is rising with rapid growth of vehicle number in some cities in developing country. Therefore, the reduction of tailpipe emissions is an effective method to decrease air pollution. As the cleaner candidate of vehicles alternatives, Electric Vehicles are being developed by
many countries. Through governmental initiatives, plans and strategies, EVs are gradually being used instead of gasoline vehicles in America, European countries, Japan, China, etc.

In China, the vehicle ownership approached to 0.26 billion at the end of 2014 and the tailpipe emissions are becoming one of the major sources of air pollution in many cities (Chinese vehicle ownership, 2014). For example, in Beijing, vehicle ownership was approximately 53.7 million at the end of 2014 (Beijing vehicle ownership, 2014), and the carbon emission from vehicles accounted for about 25% and the haze from vehicles accounted for about 31% (The sources of PM2.5 in Beijing, 2014). Therefore, the Chinese government launched a demonstration project named “Ten Cities, Thousands New Energy Vehicles” to reduce the serious air pollution in 2009. As the project’s priority pilot city, Beijing started a promotion plan to use electric taxis instead of gasoline taxis in 2011. Until 2013, 950 EV taxis served 8 suburbs of Beijing such as Yanqing, Fangshan and Daxing. Table 1 shows the plan of action of EVs in Beijing from 2014 to 2017. According to the plan, it is anticipated that all of the taxis in suburbs would be electric taxis and most new taxis in urban area would be electric taxis by 2017 (Action plan of EV in Beijing (2015)). Besides, there are a basket of plans for building infrastructures and a package of priority policies for promoting. However, whether such plan can resolve all pollution problems from traditional vehicles is still unknown.

Even though EVs are cleaner vehicles because of zero emissions during the driving process, the environmental impacts in their full life cycles are still controversial. Prior studies determined that some of the environmental impacts from EVs were transferred from use phase to production phase of vehicles and electricity (Lave et al., 1995; Ai et al., 2010; Zhang, 2011; Hawkins et al., 2012). Since the 1990s, researchers focused on the environmental impacts of electric vehicles (Wang et al., 1990; Vimmerstedt et al., 1995; Campanari et al., 2009; Huo et al., 2010; Baptista et al., 2011; Cooney et al., 2013; Nanaki and Koroneos, 2013). The main research scales included the fuel life cycle, the engine life cycle, the vehicle key parts life cycle and the vehicle full life cycle. For example, some researchers analyzed the energy saving and emission reduction by using GREET and G3EM model et al. (Delucchi, 1991; Hackney and De Neufville, 2001; Ou et al., 2010; Yagcitekin et al., 2013; Shi et al., 2013); Other researchers investigated the full life cycle impact of EVs by using the Recipe models (Hawkins et al., 2012; Zhang et al., 2013; Röder, 2001; Wagner et al., 2006); Moreover, the environmental impacts of EVs on air quality, eutrophication; global warming and human toxicity were also studied in some parts such as tires, brakes and storage batteries, and infrastructure of EVs (Zackrisson et al., 2010; Xu, 2010; Wang, 2012; Stampa et al., 2012; Lucas et al., 2012; Heymans et al., 2014).

It is undeniable that the existing studies are revealing some environmental impacts of EVs gradually. However, the following points still need to be addressed further: (1) Localized inventory data are still a challenge for the full life cycle assessment. (2) Many of the existing researches focus on the impact of each life cycle phase but neglect the impact sources analysis. (3) Considering the time and spatial difference, it is necessary to study special analysis for local environmental problems and make the targeted strategies.

To address these problems and to clarify the environmental impacts of EV taxis in Beijing, our study compared the life cycle impacts between an EV taxi (Midi) and a GV taxi (Hyundai) and developed the strategies for the future management. Based on Beijing’s EVs promotion plan and aiming to electric taxis transformation, we started with the boundary and data of the research that introduced research scope and the data sources with their characteristics, as well as data estimation and allocation (Section 2). We then proposed our analysis method that included LCA framework, analysis models and software support (Section 3). In Section 4 we discussed the research results of each phase and full life cycle and sensitive analysis. We drew with five important conclusions in Section 5. Our conclusions provide not only a targeted and efficient guide for Beijing’s EV promotion plan, but also offer detailed and useful information for the development of EVs in other cities.

2. Boundary and data

2.1. System boundary

Our research subjects were Beijing Midi EV taxi and Beijing Hyundai GV taxi. The research boundary was shown in Fig. 1. The research boundary consisted of whole life cycle of the vehicles, which included the production phase that contains raw materials preparation, vehicle production, the use phase that contained energy use, battery exchange, tire exchange and tire wear, and the end of life that contained waste battery, reused parts and main waste materials. As data limitation, our data did not include transportation, infrastructure, maintenance and sales. The function unit in our research was 1 km. The lifetime of taxi is 5.0 × 10^5 km (investigation data).

2.2. Inventory

2.2.1. Data sources

We obtained our data from several sources that included enterprise investigations, documents (published papers and yearbooks) and industrial reports. Data regarding vehicle manufacture processes, power system production, energy production and consumption of use phase, and vehicle disassembly process were obtained from investigations of vehicle enterprises, published papers (Zhang et al., 2013; Gu, 2011) and the database of GaBi6. Steel, iron and aluminum used were obtained from the database of GaBi6.

<table>
<thead>
<tr>
<th>Items</th>
<th>Number</th>
<th>Time</th>
<th>Location</th>
<th>Infrastructure</th>
<th>Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>Many taxis</td>
<td>2017</td>
<td>Suburb</td>
<td>Public charging net</td>
<td>(1) Subsidy: 1:1 for public car and Maximum 120000 Yuan for private cars</td>
</tr>
<tr>
<td>Some new taxis</td>
<td>From Urban</td>
<td>2014</td>
<td>districts</td>
<td>(1) Fast charging piles:</td>
<td>(2) Needn't Drawing lots</td>
</tr>
<tr>
<td>Bus</td>
<td>About 4500</td>
<td>2017</td>
<td>The city</td>
<td>10000(Public business area)</td>
<td>(3) No limit days for driving</td>
</tr>
<tr>
<td>Official</td>
<td>Some new vehicles should be new energy</td>
<td>From The city</td>
<td>1000 (parking in airport)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>vehicles</td>
<td>2014</td>
<td>5 km area range charging network with fifth cycle road</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private Car</td>
<td>About 170000</td>
<td>2017</td>
<td>The city</td>
<td>2:1 for Bus and 3:1 for taxi</td>
<td>(2) 3 big Charging and change stations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18% rate of parking space for charging pile of private cars in public community</td>
<td></td>
</tr>
</tbody>
</table>
Although the data from GaBi6 may have some deviation from local data, our comparative results should not be affected by it.

2.2.2. Data explanation and estimation

Unique data regarding battery and tires exchange and the electricity within a life cycle were explained in Table 2. Also, some data should be estimated according to the location ratio. Our research used two types of ratios: the "mass ratio" and the "surface area ratio". The "mass ratio" estimated the consumption quantity of electricity and raw materials such as steel during stamping and welding process in the vehicle body production phase; The "surface area ratio" estimated the raw materials such as the conditioners for metal surfaces, absorbent agents and bottom coatings or pollutants in waste waters such as COD, BOD and Oil during painting process in the body production phase. Also, certain data in production of parts and in final assembly and disassembly processes were still estimated by the "mass ratio".

3. Research methods

3.1. Method framework

Our research was based on the LCA method framework that included goal and scope definition, inventory collection and description, life cycle impact assessment, analysis and interpretation, and life cycle based management strategies (Fig. 2). We used GaBi6 software to develop a model for the analysis. The inventory database was established by GaBi6 database and from local supplemental data that included input and output data of raw materials and energy. Based on the damage oriented and environmental problem oriented analysis, the key processes and materials that led to the damage and problems were identified. In addition, the sensitivities of lifetime and electricity mix were also determined.

3.2. Gabi based analysis model

According to our boundary data and by use GaBi6 software, a plan-process-flow life cycle analysis model is set forth in Fig. 3. The plan includes two sub-plans which are a group of processes. Plans are built up by inserting processes or other plans. Processes refer to craftworks of production process, use process and discharge process. Process chains can be set-up by Plans. Processes are used to description input and output flows. The flows are used to describe mass, energy, costs by value. The flows are the linking between the processes.

3.3. Environmental impact models and indicators

Currently, the damage oriented and problem oriented are two types of LCA impact assessment models used for different analyses. Generally, the EI99 model is used for the damage oriented analysis and the CML2001 model is used for the problem oriented analysis. The EI99 model includes three damage categories: resources, ecosystem quality and human health. For resources damage analyses, the impact categories include fossil fuels and minerals. For ecosystem quality analyses, the impact categories include acidi- fractionation, eco-toxicity, land use and land conversion. For human health analyses, the impact categories include carcinogenic effects, climate change, radiation, ozone layer depletion and respiratory. The EI99 analysis includes inventory analysis, characterization (fate, exposure, effect and damage analysis), normalization and weighting. The CML2001 model includes 10 environmental impact categories that contain abiotic depletion potential-ADP, acidification potential-AP, eutrophication potential-EP, freshwater aquatic eco-toxicity potential-FAETP, global warming potential-GWP, human toxicity potential-HTP, marine aquatic eco-toxicity potential-MAETP, ozone layer depletion potential-ODP, and...
photochemical ozone creation potential-POCP and terrestrial eco-toxicity potential-TETP. The CML2001 analysis process includes inventory analysis and characterization.

In our research, we used the EI99 and the CML2001 for damage and problem analysis respectively (Fig. 4). We also analyzed key hazed-induced factors by using inventory data, as well as the sensitivity of electricity mix and lifetime based on the CML results.

4. Results and discussions

According to the inventory data obtained from mixed data sources and the Gabi6 software, we analyzed energy consumption, pollutant emissions and environmental impacts, and then concluded some important results as followings. As the spatial and
time difference, some inventory data such as electricity might be slightly updated in future.

4.1 Inventory analysis

According to the inventory, we compared the main input and output materials between the vehicles (the EV and the GV). The input materials included energy and special metals, and the output materials included CO$_2$, CO, BOD, SS, chlorine and induced haze factors (PM$_{2.5}$, NO$_x$, SO$_x$, VOCs, NH$_3$).

As shown in Fig. 5, the energy consumption was as follows: let the larger number was 100%, the Midi EV decreased in oil consumption by approximately 97% compared to the Hyundai GV, but the Midi EV also exhibited an increase in 95% of hard coal and 47% of natural gas consumption. In addition, the Midi EV also had additional raw material consumption of metal Lithium.

The Midi EV exhibited decreases in such pollutants emissions as CO$_2$, CO, BOD, SS and Chloride comparing the Hyundai GV. Meanwhile, for the induced haze factors (PM$_{2.5}$, NO$_x$, SO$_x$, VOCs, NH$_3$), Fig. 6 shows that, from the life cycle perspective, except decrease in VOCs, the Midi EV exhibited increases in PM$_{2.5}$, NO$_x$, SO$_x$, NH$_3$. The decrease in VOCs mainly resulted from the zero emission in driving process, and increases in other haze factors mainly caused by the emission increases in production phase, especially in power production process. For example, during the use phase, emissions from power energy production of the Midi EV were more than the emissions from tailpipes and the power energy production of the Hyundai GV. During the production phase, the electric consumption of the Midi EV was more than that of the Hyundai GV mainly because of the production of batteries.

4.2 Problems oriented analysis

To compare the difference of environmental impacts between the two vehicles (the EV and the GV), we analyzed 10 environmental impacts on five dimensions that included full life cycle, production phase, use phase, end of life and key processes by the CML2001 model. The sensitive analyses were also determined to reveal the influence by electric power mix.

4.2.1 Comparative full life cycle analysis

According to the characterization results, the relative proportion equaled to the percentage of that the smaller number divided the larger one. Here, let the larger number to be 100%, these relative proportions were pictured in Fig. 7. The results indicated that the Midi EV decreased the full life cycle impact of abiotic depletion potential, global warming potential, and ozone layer depletion potential and photochemical ozone creation potential. The Midi EV exhibited 50% decrease in GWP compared to the Hyundai GV mainly because of the 56% decrease in GWP during the use phase. Also, the Midi EV decreased 96% of ODP because of significantly reduction in ODP both in the use stage and production stage. The decreases in ADP and POCP from the Midi EV all came from the reduction of them in the use stage. However, the Midi EV also exhibited increases in acidification potential, eutrophication potential, freshwater aquatic eco-toxicity potential, human toxicity potential, marine aquatic eco-toxicity potential, and terrestrial eco-toxicity potential. The reasons came from the increases of these impacts potential in the production stage and the use stage: in the production stage, the impact of acidification potential, eutrophication potential, marine aquatic eco-toxicity potential, freshwater aquatic eco-toxicity potential, human toxicity potential, and terrestrial eco-toxicity potential from the Midi EV increased relative to the Hyundai GV because of the emission impact from the electricity supply, and motor and battery production. In the use stage, the impact of acidification potential, eutrophication potential, marine aquatic eco-toxicity potential, freshwater aquatic eco-toxicity potential, human toxicity potential, and terrestrial eco-toxicity potential from the Midi EV increased relative to the Hyundai GV because of electricity production.

4.2.2 Comparative analysis in production stage

Fig. 8 shows the comparative proportion of characterization values of two vehicles in production stage. While the results showed that Midi EV exhibited distinct decrease in ODP compared to the Hyundai GV, the Midi EV also increased in ADP, AP, EP, GWP, MAETP, TETP, HTP and POCP. These differences are result of the power consumption between two vehicles. During the production phase, the electric power consumption of the Midi EV is more than that of the Hyundai GV. Further, since coal power is the main power in China, the electric power production may increase the emissions of SO$_2$, NO$_x$, CO$_2$ and CH$_4$.

4.2.3 Comparative analysis in use stage

Zero tailpipe emission is the well-known contribution for the Midi EV during the use stage. Whereas, from life cycle angle, we provided more rich information through comparing the proportion of characterization values of two vehicles in use stage (Fig. 9): one of the most important contributions from the Midi EV was decreasing about 56% GWP comparing to Hyundai GVs in this stage. Also, the Midi EV exhibited distinct decrease in ADP, ODP and POCP respectively. However, the Midi EV also exhibited a clear increase in AP, EP, FAETP, MAETP, HTP and TETP respectively. Analyzing the reasons in detail, we found that the main reasons came from the difference of tailpipe emissions and driving power. For the Midi EV, tailpipe was zero and the main driving powers were coal and natural gas that emission pollutants include SO$_2$, NO$_x$, CO$_2$, CH$_4$, NMVOC, and V$^{1+}$, Ni$^{2+}$ and Se. However, for the Hyundai GV, gasoline production and tailpipe emission were the primary sources of environmental impacts in the use stage. Tailpipe emissions included some pollutants such as CO, NO$_x$, SO$_2$, PM; and the main power was gasoline that emission pollutants included CH$_4$, SO$_2$, NO$_x$, NMVOC, V$^{1+}$, Ni$^{2+}$ and Ba.

4.2.4 End of life analysis

At the end of life stage, many scrap materials such as steel, aluminum, copper, plastic, rubber and glass could be collected and recycled. In this situation, both the EV and the GV decreased in all impacts categories because of recycling, especially in ODP, AP, EP, GWP, HTP, MAETP, and TETP. Because wastes are used as the recycling materials, it is beneficial to both decrease environmental impacts and to save the raw materials.
4.2.5. Key processes contribution analysis

To analyze and effectively manage environmental problems of the life cycle, we defined six key processes: 1) power system production in the production phase; 2) non-power system production in the production phase; 3) oil and electricity production in use phase; 4) tailpipe emissions in use phase; 5) tire exchange or wear in use phase; 6) disposal and recycling after end of life.

From life cycle perspective, the use phase was the main factor that influenced the environmental impacts such as ADP, AP, EP, FAETP, POCP, HTP, TETP, GWP and ODP, which accounted for more than 50% of the full life cycle impacts for both vehicles. Production phase was the main factor that influenced MAETP for the Hyundai GV (Fig. 10). The end of life most likely contributed to a decrease in the impacts for both vehicles.

For the production phase, we analyzed two key processes that included power system production and non-power system production. Fig. 10 showed that the main impact sources of both vehicles are different. For the Midi EV, the power system production was the main contribution factor of its environmental impacts such as AP, EP, FAETP, GWP, HTP, MAETP, POCP and TETP, which accounted for more than 50% of its total impacts in the use stage. The impacts of AP and EP accounted for more than 80% of its total impacts in the use stage. The emissions of SO2 and NOx during battery manufacturing were the sources for the impacts of AP and EP. The impacts of HTP, MAETP, POCP and TETP were mostly from the production of electricity for the battery assembly. For the Hyundai GV, the non-power system production was the main contributor of ADP, AP, EP, GWP, HTP, POCP and ODP, which accounted for more than 80% of its total impacts in production stage. The coating process in car body production was the main contribution process for the impacts of AP, EP, GWP, HTP and POCP. The chassis production was the main contribution process for the impacts of ADP and MAETP.

We set three key processes for the use phase analysis, which included oil and electricity production, tailpipe emissions and tire exchange or wear. Just as in the production phase, the main
influential processes of the two vehicles were different (Fig. 10). For the Midi EV, the production of electricity for driving was the main contribution factor of the environmental impacts such as ADP, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, and TETP, which accounted for more than 90% of its total impacts in the use phase. For the Hyundai GV, tailpipe emission was the main factor causing POCP, GWP and EP impacts, which accounted for more than 60% of its total impacts in the use phase. Gasoline production was the main factor causing ADP, AP, FAETP, HTP, MAETP, ODP and TETP, which accounted for more than 60% of its total impacts in the use phase.

For the end of life, all impacts score of two vehicles were negative, which meant good environmental benefits. Many collecting and disposal materials were the same for both vehicles but for the power system. For the Midi EV, the power system was motor and power battery. For the Hyundai GV, the power was engine. Therefore, the benefits were different. The Midi EVs exhibits more benefit on ADP, GWP and POCP.

4.3. Damage oriented analysis

To compare the differences in damage between the Midi EV and the Hyundai GV, we use the EI99 model to analyze the three impact categories that include resources, human health and ecosystem quality. Resource depletion was expressed as the surplus energy needed for future extractions of minerals and fossil fuels; Ecosystem quality is expressed as the loss of species over a certain area during a certain time. Human health was expressed as Disability Adjusted Life Years (DALYs). Each impact or damage category indicator result was multiplied by the corresponding weight factors and was added to create a total or single score.

As shown in Fig. 11, the results showed that the Midi EV exhibited a 36% decrease in its full life cycle environmental impact. The contribution came from the 76% decrease in resources impact (especially lower fossil fuel consumption in use stage). However, the Midi EV also had the 67% increase in ecosystem quality and the
43% increase in human health. The main source affecting ecosystem quality was the eco-toxicity from heavy metals emissions in the process of producing power system and electricity. For human health, damage came from nonorganic respiratory impacts from coal power emissions.

Fig. 12 displays the impact scores of impact categories between the Midi EV and the Hyundai GV. We analyzed the environmental impact differences between the two vehicles in detail. Fossil fuel consumption was the main factor that decreased the impact from the Midi EV. The score of fossil fuel consumption from the Midi EV decreased 78% compared to that from the Hyundai GV since the Midi EV is powered by electricity and the Hyundai GV is powered by gasoline. In addition, the score regarding minerals from the Midi EV also increased 85% compared to that from Hyundai GVs because Midi EV consumed new materials such as Lithium while the Hyundai GV didn’t need. To the ecosystem damage, acidification/eutrophication was the main influential factor for the Hyundai GV and Eco-toxicity is the main influence factor for the Midi EV because of the differences in key processes and emissions of both vehicles. The heavy metals from the production of the power system and the production of electricity were the main pollutants that led to eco-toxicity, NOx, SOx and NH3 from the production of petroleum were the important pollutants that led to acidification/eutrophication. For human health, climate change was the major influential factor for the Hyundai GV and non-organic respiration was the main influential factor for the Midi EV, which all accounted for more than 90% of the damage impact of two vehicles. Non-organic respiration was the main influential factors that caused the impact difference between the Midi EV and the Hyundai GV. As particles were emitted from the production of electricity that supports EVs driving, the Midi EV exhibited a 70% increase in non-organic respiration compared to the Hyundai GV. This factor determined that the impact score of human health of the Midi EV was larger than that of the Hyundai GV.

4.4. Sensitivity analysis

To improve policies for controlling green house gasses and haze-induced pollutant emissions, we conducted the sensitivity analysis of key factors. Our key factors were vehicle lifetime, electric power mix and battery lifetime because they are the main effect factors of emissions per unit.

4.4.1. Sensitivity analysis of vehicle lifetime

We set the vehicle lifetime to be $5.0 \times 10^5$ km. The lifetime could be theoretically a scope from 0 to $5.0 \times 10^5$ km. Here, we choose 8 lifetimes for the sensitivity analysis, which included $1.0 \times 10^5$ km, $1.5 \times 10^5$ km, $2.0 \times 10^5$ km, $2.5 \times 10^5$ km, $3.0 \times 10^5$ km, $3.5 \times 10^5$ km, $4.0 \times 10^5$ km and $5.0 \times 10^5$ km. Fig. 13 displays the trend of carbon emission changes with the vehicle lifetime.

From Fig. 13, we found the following rules: for both the Midi EV and Hyundai GV, the trend of the carbon emission per km declined with the increase of lifetime. Meanwhile, the degree of decline was different for the two kinds of vehicles. With the lifetime changed from $1.0 \times 10^5$ km to $5.0 \times 10^5$ km, the carbon emission per km declined from 0.16 kg to 0.10 kg and the declination rate was 38% for MidiEVs. The carbon emission per km declined from 0.22 kg to
0.21 kg and the down rate was 4.5% for the Hyundai GV.

Therefore, for the sensitivity of vehicle lifetime to carbon emission per km, the Midi EV was more sensitive than that of the Hyundai GV because of the emission decreases in the use phase for the Midi EV. From life cycle perspective, the contributions from the production stage and the end of life declined as the lifetime increased. On the contrary, the contribution from the use phase increased. Therefore, the Midi EV had carbon emission increases in production stage but significant decreases in the use stage compared to the Hyundai GV. As such, the benefit of carbon emission reduction from the Midi EV will increase as the lifetime increases. Fig. 14 shows the trend of carbon emission reduction increases with the lifetime from $1.0 \times 10^3$ to $5.0 \times 10^3$ km. Compared to the Hyundai GV, the benefit of the carbon emission reduction increased from 29% to 50%. These rules were the same as the rules drawn by Hawkins research (Hawkins et al., 2012).

4.4.2. Sensitive analysis of electricity mix

The electricity structure (mix) was another key factor that affected the emissions per km of the vehicles. We choose carbon and haze-induced factors as the affected emissions factors. We set 4 scenarios for the sensitivity analysis of the electric power mix and carbon emissions, and 5 scenarios for the haze-induced factors: 1) Scenario 1 was the 2010 electricity mix of Beijing; 2) Scenario 2 was the 2015 electricity mix of Beijing; 3) Scenario 3 was the planned electricity mix of Beijing in 2017; 4) Scenario 4 was the planned electricity mix of Beijing in 2020; 5) Scenario 5 was the planned electricity mix of local power generation in Beijing in 2017.

From Table 3, we knew that the cleaner energy proportion increased and coal power proportion decreased from Scenario 1 to Scenario 4. From Fig. 15, we found that the benefit of carbon emission reduction increased from 50% to 53%. Therefore, we concluded that improving the cleaner energy proportion was beneficial to increase the benefit of carbon emission reduction of EV.

We chose PM$_{2.5}$, NO$_x$, SO$_x$, NH$_3$ and VOCs as the key haze-
induced factors (He et al., 2013). According to the inventory analysis, the VOCs emission quantity from Midi EV was lower than that from the Hyundai GV while the Midi EV exhibited increases in all other haze-induced factors. To analyze the emission trends with the changes of the electricity mix for effective management, we added scenario 5 (see Table 3).

**Fig. 16.** The difference changes of haze-induced factors between the Midi and Hyundai.

Table 3

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Coal power</td>
<td>78.57%</td>
<td>67.55%</td>
<td>60.66%</td>
<td>59.67%</td>
<td>–</td>
</tr>
<tr>
<td>Natural gas power</td>
<td>10.43%</td>
<td>24.75%</td>
<td>30.94%</td>
<td>29.80%</td>
<td>80.41%</td>
</tr>
<tr>
<td>Hydro power</td>
<td>3.69%</td>
<td>3.03%</td>
<td>3.32%</td>
<td>3.67%</td>
<td>2.76%</td>
</tr>
<tr>
<td>Pumped storage power</td>
<td>4.30%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Wind power</td>
<td>2.56%</td>
<td>3.13%</td>
<td>3.36%</td>
<td>4.48%</td>
<td>3.31%</td>
</tr>
<tr>
<td>Solar power</td>
<td>–</td>
<td>0.77%</td>
<td>0.96%</td>
<td>1.23%</td>
<td>2.76%</td>
</tr>
<tr>
<td>Waste heat</td>
<td>0.26%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Biomass energy</td>
<td>0.19%</td>
<td>0.77%</td>
<td>0.96%</td>
<td>1.15%</td>
<td>2.76%</td>
</tr>
</tbody>
</table>

**Fig. 15.** Carbon emission reduction changes from Scenario 1 to Scenario 4.

Fig. 16 shows that the different fluctuation of haze-induced factors between the Midi EV and the Hyundai GV under the 5 scenarios. From Scenario 1 to Scenario 5, with the decrease of coal power proportion and the increase of new energy proportion, the difference of all emissions except NH3 declined and the degree of declination in the Scenario 5 was most significant. The difference change of NH3 was not obvious. Further, in Scenario 5, the difference of SOx was negative, the differences of PM2.5 approached to zero, and only the difference of NOx was still positive. If the difference value was negative, then the emission of the Midi EV was less than the Hyundai GV. If the difference value was positive, then the emission of the Midi EV was more than the Hyundai GV.

We concluded the followings from the sensitivity analysis of electricity mix. With the proportion of decrease of coal power, the emission reduction of the Midi EV on haze-induced factors was distinct. For SOx, the decreased effect was the highest. If the proportion of coal power was decreased to less than or equal to 28%, the emissions from the Midi EV were lower than the Hyundai GV (Fig. 17). For PM2.5, the decreased effect was good. When we replace coal power with natural gas, the deference of the emission (between Scenario 5 to Scenario 1) was reduced by 90%. For NOx, the decreased effect was limited. From Scenario 5 to Scenario 1, the deference of the emission was only reduced by 50%; For NH3, the decreased effect was not obvious. Overall, decreasing the coal power proportion and increasing cleaner energy (natural gas) proportion was beneficial to the emission reduction of EVs. Further, suitable proportion was the key to improving the reduction effect.

### 4.4.3. Sensitive analysis for battery lifetime

According to the above analysis of key processes, battery production was one of the principle sources of pollution from the Midi EV. Therefore, battery lifetime may impact the emissions of the Midi EV. We used carbon emission as an example, and analyzed the sensitivity of the battery lifetime. Under the existing technology, the life cycle of the Lithium iron phosphate battery is 1500 to 2000 times (Wang, 2011) and the continued driving range for a full charged battery is 100–300 km (Yu and Shi, 2010). Therefore, the range of a battery lifetime was $1.5 \times 10^5$–$6.0 \times 10^5$ km.

We established four scenarios based on the driving range of a battery during the lifetime of an electric vehicle for the analysis. Scenario 1 used 4 batteries during the lifetime of an electric vehicle. The driving range of a battery was $1.50 \times 10^5$–$1.66 \times 10^5$ km; Scenario 2 used 3 batteries during the lifetime of an electric vehicle. The driving range of a battery was $1.67 \times 10^5$–$2.49 \times 10^5$ km; Scenario 3 used 2 batteries during the lifetime of an electric vehicle. The driving range of a battery was $2.5 \times 10^5$–$4.99 \times 10^5$ km; Scenario 4 used 1 battery during the lifetime of an electric vehicle. The driving range of a battery was $5.0 \times 10^5$–$6.0 \times 10^5$ km.

We analyzed the benefits of carbon emissions reduction from three processes shown in Fig. 18. We found that the carbon emission reduction increased for all three processes from Scenario 1 to Scenario 4 and the most obvious increase was the process of the power system production. In addition, for the power system production and total production phase, from Scenario 1 to Scenario 3, the value of emission reduction was negative, which meant...
emissions from the Midi EV was larger than that from the Hyundai GV, but the value changed to positive from Scenario 3 to Scenario 4. Therefore, the carbon emissions from the power production or the total production phase of the Midi EV would be lower than that from the Hyundai GV if only one battery was used during the lifetime of the electric vehicle.

5. Conclusions

Electric vehicles substitution for traditional gas vehicles is the trend for sustainable transportation. The management of the transition is the important prerequisite to promote its ameliorating role on the eco-environmental issues. Meanwhile, assessment is of vital importance for efficient management. Based on life cycle thinking and the example of Beijing electric taxi transformation, we conducted a life cycle assessment and sensitivity analysis, and developed analytical methods that included problem and damage oriented models. We also concluded as followings: (1) From the full life cycle perspective and based on 2010 Beijing electricity mix, the environmental impact of the Midi EV was less than the Hyundai GV, which was the result of lower fossil fuel consumption during the use phase. The role of carbon emission reduction was significant. Nevertheless compared to Hyundai GV, the Midi EVs also exhibited the potential for increases in ecosystem quality impacts with eco-toxicity and acidification/nitrification, as well as human health influence with inorganic respiratory. (2) Electricity production in the use stage, and electric motors and batteries production in the production stage were the key processes for controlling environmental impacts during EV management. (3) Improving the proportion of cleaner energy was beneficial to control the emissions of haze-induced pollutants. Prolonging the lifetime of the EV and the lifetime of the battery were helpful to reduce carbon emission. (4) Cleaner electricity, efficient electric motors and long lifetime batteries, and cleaner electric motor and battery production were crucial to improving environmental benefits from the EV transition. (5) It was necessary to study both the benefits and risks of the transformation. Our work not only provides a targeted and efficient guide for the EV promotion plan in Beijing but also provides detailed and useful information for EV development in other cities.

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