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Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case

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ABSTRACT

Electric vehicle, as the most promising clean vehicle technology, has gained high priority in global transport technology roadmap. Although electric vehicles offer multiple benefits within the vehicle use phase, their energy consumption and greenhouse gas emissions within the vehicle production phase are much higher than conventional vehicles. Recycling is considered as an effective way to tackle this issue. By employing a life cycle assessment framework, this study compares the energy consumption and greenhouse gas emissions from electric vehicle production under the circumstances of no recycling and full recycling. Database is established based on the China 2025 case, where a large number of electric vehicles are expected to reach their end of life in the years to come. The results indicate that greenhouse gas emissions from electric vehicle production with and without recycling are 9.8 t CO_2eq. and 14.9 t CO_2eq., implying a 34% reduction through recycling. Specifically, the recycling of steel, aluminum and the cathode material of traction battery, among others, contribute to 61%, 13% and 20% of total reduction, respectively. Although the recycling of conventional vehicle components currently contributes the most to the overall reduction, the recycling of battery has a huge growth potential in the future. Based on the analysis, it is recommended that China should prioritize the recycling of electric vehicles, especially the batteries, to realize the cleaner production of electric vehicles.

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1. Introduction

China has the world's largest vehicle market. Vehicle production in China reached 24.5 million in 2015, accounting for approximately one quarter of the global total (OICA, 2016). Over the past decade, China has given priority to the development of Electric Vehicles (EVs). China produced over 0.25 million EVs in 2015, four times higher than the 2014 level (CAAM, 2016a,b). The government aims that the sales of EVs and Plug-in Hybrid Electric Vehicles (PHEV) reach 2 million in 2020, and 5 million in 2025 (Chinese State Council, 2012). The life cycle environmental impacts of EVs can be divided into three phases: production, use and recycling. Many researches have revealed that although the energy consumption and Greenhouse Gas (GHG) emissions of EVs within the vehicle production phase account for a relatively small proportion when considering the whole life cycle, the values are much higher than those of conventional vehicles and cannot be ignored (Hawkins et al., 2013; Sharma et al., 2013; Tagliaferria et al., 2016). When it comes to the use phase, the dominant phase accounting for the largest proportion of the total life cycle energy consumption and GHG emissions of EVs, the values depend substantially on the energy structure in different regions (Nanaki and Koroneos, 2013). EVs can perform well only if non-fossil fuels are used for the power generation (Bauer et al., 2015). In China, the situation is severe due to limited manufacturing techniques and coal-dominated energy structure (Qiao et al., 2016), and the environmental benefits of EVs haven't met expectations (Wang et al., 2013). Recycling is considered as an effective way to tackle this issue.

Vehicle recycling has already attracted global attention. Globally, the number of End-of-Life Vehicles (ELVs) reached 40 million in 2010 and kept growing rapidly over recent years (Sakai et al., 2014). This leads to millions of tons of waste to be treated, within which huge potential of material recovery exists. In order to obtain

Abbreviations: ANL, Argonne National Laboratory; ASCM, Automotive System Cost Model; ASR, Automotive Shredder Residue; BatPaC, Battery Performance and Cost; BF-BOF, Blast Furnace-Basic Oxygen Furnace; CAAM, China Association of Automobile Manufacturers; EAF, Electric Arc Furnace; ELV, End-of-Life Vehicle; EV, Electric Vehicle; GHG, Greenhouse Gas; GREET, Greenhouse Gases Regulated Emissions and Energy Use in Transportation Model; ICEV, Internal Combustion Engine Vehicle; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; NBSC, National Bureau of Statistics of China; NMC, $Li(Ni_xCo_yMn_{1-x-y})O_2$; OICA, Organisation Internationale des Constructeurs d'Automobiles; PHEV, Plug-in Hybrid Electric Vehicle.

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the largest environmental benefits from the treatment of ELVs, different strategies have been applied in many countries (Cossu and Lai, 2015). In the U.S., driven by the profit and regulations, about 95% of ELVs are recycled and over 80% of the vehicle by weight is recovered (Kumar and Sutherland, 2009). In Europe, the European Directive 2000/53/EC forces European Member States to take 85% of ELVs into recycling and the recovery rate should reach 95% by weight by 2015 (Santini et al., 2011). In Japan, the ELV recycling law has been put into force since 2005. Over 95% of ELVs are recycled (Zhao and Chen, 2011). In China, although a series of regulations have been promulgated since 2001, the recycling of ELV is still not well enforced, and many informal sectors are illegally treating ELVs, causing huge waste (Hu and Wen, 2015). Recently, much more detailed standards have been applied to ELV recycling (Zhao et al., 2016). For most of the regulations, the recycling requirements are based on the case of conventional Internal Combustion Engine Vehicles (ICEVs). As EVs only started to penetrate the market over recent years, there are still significant gaps in existing regulations on the recycling of EVs.

Under such circumstance, the energy consumption and environmental impacts of EV recycling should be evaluated to help the government enact new regulations. Currently, scholars have paid high attentions to the Life Cycle Assessment (LCA) of vehicle recycling from a grave-to-gate point of view. Gerrard and Kandlikar (2007) assessed the impacts of 2000/53/EC regulation on ELV recycling and analyzed the vehicle recycling techniques in Europe. Belboom et al. (2016) compared the life cycle environmental impacts of three different ELV dismantling techniques on the basis of industrial data in Belgium, finding that post shredding treatments could be developed for a higher material and energy recovery rate. Li et al. (2016) estimated the life cycle environmental impacts of end-of-life Corolla taxis in China. The author established a vehicle recycling scenario in China and took the material replacements into consideration, which formed a complete research framework for ICEVs. Cheng et al. (2012) studied the vehicle recycling in Taiwan and revealed that energy consumption during recycling process should be paid high attention.

Meanwhile, numerous studies focused on one or two stages of the vehicle recycling process. Halabi et al. (2015) carried out an LCA on advanced machine-based dismantling of ELVs, which provided an important supplement to this field. Vermeulen et al. (2011) conducted a study on the Automotive Shredder Residue (ASR) management, the most important stage after dismantling. The results indicated that ASR recovery might be a breakthrough for vehicle recycling. Cossu and Lai (2015) studied ASR management in another way. Their results revealed that energy recovery would play an important role. Besides, Diener and Tillman (2015) and some scholars evaluated the life cycle energy consumption and environmental impacts of the remanufacture for individual components, as well as the engine (Smith and Keoleian, 2004). And some other scholars studied the recovery of materials in recycled vehicles, for example, Ohno et al. (2015) evaluated the efficient and impacts of recovery of steel scrap derived by ELVs in Japan and provided important conclusions, and as well as copper (Brahmst, 2006) and plastic (Duval and MacLean, 2007).

On the other hand, with the development of EVs, more and more studies on the recycling of traction battery have been published in recent years. Espinosa et al. (2004) established original recycling models for different kinds of batteries, including lead acid, nickel–cadmium, lithium and Li-ion batteries. Georgi-Maschler et al. (2012) summarized the recycling process for Li-ion batteries developed before 2012. They evaluated different recycling techniques and put forward a new recycling process with a combination of pyrometallurgical and hydrometallurgical processes. Dunn et al. (2012) estimated the energy consumption and environmental impacts of Li-ion battery recycling, while the Grave-to-Cradle and Cradle-to-Gate stages were both taken into consideration. They formed an important life cycle model for traction batteries. On the basis of Dunn's results, Gaines (2014) discussed the impediments to overcome and raised a vision of recycling system for Li-ion batteries in the future. However, Richa et al. (2014) pointed out that only 42% of the end-of-life Li-ion battery by mass could be recycled with the primary technology. Ordoñez et al. (2016) compared physical and chemical recycling processes for Li-ion batteries, and revealed that techniques remained to be developed to improve the recovery rate. Xie et al. (2015) carried out an LCA on Li-ion battery recycling with the industrial data from one battery recycling plant in China. Simon et al. (2015) evaluated the metal requirements and impacts on reserves of active materials by Li-ion battery recycling in Europe. The author provided an important supplement to the future LCA system on Li-ion batteries. Furthermore, a monograph "Advances in Battery Technologies for EVs" was published in 2015, containing a detailed description of the comprehensively used recycling techniques (Scrosati et al., 2015).

A mature framework of vehicle recycling analysis and a rudiment of traction battery recycling model have been established by existing studies, which have laid the foundation for evaluating the environmental impacts of EV production from a life cycle perspective. However, existing studies also suggested that the grave-to-gate environmental impacts of EV recycling varied a lot among different techniques, implying significant regional disparities. When it comes to the situation in China, few studies have focused on this topic due to the lack of unified standards. Meanwhile, the Chinese government aims to achieve a 60% – 65% decrease in CO_2 intensity (CO_2 emissions per unit of Gross Domestic Product) by 2030 (Chinese Government, 2015). To realize this target in the transport sector, EV industry would be promoted to become much larger. Under such a circumstance, EV recycling ought to be fully developed to improve the environmental impacts.

To fill the research gaps, this study aims at estimating the impact of recycling on energy consumption and greenhouse gas emissions from EV production. According to the government's expectation of EV production and life span (Chinese State Council, 2012), the first large batch of end-of-life EVs should be treated around 2025, based on which a China 2025 scenario is developed. This study assumes that the recycling techniques in China would successfully reach the world's advanced level as planned (Chinese State Council, 2015). To reflect the overall situation, an LCA framework is employed and China-specific database is established. Furthermore, this study incorporates several results on similar topics from existing literatures as benchmarks.

2. Recycling techniques

2.1. Vehicle specification

A standard mid-size electric passenger car with conventional materials is chosen as the reference vehicle in this study. However, since the detailed specification of EV is unclear in China, this study imports the relevant factors from Burnham (2012) and Automotive System Cost Model (ASCM) (Das, 2004). For more details, the total weight is adjusted to match the average case results in model year 2010 provided by Autonomie, and the material compositions for different components are estimated based on enterprise investigations, dismantling reports, literature review and basic assumptions. On the other hand, several other researches have provided different material compositions of EVs, which may largely influence the results. For example, Bauer et al. (2015) carried out the LCA for EVs currently and in the future. The author simulated a 1977 kg EV in 2012 and a 1643 kg EV in 2030, and the mass reduction was mainly caused by the use of lightweight materials such as alu-

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