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Life cycle environmental assessment of charging infrastructure for electric vehicles in China

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ABSTRACT

This study presents a comprehensive environmental analysis of the four main types of chargers for electric vehicles (EVs) in China to evaluate the energy consumption and greenhouse gas emissions in their manufacturing, use, and end-of-life stages. The changes in the global warming potential (GWP) of chargers during 2020–2040 are also projected by scenario analysis, considering the electricity mix, types of chargers, and the ratio of vehicle and charger quantities as the three key factors. The results show that the home charger has the lowest cumulative energy demand (CED) and GWP, followed by public alternating current (AC) and direct current (DC) chargers, and the public mix chargers (integrating both AC and DC). The CED of single charger is 1.36 MJ/kWh, accounting for 2.43% of the results of EVs, and the GWP is 94.06 g CO_2 e/kWh, accounting for 1.89% of those of EVs. The developing and developed stages of China's future charger installation are differentiated in this study. In the developing stage, the proportion of GWP of chargers to that of EVs ranges from 1.31 to 3.28% in 2030 and 1.01–6.06% in 2040, while, in the developed stage, it ranges from 1.16 to 2.90% in 2030 and 0.89–5.36% in 2040. In future charger development plans, it is strongly recommended to consider the environmental burdens of different charger types, and encourage the use of home and public AC chargers. Policy makers of EVs and charger development are recommended to pay attention to the ratio of vehicle and charger quantities. As determined in by our study, it is unnecessary to pursue the uncontrolled increase in the number of chargers.

1. Introduction

Conventional internal combustion engine vehicles (ICEV) not only consume a large amount of fossil resources, but also emit gases to the atmosphere, such as carbon dioxide, hydrocarbons, carbon monoxide, and nitrogen oxides (Tie and Tan, 2013). Despite their widespread use worldwide, ICEVs contribute to large energy consumption, great greenhouse gas emissions, and severe air pollution. Electric vehicles (EVs, including battery (BEV) and plug-in hybrid electric vehicles (PHEV)) are powered by a battery pack, thus considerably decrease gas emissions and enhance fuel efficiency during operation (Yong et al., 2015). Recently, EVs have been widely promoted as an ideal alternative to ICEVs in many countries (da Silva and Moura, 2016; Taefi et al., 2016; Vidhi and Shrivastava, 2018; Zheng et al., 2012).

At the end of 2017, China had the largest EV market with over 1.7 million EVs, 1.5 million of which were BEVs (China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, 2018). According to the “The Development Plan for the Industry of Energy-Efficient Vehicle and New Energy Vehicle (2012–2020)”, the sales of five-million new-energy vehicles (including hybrids and EVs) will be achieved by 2020 (China State Council (CSC, 2012). However, the production and transportation of electricity may use more energy, and emit CO_2 and other gases (Lave et al., 1995). Thus, assessing the environmental influence of EVs has become a topic of great interest (Hawkins et al., 2012, 2013; Samaras and Meisterling, 2008). Many studies have assessed the environmental impacts of EVs to provide scientific support to the government's future transportation plans in different regions, such as China (Hao et al.,

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2017; Huo et al., 2010), the U.S.(Noori et al., 2015; Tamayao et al., 2015), European countries (Buekers et al., 2014; Casals et al., 2016), Canada (Kantor et al., 2010), Australia (Wolfram and Wiedmann, 2017), South Korea (Choi et al., 2018), and India (Vidhi and Shrivastava, 2018). However, most studies only focused on the environmental burdens of the EVs without considering those of other supporting facilities, such as the charging infrastructure.

The batteries of EVs require charging over time, thus, the development of charging infrastructure for EVs is also important (Yong et al., 2015). There are two types of charging infrastructure in the market, i.e., the charging point (charger) and the charging station. The chargers connect automobiles to the grid by providing alternating or direct currents, and a charging station can be simply regarded as a combination of several chargers. Therefore, this study regards chargers as the charging infrastructure of EVs. China has launched a series of policies to propel the development of charging infrastructure from 2015. According to the “Guide to the Development of Electric Vehicle Charging Infrastructure”, more than 4,800,000 chargers will be installed in 2020 to meet the requirements of future electric vehicles (National Development and Reform Committee (NDRC, 2015). With strong governmental support and a high electric vehicle volume, China had installed over 445,700 chargers by the end of 2017 (China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, 2018), which represented almost half of the global charger supply.

There are four types of chargers in China: home chargers, public AC chargers, public DC chargers, and public mix chargers. The home and public AC chargers provide 7–40 kW of alternating current output and take several hours to charge one battery pack. DC chargers, however, provide 60–360 kW of direct current output, and their charging time is less than half an hour. Public mix chargers integrating AC and DC can provide both direct and alternating currents. The main characteristics of these four types of chargers are presented in Table 1.

Recent studies on the charging infrastructure of electric vehicles mainly cover aspects such as improving charging technology (Du et al., 2010; Kuperman et al., 2013), the relationship between infrastructure density and EV uptake (Harrison and Thiel, 2017; Sierzchula et al., 2014), planning optimal installation locations (Dong et al., 2014; Frade et al., 2011), and cost-effectiveness analysis of the installation and use stages (Bi et al., 2017; Peterson and Michalek, 2013). However, the energy consumption and environmental influence of the charging infrastructure have not been discussed in depth, especially from the view of the whole life-cycle of charging infrastructure, covering manufacturing, use, and end-of-life.

Life-cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's or service's life-cycle, i.e., from raw material acquisition to waste management via the production and use phases (ISO, 2006). Businesses and government policies can utilize the LCA method to assess their supply chains more systematically (Gharaei et al., 2019a; Gharaei et al., 2019b, c; Gharaei and Pasandideh, 2016, 2017a, b; Gharaei et al., 2018; Gharaei et al., 2017; Helbig et al., 2016; Hoseini Shekarabi et al., 2018; Pasandideh et al., 2015). Also, a comprehensive survey of the energy consumption and environmental burdens of electric vehicles can be performed in detail using LCA (Choma and Lie Ugaya, 2017; Huo et al., 2010; Ma et al., 2017; Mousazadeh et al., 2009; Zackrisson et al., 2010). In this research field, some studies have compared the environmental impacts of EVs with those of conventional vehicles (Faria et al., 2012; Hawkins et al., 2013), some have focused on the LCA of the lithium battery packs used in EVs (Majeau-Bettez et al., 2011; Zackrisson et al., 2010), and some have discussed the influence of electricity generation on the sustainability of EVs in detail (Faria et al., 2013; Rangaraju et al., 2015). However, only few LCA studies on EVs considered supporting facilities.

Chester and Horvath (2009) suggested that the infrastructure and supply chains should also be considered in the LCA of passenger transportation. Their analysis selected traditional fuel vehicles, trains, and airplanes as objectives, and comprehensively calculated the associated energy consumption, GHG emissions, and other three typical air emissions. Van Vliet et al. (2011) proposed a life-cycle cost and GHG emissions analysis on electric vehicles considering two charging patterns: uncoordinated and off-peak. Their results showed that the off-peak charging pattern reduced the GHG emissions and EV charging price from those of the uncoordinated pattern. Traut et al. (2012) proposed an optimization model to minimize the annual life-cycle GHG emissions and costs from the personal vehicle fleet. Two charging modes were compared, home charging and workplace charging. The results showed that workplace charging does not reduce GHG emissions significantly. However, workplace charging provides additional GHG reduction alongside grid decarbonization. Cooney et al. (2013) compared the environmental impacts of electric buses with those of diesel buses in the United States, covering the whole life-cycle, including the manufacture, maintenance, and disposal of charging infrastructure. Similarly, Lee et al. (2013) compared the life-cycle energy consumption and GHG emissions of electric and diesel urban delivery trucks. Its system boundary included the production and installation of electric vehicle supply equipment (EVSE). Nansai et al. (2001) conducted an environmental LCA of the charging infrastructure of EVs. The system boundary includes production, transportation, and installation, in consideration of carbon dioxide, sulfur oxides, nitrogen oxide, and carbon monoxide emissions. Further, the contribution of charging stations to the life-cycle air emissions of EVs was assessed. Lucas et al. (2012) conducted an LCA of the energy supply infrastructure of both EVs and ICEVs in Portugal, focusing on energy use and CO_2 emissions. The life-cycle included the construction, maintenance, and decommissioning phases, and they concluded that the charging infrastructure of EVs has higher energy consumption and emits more CO_2 emissions than ICEVs. However, it is necessary to conduct an environmental impact assessment of chargers in China as China has exhibited largest charger uptake, and it is not suitable for China to apply these studies due to its unique and complex charging systems.

The aim of this study is to compare the energy consumption and

Table 1
Chargers in China.

	Home charger	Public AC charger	Public DC charger	Public mix charger
Voltage	Single- phase	Single-phase Three-phase	Three-phase	Three-phase
Rated power (kW)	7, 40	7, 40	60–360	60–360
Charging time	8 h	3–8 h	80% in 30 min	80% in 30 min
Lifetime (year)	8	8	12	12
National uptake	245,683	102,048	75,922	66,053

Resource: China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, up to Feb. 2018).

greenhouse gas emissions of four types of chargers in China within the whole life-cycle of manufacturing, use, and end-of-life, and determine the proportion of environmental impacts of chargers to that of EVs. It also aims to evaluate the future environmental impacts of charging infrastructure in China and support future development plans.

The remainder of this article is structured as follows: Section 2 describes the research methodology, including the life-cycle models and data resource. Section 3 shows the LCA results for both chargers and the EV system. Section 4 elaborates the projection of the life-cycle environmental impacts of future charger installation, and Section 5 presents a discussion and the conclusion of this research.

2. Methodology

The goal of this study is to estimate the environmental impacts of four types of chargers and their proportion to the environmental burdens of electric vehicles. First, the life-cycle environmental impacts of the four types of chargers (home, public AC, public DC, and public mix) are compared. Then, a new concept as the "model charger" is introduced, and its environmental impacts are designated as the weighting average of the above four results. Following this, the environmental impacts of EVs are expanded by adding the impacts of the model charger. The expanded results are defined as the environmental impacts of an "EV system". Finally, the proportion of the environmental impact of the model charger to that of the EV system is calculated.

2.1. Charger

The system boundary of chargers is defined in Fig. 1, and it contains all life stages of a charger from resource extraction to disposal. The functional unit of chargers is per kWh of electricity used by one mid-size passenger EV.

In the life-cycle analysis of four types of chargers, the cumulative energy demand (CED) and global warming potential for 100 years (GWP) methods were selected as the energy consumption and greenhouse gas emissions are the focus of transportation system studies (Faria et al., 2013; Ou et al., 2012). GWP is selected in the future scenario analysis, and the methodology can be extended to other impact categories. The SimaPro software is used as the supporting tool. To show the environmental impacts of chargers clearly, a new concept is introduced as the "model charger". The environmental impacts of the model charger are estimated based on Formulae (1) and (2).

The energy consumption (MJ/kWh) and global warming potential (g CO_2 e/kWh) of a single model charger can be calculated as

$$CED_c = \sum_{i=1}^{4} CED_i \times r_i \tag{1}$$

$$GWP_c = \sum_{i=1}^{4} GWP_i \times r_i \tag{2}$$

where.

CED_c: cumulative energy demand of a single model charger, MJ/kWh;
GWP_c: global warming potential of a single model charger, g CO_2 e/kWh;
CED_i: cumulative energy demand of a type-i charger, MJ/kWh ($i=1$: home charger; $i=2$: public AC charger; $i=3$: public DC charger; $i=4$: public mix charger);
GWP_i: global warming potential of a type-i charger, g CO_2 e/kWh;
r_i: quantity ratio of a type-i charger.

The specific methods and primary data for the three life stages will be discussed in detail.

2.1.1. Manufacturing stage

Fig. 2 shows the average material composition and weight of each type of charger. The chargers consist of the following major components: electronic shell, connector (or plug) and cable, power supply, transformer, contactor, and resistor. Therefore, the major materials used in chargers are iron and steel, which together account for over 80% of the total weight. In addition, aluminum and copper account for 5–8% of the total weight respectively, and rubber accounts for 3–5%. Home and public AC chargers contain less material, weighing less than 50 kg; whilst public DC and public mix chargers are 7–14 times heavier, ranging from 200 to 250 kg.

Electricity consumption is included in the manufacturing stage. The primary data for electricity consumption and relative waste discharge during this stage were obtained from the manufacturers. The upstream energy consumption and pollutant emissions for the production of the main material were acquired from the CAS RCEES 2014 model.

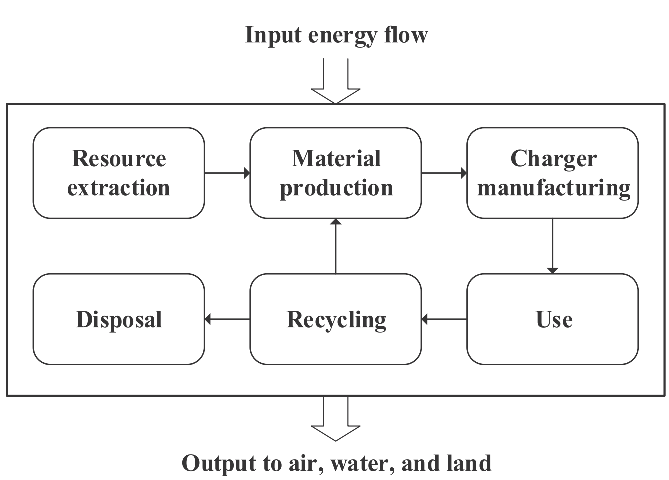

Fig. 1. System boundary of a charger.

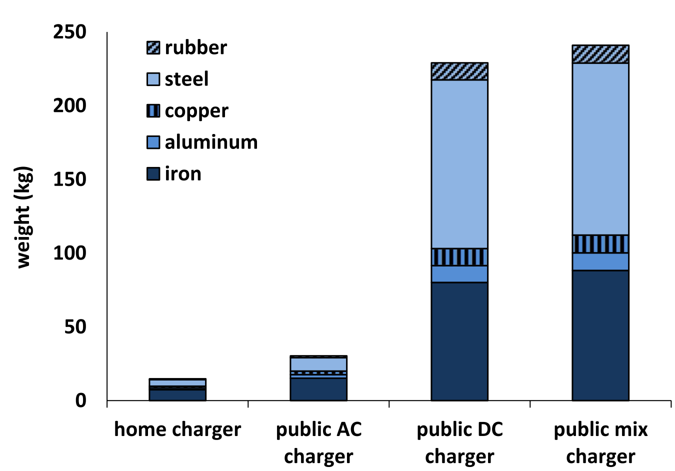

Fig. 2. Material composition of the four types of chargers.

2.1.2. Use stage

During operation, chargers transmit electricity from electricity plants to electric vehicles. In the use stage, there is a small degree of electricity loss due to the technology limits of chargers at a loss rate of 5–15%. Therefore, this study only considers electricity loss in the use stage.

As each main type of charger has different models with different rated power and electricity loss rates, average values were selected based on the quantity of each model (from EVCIPA). The working efficiency of the chargers is estimated by contacting their major operators. Thus, the electricity loss during the lifetime of a single charger is approximately 4000 kWh for a home charger, 6000 kWh for a public AC charger, 330,000 kWh for a public DC charger, and 390,000 kWh for a public mix charger.

2.1.3. End-of-life stage

As chargers have been developed for less than five years in China, the estimation of the end-of-life stage is more of a prediction than a calculation. It is predicted that the major material recycled will be metals, the recycling rates of which are 85% for iron, 90% for steel, and 95% for aluminum and copper. Landfill is considered as the final disposal method. The relative data for energy and material inputs and outputs were obtained from Li (2015).

2.2. EV system

An EV system is defined as the combination between an electric vehicle and its chargers. Fig. 3 shows the system boundary of the EV system. In this study, the charger is the model charger. All life stages of the charger are included in the system boundary of the EV system, which has a functional unit of "per kWh of electricity used by one mid-size passenger EV".

The CED and GWP of the EV system are calculated by adding the results of the EV and model charger (Formulae (3) and (4)). The proportion of environmental impacts of chargers to those of a single EV system is also estimated by Formulae (5) and (6). In China, there is no one-to-one correspondence between the vehicle and charger. Therefore, for each EV system, the impacts of chargers should not be simply regarded as the impacts of a single charger. Thus, the ratios of EV and charger quantities (r_c) are introduced in Formulae (3)–(6).

The life-cycle CED for a single EV is 2.3 MJ/km (Zhou et al., 2013), and the GWP is 209 g CO_2 e/km (Wu et al., 2018). The energy consumption rate of EVs in China ranges from 14 to 17 kWh/100 km (Hao et al., 2017), and the rate is regarded as 15.5 kWh/100 km in this study (Wu et al., 2018). Therefore, the CED and GWP of a single EV (CED_{ev} and GWP_{ev}) are 14.8 MJ/kWh and 1348.4 g CO_2 e/kWh, respectively.

The energy consumption (MJ/kWh) and global warming potential (g CO_2 e/kWh) of a single EV system can be calculated as

$$CED_s = CED_c \times \frac{1}{r_c} + CED_{ev} \tag{3}$$

$$GWP_s = GWP_c \times \frac{1}{r_c} + GWP_{ev} \tag{4}$$

and the proportion of the energy consumption and global warming potential of chargers to that of an EV system can be calculated as

$$p_{CED} = \frac{CED_c \times \frac{1}{r_c}}{CED_s} \tag{5}$$

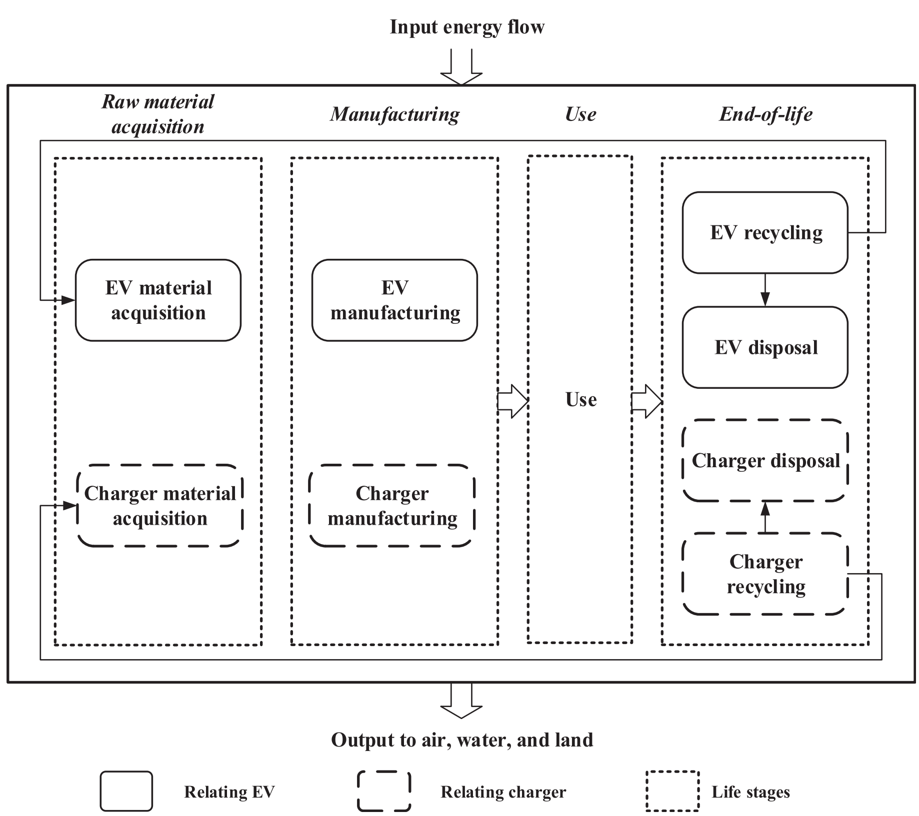

Fig. 3. System boundary of the EV system (electric vehicles and chargers).

$$p_{GWP} = \frac{GWP_c \times \frac{1}{r_c}}{GWP_s} \tag{6}$$

where.

CED_s: cumulative energy demand of a single EV system, MJ/kWh;
GWP_s: global warming potential of a single EV system, g CO_2 e/kWh;
r_c: ratio of vehicle and charger quantities;
CED_{ev}: cumulative energy demand of a single EV, MJ/kWh;
GWP_{ev}: global warming potential of a single EV, g CO_2 e/kWh;
p_{CED}: proportion of the CED of chargers to that of an EV system;
p_{GWP}: proportion of the GWP of chargers to that of an EV system.

2.3. Data resource

The LCI data of chargers were collected at all stages of the charger's life-cycles. Primary data were collected from 12 leading manufacturers and operators, which occupy over 70% of the market share. Other data were obtained from CAS RCEES 2014, a Chinese localization LCA database. The charger uptake data were from the industry association of charging infrastructure, the China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA). Finally, the data for the national uptake of electric vehicles in 2017 were obtained from the China Automotive Technology & Research Center. Co., Ltd (CATARC).

3. LCA results

The results for chargers are presented in the following three parts: results for different types of chargers, results for the model charger, and the proportion of the environmental impacts of chargers to those of the EV system.

The results for the different types of chargers are presented in Fig. 4. Among the four charger types, home chargers have the smallest life-cycle CED of 1.18 MJ/kWh, followed by public AC and DC chargers (1.32 MJ/kWh and 1.62 MJ/kWh, respectively), and public mix chargers have the largest CED of 1.77 MJ/kWh. Similarly, home chargers have the smallest life-cycle GWP of 82.52 g CO_2 e/kWh, followed by public AC and DC chargers (91.58 g CO_2 e/kWh and 111.02 g CO_2 e/kWh, respectively), and public mix chargers have the largest GWP of 121.60 g CO_2 e/kWh. Home and public AC chargers have relatively smaller energy consumption and greenhouse gas emissions owing to their smaller material consumption and electricity loss, and the results of public DC and public mix chargers are higher due to their larger material consumption and electricity loss. During the life stages, the use stage causes most of the environmental impacts, which indicated that the electricity loss in the use stage is a major contributor.

The environmental impacts of the model charger were also calculated (Table 2); its life-cycle CED and GWP are 1.36 MJ/kWh and 94.06 g CO_2 e/kWh, respectively. The results of the model charger are closer to those of public AC chargers due to their large quantity ratios.

Prior to February 2018, there were 1.8 million and 0.49 million EVs and chargers in China, respectively. Thus, the total ratio of vehicle and charger quantities is 3.69. The proportion of environmental impacts of chargers to that of the EV system is then calculated. Table 2 shows the proportion of the environmental impacts of the model charger to those of the EV system. The CED proportion is 2.43%, and the GWP proportion is 1.89%. Although the proportion of the CED and GWP of chargers is below 3%, the impact of the charger should not be ignored in environmental assessments of EVs, as chargers are the most important supporting infrastructure of EVs.

4. Projections of life-cycle impacts of future charger installation

4.1. Affecting factors

To reduce more environmental impacts in the future installation of chargers, a LCA on the GWP of chargers is conducted by scenario analysis considering key factors for 2020, 2025, 2030, 2035, and 2040. Three key factors are discussed: the electricity mix, types of chargers, and ratio of vehicle and charger quantities.

Table 2
LCA Results of the model charger, EV system, and the charger's proportion.

Impact category	Model charger	EV system	Proportion of charger
CED (MJ/kWh)	1.36	14.84	2.43%
GWP (g CO_2 e/kWh)	94.06	1348.38	1.89%

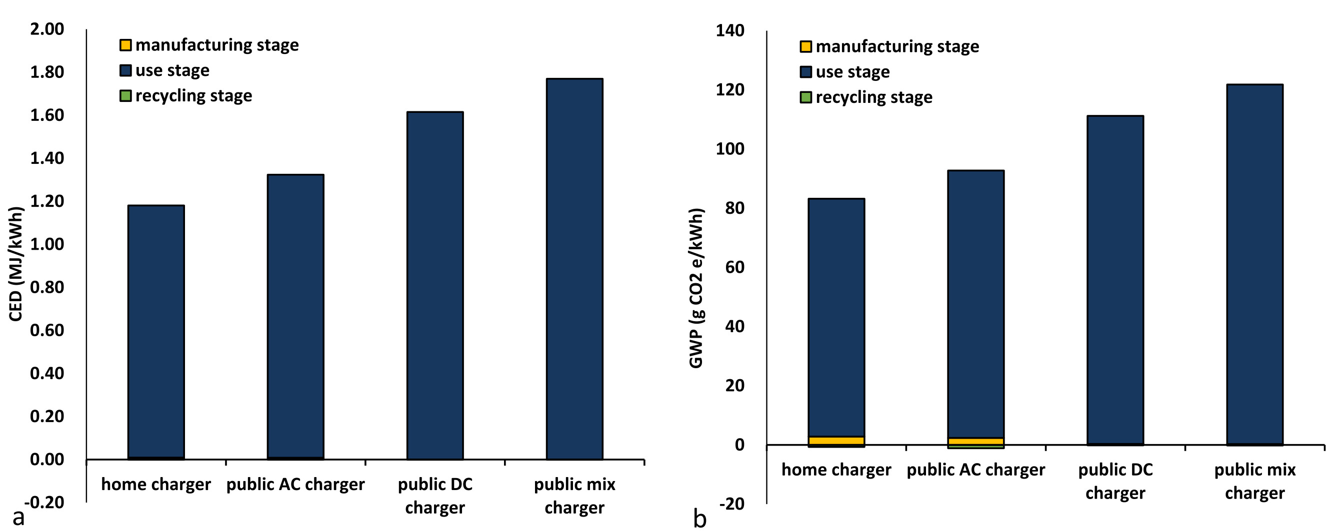

Fig. 4. Life-cycle (a) CED and (b) GWP of chargers.

4.1.1. Electricity mix

The electricity mix in China is still dominated by thermal power (Ding et al., 2017). Nevertheless, its proportion is assumed to decrease gradually, while the proportion of clean energy is assumed to increase in the future. As both the electric vehicles and chargers consume electricity during their use, their environmental impacts are influenced by the electricity supply. Table 3 shows the tendency of the electricity mix.

4.2. Types of chargers

The difference between the energy consumption and greenhouse gas emissions of the four types of chargers is presented in this study. Therefore, the quantity ratios of the different types of chargers also have a strong influence on the future LCA results. However, the relative uptake of the four types currently varies greatly between 31 provinces of China (China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, 2018), and the Chinese government has not proposed a plan for the future quantity ratio of each charger type. Therefore, it is difficult to predict the future quantity of each type of charger. Thus this study selects two representative cities and takes their quantity ratios of the four types of chargers as the future national ratios.

Charger installation is currently concentrated in the developed eastern coastal regions. Beijing, Shanghai, and Guangdong occupy over 60% of the national charger uptake, while the proportions of the 22 other provinces are below 5% of the total uptake (China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, 2018). Therefore, it can be concluded that, the development of electric vehicles and chargers in China has just begun. In this stage of China's charger installation, public chargers for buses, taxis, and lorries have not been widely installed due to the lack of policy support, and personal passenger electric vehicles typically dominate the EV market.

This study assumes that the charger installation in China will develop into two more stages in the future, i.e., the developing and developed stages. It is widely acknowledged that the EVs development in China has mostly been driven by policy, and one of the main policies is the electrification of public transportation (International Energy Agency (IEA) et al., 2018). Therefore, it can be predicted that the policy support will increase in the developing stage, and electric public transportation will then develop rapidly, resulting in a large number of public chargers, especially DC and mix chargers. In the developed stage, however, electric vehicles will be the result of market choice rather than policy support. At that time, the number of home chargers will further surpass other types.

Among 31 provinces of China, Beijing and Tianjin have relatively larger charger uptake. The charger quantity per million population in Beijing and Tianjin are 1651 and 682, ranking first and third respectively in China (China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, 2018). Besides, the proportions of the four types of chargers in Tianjin are approximately the same, which meets the characteristics of the developing stage. And Beijing meets the characteristics of the developed stage, where home chargers are the most common. Based on the above analysis, the quantity ratios of the four types of chargers in Tianjin and Beijing are designated as those in the developing stage and developed stage of China, respectively (Table 4).

4.2.1. Ratio of vehicle and charger quantities

As mentioned above, the ratio of vehicle and charger quantities (r_c) influences both the environmental impacts of the EV system and the charger proportion. In the future national LCA, however, it is difficult to predict both future EV and charger uptake due to the vague policy direction and other uncertain factors. So far, neither government plans nor academic prediction studies have extended 2040. Therefore, three tendencies are discussed in this study: remaining stable, increasing, and decreasing.

4.3. Scenario analysis design

A scenario analysis of the life-cycle GWP of chargers in 2020–2040 is conducted based on the three key factors, which aims to show the effect of each factor on the tendency of the GWP of chargers. Three scenarios are designed with three tendencies for r_c: remaining stable, increasing, and decreasing. In the first tendency, this study defines a stable value of r_c as 3.7 in 2020–2040. The increasing tendency is defined as an increase in r_c of 0.5 every five years, while the decreasing tendency is defined as a decrease in r_c of 0.5 every five years. Each scenario considers two stages of development: the developed stage (Beijing as representative city, Scenario 1_b, 2_b, 3_b) and the developing stage (Tianjin as representative city, Scenario 1_t, 2_t, 3_t). The influence of electricity mix on the GWP of chargers is also included in the analysis. Table 5 shows the details of the three scenarios.

4.4. Results of scenario analysis

With the development of the electricity mix, both the GWP of the model charger and EV system will decrease, along with the GWP proportion of the model charger. As shown in Fig. 5 (1_b) (scenario 1_b), in the developed stage, the GWP of chargers is 24.52 g CO_2 e/kWh in 2017, accounting for 1.80% of that of the EV system. In 2030, however, the GWP is 17.42 g CO_2 e/kWh, accounting for 1.57% of that of the EV system. Further, in 2040, it is 14.84 g CO_2 e/kWh, accounting for 1.45%. The decreasing tendency is similar in the developing stage (Fig. 5 (1_t), scenario 1_t).

The changing tendency may vary greatly when considering the ratio of vehicle and charger quantities. If r_c increases by 0.5 every five years, the tendency decreases much more rapidly as more vehicles share the GWP of a single charger. For example, as shown in Fig. 5(2_b) (scenario 2_b), the GWP of chargers in the developed stage is 12.90 g CO_2 e/kWh in 2030, accounting for 1.16% of that of the EV system, while that in 2040 is 9.03 g CO_2 e/kWh, accounting for 0.89%. In contrast, if r_c decreases by 0.5 every five years, the GWP of chargers and the GWP proportion will both increase. As shown in Fig. 5(3_b) (scenario 3_b), the GWP of chargers is 32.90 g CO_2 e/kWh in 2030, accounting for 2.90% of that of the EV system, and it increases

Table 3
Future electricity mix.

Year	Thermal power (%)	Hydropower (%)	Nuclear power (%)	Wind power (%)	Solar power (%)
2020	70.9	15.0	7.7	4.9	1.5
2025	66.4	14.0	11.9	5.6	2.1
2030	61.0	13.5	16.2	6.6	2.6
2035	56.1	12.7	20.0	7.5	3.7
2040	51.1	12.0	23.8	8.4	4.6

Source: Luo et al. (2014).

Table 4
Quantity ratios of the four types of chargers in Beijing and Tianjin.

	Home charger	Public AC charger	Public DC charger	Public mix charger
Beijing	0.70	0.11	0.11	0.08
Tianjin	0.29	0.20	0.19	0.31

Source: China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA, up to Feb. 2018)

Table 5
Scenario analysis design.

Scenarios		2017	2020	2025	2030	2035	2040
Developed Stage	Developing Stage	r_c					
Scenario 1_b	Scenario 1_t	3.7	3.7	3.7	3.7	3.7	3.7
Scenario 2_b	Scenario 2_t	3.7	4.0	4.5	5.0	5.5	6.0
Scenario 3_b	Scenario 3_t	3.7	3.0	2.5	2.0	1.5	1.0

to 55.48 g CO_2 e/kWh in 2040, accounting for 5.36%. The changing tendency is similar in the developing stage (Fig. 5(2_t), (3_t), scenario 2_t, 3_t). Thus, an unlimitedly increasing number of chargers would not be conducive to reducing environmental impacts. Therefore, attention should be paid to the r_c in the EV and charger development policies. It is unnecessary for policymakers to pursue an uncontrolled charger quantity and an r_c of 1.

By comparing the developed and developing stages, the GWP changing tendency is also affected by the quantity of the different types of chargers. As shown in Fig. 6, the developing stage releases more GWP emissions than the developed stage, even though they have the same changing tendencies. In 2017, the GWP proportion of chargers in the developed stage is 1.80%, while that in the developing stage is 2.04%. In scenarios 1_b and 1_t, the decreasing tendency in the developing stage is more rapid than that in the developed stage. In 2040, the GWP proportion of chargers in the developing stage is 1.64%, which is 0.19% more than that in the developed stage (1.45%). In scenarios 2_b and 2_t, the decreasing tendency in the developing stage is also more rapid than that in the developed stage. In 2040, the GWP proportion in the developing stage is 1.01%, which is 0.12% more than that in the developed stage (0.89%). In scenarios 3_b and 3_t which have the largest GWP emissions, the increasing trend of the developing stage is more rapid. In 2040, the largest GWP proportion in the developing stage is 6.06% of the EV system, which is 0.70% more than that in the developed stage (5.36%). The developed stage releases less GWP emissions mainly owing to its larger quantity of home chargers, which takes 70% of the total charger uptake. Therefore, the effects of charger type on the environmental impacts of chargers should be considered in future government plans, and preference should be given to chargers with low environmental impacts, such as home and public AC chargers.

4.5. Sensitivity of the ratio of vehicle and charger quantities

Three tendencies of the ratio of vehicle and charger quantities are discussed in the scenario analysis. To more accurately test the impacts of this factor, another prediction analysis is presented in Fig. 7. The annual GWP of chargers is calculated under six different r_c values from 2020 to 2040, which are 1, 2, 3, 3.7, 4, and 5, respectively. The GWP of a single charger in each year is adjusted based on differences in the electricity supply. The quantity ratios of different types of chargers in each year are not available, therefore, they are designed based on their relative GWP, among which the type with the smallest GWP shares the largest quantity ratio. The designed ratios of the four types are constant in each year. The uptake of EVs in each year is predicted based on the uptake of civil vehicles in China during 1985–2005, assuming that the development trend of EVs is the same.

As shown in Fig. 7, the annual GWP of chargers increases over time under all six ratios. In each year, the GWP of chargers is higher with a smaller ratio. If the r_c remains constant at 3.7, the GWP of chargers is 4.3 Mt in 2020 and 32.7 Mt in 2040. If r_c increases to 5, the GWP of chargers is 3.2 Mt in 2020 and 24.2 Mt in 2040. Finally, if the r_c decreases to 1, the GWP of chargers is 15.8 Mt in 2020 and 120.9 Mt in 2040. As adjustments to r_c result in clear changes in the charger GWP, care must be taken when preparing future EV and charger development plans. The ratio of vehicle and charger quantities deserves more attention in EV and charger development policies. Moreover, it is not environmentally beneficial to pursue the smallest r_c value.

5. Discussion and conclusion

5.1. Discussion

This study assesses the environmental impacts of chargers in China and estimates their proportion to the environmental impacts of the EV system. The CED of single charger is 1.36 MJ/kWh, accounting for 2.43% of the results of EVs, and the GWP of single charger is 94.06 g CO2 e/kWh, accounting for 1.89% of that of EVs. In a study involving the LCA of charging infrastructure in Portugal (Lucas et al., 2012), the CED of single charger was 0.07–0.16 MJ/km, accounting for 2.7–6.3% of that of EVs, and the GWP was 4.1–8.1 g/km, accounting for 3.9–7.9% of that of EVs. The results in this study are slightly lower for the following three main reasons. First, the auxiliary building material is included in the manufacturing process of the previous study, but not here as the main research object of this study is the charger. Further, GWP of EVs in the previous study is 103 g/km, which is reasonable in Portugal, but lower than that in China (209 g/km). Moreover, the CED of EVs in this study is from research conducted in 2013, which may be slightly higher than the current energy consumption. The primary data for chargers used in this study are from 12 leading manufacturers and operators, covering over 70% of the national charger uptake. The market data for chargers and electric vehicles are from an industry association, and the background data are from the Chinese localization LCA database and national statistics. Both the comparative analysis and data sources indicated that the results in this study are within a reasonable range.

There are still limitations to this study. First, the electricity loss rate in the use stage of chargers is assumed to be constant in this study. However, this factor may decrease due to the development of charger technology. Second, in the future prediction analysis, the relative quantity of the four types of chargers is assumed based on representative cities. However, there are many factors affecting the development of the quantity of each type of charger. Thus, the analysis is simplified here. Finally, the ratio of vehicle and charger quantities is discussed in depth here, and it is concluded that an uncontrolled increase in the number of chargers would not benefit the environment. However, the best value or range of r_c is not provided, as it is decided by the complex effects of many factors, such as charging requirements, installation location, and charger types. This will be discussed in later studies.

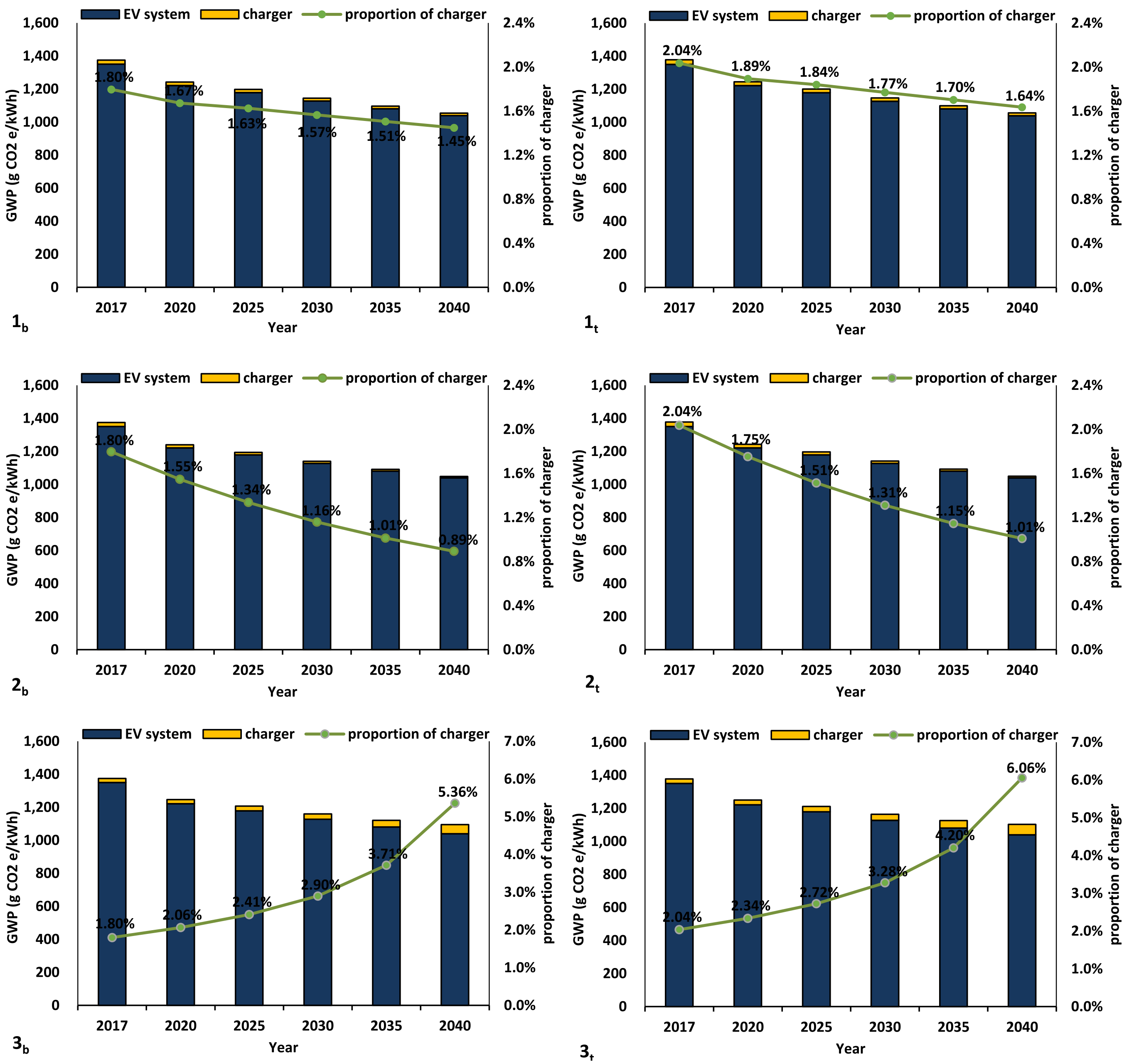

Fig. 5. GWP results of scenario analysis: (1_b) scenario 1_b; (2_b) scenario 2_b; (3_b) scenario 3_b; (1_t) scenario 1_t; (2_t) scenario 2_t; (3_t) scenario 3_t.

To support the future national plans for chargers, two suggestions are given to policymakers. The first is to encourage the use of home and public AC chargers in future charger installation. Recent charger development policies have not considered the environmental impacts of different charger types. Home and public AC chargers are more environmentally beneficial than public DC and mix chargers, thus, preference should be given to home and public AC chargers in future government plans. The other suggestion is to consider the ratio of vehicle and charger quantities in EV development policies. Adopting an appropriate charger quantity is the foundation of EV development. However, an uncontrolled increase in the number of chargers will lead to environmental burdens and economic cost. Therefore, it is unnecessary to pursue an r_c value of 1.

There are three directions for future studies. The first is to discuss the ideal range of r_c in future charging infrastructure development, considering the environmental impacts, consumer demand, location planning and other factors. The second is to discuss more types of the charging infrastructure such as the battery swapping station, and more neglected processes such as the charger maintenance (Duan et al., 2018), under the support of first-hand data collection. The third is to combine the LCA of charging infrastructure with management and economics methodology, such as organizational strategies (Mohammad Ali et al., 2016; Sobhanallahi et al., 2016) and reward-driven systems (Gharaei et al., 2015), to better guide government policies.

6. Conclusion

This study conducted an environmental impact assessment of the four main types of chargers in China using life-cycle

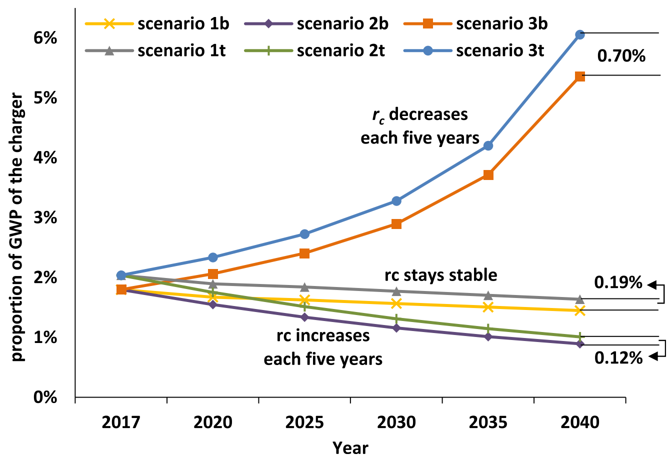

Fig. 6. Proportion of GWP of the charger in scenario analysis.

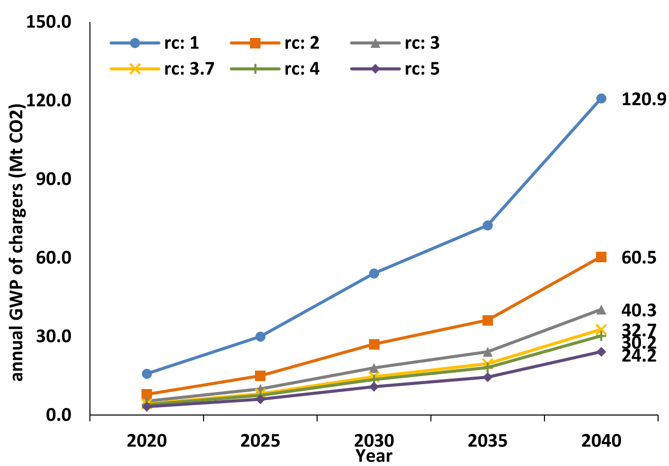

Fig. 7. Annual GWP of chargers at different vehicle and charger ratios (r_c).

assessment, considering the cumulative energy demand and global warming potential. Further, it involved a LCA and estimated the proportions of environmental impacts of chargers to those of the EV system. The environmental impacts of national installation of chargers are also projected. The highlights of this study can be summarized as follows.

First, home chargers have the smallest energy consumption and greenhouse gas emissions, followed by public AC and DC chargers, and public mix chargers have the largest. This is due to the differences in the materials and charging technologies. Therefore, it is strongly recommended to consider the different environmental burdens of charger types in future government plans, and encourage the use of home and public AC chargers.

Second, the CED and GWP of a single model charger are 1.36 MJ/kWh and 94.06 g CO_2 e/kWh, accounting for 2.43% and 1.89% of those of a single EV system, respectively. The impact of the charger should not be ignored when assessing the environmental impacts of EVs.

Finally, the future tendency of the proportion of GWP of chargers is mainly affected by the electricity mix, types of chargers, and ratio of vehicle and charger quantities. In the developing stage, the GWP proportion ranges from 1.31 to 3.28% in 2030 and 1.01–6.06% in 2040. However, in the developed stage it ranges from 1.16 to 2.90% in 2030 and 0.89–5.36% in 2040. A decrease in the ratio of vehicle and charger quantities (r_c) of 0.5 every five years will increase environmental burdens. Thus, it is recommended that future EV and charger development policies consider the r_c. It is unnecessary to pursue an uncontrolled number of chargers and a r_c of 1.

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