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Optimal electric vehicle production strategy under subsidy and battery recycling

Huaying Gu[a], Zhixue Liu[a], Qiankai Qing[b,c,*]

[a] School of Management, Huazhong University of Science and Technology, Wuhan 430074, China
[b] School of Automobile and Traffic Engineering, Wuhan University of Science and Technology, Wuhan 430081, China
[c] School of Automation, Huazhong University of Science and Technology, Wuhan 430074, China

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ABSTRACT

Government subsidy and battery recycling are two common practical issues in the electric vehicle (EV) market. This study investigates a loss-averse EV manufacturer's optimal production strategy under uncertain market demand in the presence of both government subsidy and battery recycling. An analytical model is built and related optimal solution and numerical experiments are provided. Results indicate that increased subsidy promotes the manufacturer's optimal production quantity and expected utility. Increased battery recycling rate promotes the manufacturer's optimal production quantity. However, the manufacturer's expected utility decreases with the battery recycling rate if the optimal production quantity is sufficiently small. This result implies that the manufacturer may prefer a relatively small battery recycling rate when the market scale is small. Consequently, the government should establish regulations to promote battery recycling for environmental protection. We find that either subsidy or battery recycling can offset the negative effects of loss aversion on the optimal production quantity and expected utility. The majority of our results still hold if we consider multiple repurposing options for used batteries or an alternative subsidy mechanism. In particular, the manufacturer's optimal production quantity and expected utility are higher under cost subsidy mechanism than under consumer subsidy mechanism.

1. Introduction

Electric vehicles (EVs), which primarily refer to plug-in hybrid EVs (PHEVs) and battery EVs (BEVs), are an increasingly attractive transportation option (Coffman et al., 2017). The adoption of EVs could be a promising solution to address the challenges resulted from climate change and crude oil scarcity in the 21st century (Kieckhäfer et al., 2014). If successfully and continuously introduced, EVs will result in a substantial reduction of greenhouse gas emissions and consequently contribute to environmental health to a certain degree. As noted by Casals et al. (2017), EV is one of the most promising alternatives for sustainable transportation.

Because of its huge potential benefits, the EV market is undergoing an explosive development in recent years. According to statistics, the new registrations of EVs increased by 70% between the years of 2014 and 2015, with approximately 0.55 million EVs sold globally in 2015 (IEA, 2016). Furthermore, the International Energy Agency's electric vehicles initiative, which includes 16 member countries, aims to reach a global deployment of 20 million EVs by 2020.

The rapid and sustainable development of EV market cannot occur without the effective participation of EV manufacturers. Although the EV market has attracted an increasing number of enterprises to invest on EV production, there still exist some challenges and barriers faced by both incumbent EV manufacturers and new market entrants. In particular, how to make decisions on reasonable production strategy is a primary challenge for an EV manufacturer. The reason is twofold. First, choosing appropriate production quantity is rather difficult for the EV manufacturer because the EV market is still at its early development stage and thus the market demand is highly uncertain. Second, and probably more important, the EV production strategy is affected by various external and internal factors. Together, these factors may significantly impact and complicate the EV manufacturer's production decision.

Among these impact factors, government subsidy is considered as an important method to adjust the production strategy of EV manufacturers (Zhang, 2014; Zhang and Zhang, 2015). Many countries such as the United States and China have provided considerable subsidy and tax credits for the EV industry or consumer to promote the EV market. For example, as the largest EV market worldwide, China launched a strong incentive EV subsidy scheme in January 2009, followed by an

* Corresponding author.
E-mail address: qingqiankai@wust.edu.cn (Q. Qing).

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update in September 2013. This scheme specifies the subsidy duration, scope, standard, phase-out mechanism and pilot cities for both public and private purchases and uses of EVs (Hao et al., 2014). The rationality of such government actions is directly supported by Zhang (2014) who first investigates the economic influence of government subsidy on the EV manufacturer's optimal production decision.

Another impact factor that plays an important role in the EV manufacturer's production strategy is battery recycling, although it is generally overlooked by the existing literature. As predicted by the China Automotive Technology and Research Centre (CATRC), the volume of scrapped EV battery in China is expected to reach 120 thousand to 170 thousand tons by the year of 2020. It is widely acknowledged that battery recycling is essential for EV industry because used batteries that are not handled properly might do great harm to the environment. Because of this issue, battery recycling is usually mandatory for EV manufacturers in practice. For example, EV manufacturer Build Your Dreams (BYD) is required by the government of China to be responsible for recycling used batteries. The existing literature on battery recycling generally focuses on battery technology (Samba et al., 2014) and economic and environmental impacts of battery re-use (Ahmadi et al., 2014, 2017; Heymans et al., 2014; Neubauer and Pesaran, 2011). Hence, they ignore the impact of battery recycling on EV manufacturer's optimal production decision.

This paper investigates an EV manufacturer's production strategy under government subsidy and battery recycling. The impacts of government subsidy and battery recycling on the EV manufacturer's optimal production decision are analyzed under the coexistence of these two factors. The analytical work is based on the classical newsvendor model (see Qin et al., 2011 for extensive reviews). In our base case, we consider that the EV manufacturer has a certain repurposing option for used batteries and adopt a subsidy mechanism under which customers are subsidized. We then extend our analysis to the case in which the EV manufacturer has multiple repurposing options, and the case in which the EV manufacturer's production is subsidized under an alternative subsidy mechanism. Our results suggest that under different subsidy mechanisms, government subsidy has an increasing effect on the EV manufacturer's optimal production quantity and expected utility. However, the battery recycling rate may have a decreasing effect on the EV manufacturer's expected utility.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes our model. Section 4 provides our main results. Section 5 extends the proposed models. Section 6 illustrates the results using numerical experiments. Section 7 discusses the results and limitations of this study. Section 8 summarizes the main findings and presents some useful policy implications. All proofs are in the supplementary material.

2. Literature review

EV, which is propelled by one or more electric motors instead of an internal combustion engine, is considered to have the capability to reduce the transportation sector's carbon footprint and crude oil dependence as well as the ability to protect the natural environment Wu et al., 2015b). Due to the potential benefits of EVs, the development of EVs has attracted increasing attention from environmental advocates, governments, industry managers, and academics. The prominent body of the EV development literature covers a wide range of domains, including EV adoption (Lim et al., 2015; Matthews et al., 2017), charging and swapping infrastructure planning (Madina et al., 2016; Mak et al., 2013; Wu et al., 2015a), and government incentive policies for EV consumers or manufacturers (Hao et al., 2014; Huang et al., 2013; Langbroek et al., 2016; Li et al., 2016; Luo et al., 2014). For example, Lim et al. (2015) investigate the influences of both range anxiety and resale anxiety on the mass adoption of EVs.

Although EV is beneficial to the environment compared with the internal combustion engine power vehicle (ICEV), the prohibitive cost of batteries, scare number of charging stations, and the EV's limited range have impeded EV development (Daziano and Chiew, 2012; Madina et al., 2016). In fact, many countries have implemented a number of policies to help overcome such obstacles. One of the most widely adopted measures is that the government to provide subsidy to promote broader use of EVs in the nascent stage, such as in the United States and China. Recently, Hao et al. (2014) present the rationale of China's two-phase EV subsidy scheme, which was launched in January 2009 and then updated in September 2013. Additionally, Luo et al. (2014) study EV supply chain under a government's price-discount incentive scheme. They find that the subsidy ceiling or discount rate is more effective in influencing the optimal wholesale pricing decision of the manufacturer when the unit production cost is relatively higher or lower, respectively.

In addition to subsidy, the EV production strategy plays an essential role in the successful development of the EV market (Zhang, 2014). Prominent examples of this factor include Zhang (2014), who investigates the influence of subsidy, loss aversion and consumer tradeoffs on the EV manufacturer's optimal production strategy. Later on, Zhang and Zhang (2015) further discuss the optimal EV production decision under subsidy and shortage cost. However, they do not consider battery recycling despite its high importance to natural environment and EV development (Ahmadi et al., 2014; Neubauer and Pesaran, 2011).

A number of studies on EV batteries emerge in recent years (Ahmadi et al., 2017; Assunção et al., 2016; Jaguemont et al., 2016; Jiao and Evans, 2016; Tagliaferri et al., 2016; Yano et al., 2016). However, most of these studies focus on battery technology (Samba et al., 2014) and the economic and environmental analysis of re-use EV batteries (Ahmadi et al., 2014, 2017; Heymans et al., 2014; Neubauer and Pesaran, 2011; Saxena et al., 2015). For example, Heymans et al. (2014) simulate a residential energy profile and regulated cost structure to analyze the feasibility and cost savings from repurposing an EV battery unit for peak shifting. Using a parameterized life cycle model, Ahmadi et al. (2014) analyze the environmental feasibility of reusing EV batteries. Then, Ahmadi et al. (2017) characterize the extended lifetime of Li-ion battery packs using a complex functional unit to cover both use and reuse phases over an 18-year lifetime. Based on the above research, the present study focuses on the impacts of battery recycling on the EV production strategy.

As for the modeling framework, this study is closely related to the literature on the newsvendor model and closed-loop supply chain model. The newsvendor model is known as one of the most important method to study inventory problem. In a classic newsvendor problem, a risk-neutral newsboy needs to order a certain quantity at a regular price before a selling season. If the demand realized is less than the quantity ordered, then the demand gets satisfied and the leftover inventory has a salvage value that is lower than the selling price, otherwise the demand do not get satisfied. The newsvendor model, which was pioneered by Edgeworth (1888), has been extensively studied in the literature (Babich, 2010; Cohen et al., 2016; Krass et al., 2013; Qin et al., 2011). For example, Cohen et al. (2016) present a model to analyze the interaction between a government and a supplier when they design consumer subsidy mechanisms for green technologies, considering the response of the manufacturing industry.

A common assumption in these studies is that the decision makers are risk-neutral rather than loss-averse. However, evidence suggests that enterprise managers' decision-making behaviours deviate from expected profit maximization due to loss aversion (Feng et al., 2011; Fisher and Raman, 1996). As one of the key features in the prospect theory, loss aversion refers to the case in which a decision maker is more sensitive to losses than to an equivalent amount of gains (Kahneman and Tversky, 1979). Although the loss aversion behaviour has been observed decades ago, this concept has not been frequently considered in inventory models until recently (Ho et al., 2010; Hu et al., 2016; Liu et al., 2015; Schweitzer and Cachon, 2000; Wang and