Does Energy Storage Provide a Profitable Second Life for Electric Vehicle Batteries?

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Abstract: Electric vehicles (EVs) are increasingly being seen as part of the solution to address environmental issues related to fossil fuel use. At the forefront of the EV revolution is China where EV sales have witnessed a dramatic increase. A direct consequence of a larger number of EVs on the roads is the growth in retired batteries once they have reached the end of their useful life inside an EV. This increasing stockpile of retired batteries raises the question of whether and how they can be disposed of, reused, repurposed or recycled. In this paper we investigate under which circumstances the use of second life batteries in stationary energy storage systems in China can be profitable using an operational optimization model. Our results show that an EV battery could achieve a second life value of 785 CNY/kWh (116 USD/kWh) if it is purchased with a remaining capacity of 80% and being abandoned when the capacity reaches 50%. Profit margins for energy storage firms are reduced if the acquisition costs of second life batteries are considered. The price range for second life batteries is assumed to range between a lower limit of the 'Willing to sell' price from the perspective of EV owners and an upper limit being the 'Market evaluation' price based on battery condition and the market price for a new EV battery. It's found that when the remaining capacity in retirement is below 87%, the application of retired battery energy storage can achieve pareto improvement from the perspective of social welfare. In addition, it's estimated that the optimal remaining capacity in retirement would be 77%. Our results suggest that EV adoption rates can be improved if a second life market can be successfully established.

Key word: Price arbitrage model; Energy storage; Electric vehicles; Second life batteries

Classification codes: L92; R42;

1. Introduction

The global transport sector is about one-third of total final use energy consumption (Pablo-Romero et al., 2017). For China and other energy importers this reliance on imported energy and lack of credible alternatives has implications for energy security (Xie and Hawkes, 2015). According to the (IEA, 2017), global CO_2 emissions from fossil fuel combustion were estimated to be 32.3 billion tonnes in 2015. Around 7.7 billion tonnes came from the transport sector, accounting for 24% of global CO_2 emissions. These security and environmental concerns particularly important for those developing countries with a growing transport demand such as China where, for example, pollutants from internal combustion engine vehicles are one of the primary sources of Particulate Matter (PM) (Hao et al., 2017) and the associated health implications. China is also the largest net importer of oil, with a dependency of 65.5% on foreign oil in 2016 and predicted to 80% by 2030 (Wang et al., 2018).

One promising solution that addresses both the security and environmental concerns is the widespread adoption of Electric Vehicles (EVs). However, an increase in the global demand for EVs raises the question of what to do with the EV batteries at the end of their useful service life in the vehicle. Considering the technical and economic challenges related to battery recycling, finding a credible second use for retired batteries would be an attractive option in terms of reducing the costs of future EVs and mitigating the environmental impact from battery disposal or recycling.

In China, the EV industry has undergone rapid development in recent years, to deal with increasingly problematic challenges of energy security and carbon emission reduction. To support the emerging EV market in China, a number of policy measures have been implemented. In recent years, declining battery costs and government policy incentives has resulted in a rapid growth in EV sales. The 'Energy Saving and New Energy Vehicles Development Plan (2012–2020)' has a goal of deploying 5 million New Energy Vehicles by 2020, with the majority being EVs (Qiao et al., 2019). A consequence of the rapidly growing EV market is an increase in the number of retired batteries, which is estimated to reach 120 - 170 thousand tons by 2020 (Liao et al., 2017). This has led to concerns about the high cost of recycling or the low reuse potential (Gu et al., 2017; Zeng et al., 2015; Zeng et al., 2014)

As a result, there is great need for developing a second life market for EV batteries, to promote a cascaded life cycle. The second use of EV batteries has the potential to significantly benefit existing grid-related applications. If retired batteries can be repurposed and included as part of an energy storage system this may lead to a new revenue stream that can be generated from the sale of electricity system services, including the potential profit from price arbitrage. Such repurposing has the additional benefit of giving an economic value to second life batteries and that in turn has the potential to make the initial consumer price of a new EV more affordable leading to greater EV penetration rates. In addition, the use of batteries for storage has the potential to allow electricity generating companies to shift demand from peak load to off-peak load that will help to improve the efficiency and stability of the power grid. Given the very large number of retired batteries that are expected to become available over the next few years, second use has the potential to transform markets in need of cost-effective energy storage (Neubauer and Pesaran, 2011).Second life batteries are generally defined as batteries that have been retired from EVs when they has reached End-of-Life (EOL) but are still performing well enough to be used in less demanding stationary applications (Sun et al., 2018). The use of EV batteries for load-shifting, peak-shaving and energy backup has been studied by Divya and Østergaard (2009), Shi and Luo (2013), Ruan et al. (2017) and Schmidt et al. (2017). The high cost of Li-ion batteries is generally regarded as the primary barrier to their adoption in energy storage applications. As a result, many studies focus on the reuse of EV batteries for energy storage applications as these so-called second life batteries could be sourced at a significantly lower cost (Ahmadi et al., 2014; Heymans et al., 2014; Neubauer and Pesaran, 2011; Wolfs, 2011).

From a technical perspective, it is generally believed that second life batteries from EVs can be used for grid-based energy storage systems in a stationary environment when confronted with high charge or discharge rates (Liao *et al*., 2017). Ahmadi et al. (2014) assume that after losing 20% of its rated capacity, a second life battery can be reused for energy storage until it loses a further 15% of its capacity. Based on a parameterized life cycle model, they argue that a 56% reduction in CO2 emissions is possible if one substitutes the natural gas generation for peak generation with a second life battery to store off-peak electricity to meet subsequent peak demand. Shokrzadeh and Bibeau (2012) examine how retired batteries from EVs can be reused as part of a strategy to integrate wind power to minimize grid outage impacts, and their results suggest that the reuse of second life batteries has the potential to maximize the renewable energy ratio with a minimal grid impact.[1] The utilization of second life batteries from EVs, coupled with photovoltaic generation has also been assessed by numerous studies including (Aziz et al., 2015; Saez-de-Ibarra et al., 2015; Tong et al., 2013).

From an economic perspective, along with a booming EV market that is increasing research interest in understanding whether the reusing of second life batteries from EVs for energy storage applications is economically feasible. The major challenge is how to obtain a reliable estimation of the market price for second life batteries, which is premised on the possibility of reusing retired EV batteries in certain stationary grid-connected applications.

The first techno-economic feasibility study into the used second life batteries from EVs was presented by the U.S. Advanced Battery Consortium (USABC) (Pinsky, 1998; Pinsky et al., 2002). Cready et al. (2003) went on to estimate the costs related to the second life batteries, taking into consideration the acquisition, transportation, battery testing and refurbishment costs. This research provides a baseline for studies focusing on the techno-economic feasibility analysis of using second life batteries (Martinez-Laserna et al., 2018a). Following the costs related to the second life batteries estimated by Cready et al. (2003) and the potential revenues from energy storage applications defined by Eyer and Corey (2010), Williams and Lipman (2011) evaluate the costs for second life batteries using three different models of EV and calculate the potential benefits from repurposing those second life batteries into energy storage devices. Han et al. (2018) propose an economic evaluation method of the photovoltaics (PV) combined energy storage charging station using second life batteries. Neubauer and Pesaran (2011) assess the impact of the second use of EV batteries on the initial cost of the batteries and explore the potential for grid-based energy storage applications to serve as a market for second life batteries. Assunção et al. (2016) evaluate both the technical and economic viability of the second life batteries in residential buildings with a PV system, taking into account the consumption and grid injection tariffs. Madlener and Kirmas (2017) assess the economic

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[1] Renewable energy ratio is a performance indicator to calculate the actual fraction of used renewable energy sources based on total primary energy.

viability of second life batteries from EVs for load shifting and peak shaving in residential applications and conclude that the value would be between €-326 to €825. Other studies that examine the second use of EV batteries include Neubauer et al. (2012), Debnath et al. (2014), Ambrose et al. (2014), Debnath et al. (2016) and Wankmüller et al. (2017).

Besides costs related to second life batteries, battery ageing is an important factor to consider for the economic feasibility analysis. Many studies, such as Stroe et al. (2017) and Martinez-Laserna et al. (2018b), have investigated the performance and degradation of second life batteries, and Casals et al. (2019) conclude that second life battery lifespan depends on its use, and is estimated to be around 6 years in area regulation grid services. Song et al. (2019) use a dynamic battery degradation model to compares the profits that second-life and new batteries can bring to a wind farm.

Based on existing literature, this study takes China as a case study to evaluate the potential profit from using second life EV batteries in energy storage systems. We focus on China as it is the world's largest market for EVs, and it is expected to be a major player in the energy storage market.

Our contributions are mainly on the following aspects:

1) Previous studies have tended to carry out feasibility studies for second life batteries based on the potential revenue streams for energy storage systems. These potential revenue streams have been summarised by many studies, for example, (Eyer and Corey, 2010) estimate potential profits from various applications including arbitrage, electric supply capacity, load following and many other ancillary services for the US market. However, these potential profits are very different from country to country due to differences in the electricity market and regulations. Therefore, instead of based on these potential revenue streams for energy storage applications, this paper adopts a dynamic programming approach and build an energy arbitrage model and assesses the maximum potential profit for energy storage systems using second life EV batteries for China, where the energy storage industry is still at the early stage of development (Tan et al., 2018).

2) To date, little research has been done to evaluate the cost of the second-use battery energy storage in China (Han et al., 2018; Sun et al., 2018). To fill this gap, we evaluate the market price for second life batteries in a Chinese context, and innovatively provide an estimation

range between "willing to sell price" and "market evaluation price".

3) In much of the literature, a battery is deemed to reach the EOL when its energy capacity drops below around 70%-80% of the rated capacity (Tong *et al*. 2017 and Stroe *et al*. 2018). However, Wood *et al*. (2011) suggest that the retirement threshold of 70-80% of the remaining capacity is overly conservative, as those batteries can continue to meet daily travel needs. And Saxena *et al*. (2015) argue that those previous studies that assume that EV batteries retire at 70-80% of remaining capacity is not the correct retirement threshold. To overcome this issue and provide a meaningful evaluation, we carry out an economic feasibility analysis for different remaining energy capacities in retirement for second life batteries.

4) Finally, this paper first proposes a business model that demonstrates the cascade utilization of EV batteries to provide a reference for policy makers wanting to evaluate how EV manufactures can design their business strategies.

The remainder of this paper is organized as follows: Section 2 describes the optimization methodology for maximizing the potential profit from arbitrage and introduces our battery degradation model; Section 3 presents the model results and provides some sensitivity analysis of the main influencing factors; Section 4 provides an evaluation of the market price for second life batteries; Section 5 discusses a business model for reusing second life batteries from EVs; Section 6 concludes and provides a number of policy suggestions.

2. Methodology

2.1 The energy arbitrage model for second life batteries from EVs

For energy storage systems that use second life EV batteries, arbitrage in the energy market is a potentially important source of revenue. This paper proposes an approach for operational optimization, that allows us to determine when and how much the energy storage system should charge or discharge. The objective function is given by Equation (1).

$$\max R = \sum_{t=1}^{T} e_t p_t \tag{1}$$

Where, R is the potential profit from energy arbitrage; e_t is the amount of electricity that the energy storage system purchases from or sells to the grid: $e_t < 0$ means the energy storage system purchases electricity from the grid, while $e_t > 0$ means the energy storage system sells electricity to the grid; p_t is the electricity price at time *t*. Note that energy storage systems are not allowed to sell electricity back to the grid directly in the Chinese electricity market. However, demand side users can meet their own electricity demand by using electricity provided by energy storage systems. In other words, demand side users can reduce their electricity costs by using the electricity stored during off-peak hours to meet their demands during peak hours when electricity prices are high.

However, it is challenging to derive the globally optimal solutions for Equation (1). The optimization method is to determine the value of e_t at each time step. Trying to find the maximum potential profit for a whole year based on half-hourly electricity prices means there will be 17,520 decision variables for this optimization problem. In order to solve this large optimization problem for portfolio optimization, we take a dynamic programming approach, which simplifies a complicated problem by breaking it down into a series of simpler sub-problems in a recursive manner.

For an energy storage system, the state of the system can be described by the quantity of electricity stored in the system and the corresponding cost. At the initial state, both the quantity of electricity and the corresponding cost are assumed to be zero. Sub-problems are defined by time, i.e. $\{T_1 \quad T_2 \quad \cdots \quad T_n\}$. The values T_i at earlier times can be found by working backwards, using a recursive relationship derived from the Bellman equation (Dixit, 1990).

The sub-problem T_1 is defined by Equation (2).

$$\max R_{y,1} = \sum_{t=1}^{T_1} e_t p_t + (S_{T_1} - S_0)\overline{p}_{T_1} \tag{2}$$

Where, S_t denotes the quantity of electricity stored in the energy storage system at time t; while S_0 is the quantity of electricity stored at the initial state. $\overline{p}_{T_1}$ represents the average buying price for the stored electricity. R_y is the potential profit from energy arbitrage at year y. When evaluating the total profit from arbitrage for a whole year, it could involve accumulated electricity from hundreds of charge/discharge cycles, so the setting of initial stored electricity will not affect the optimization process as it only takes up a negligible share in the total electricity calculated. As a result, we set the initial stored electricity at the first sub-problem T_1 as zero, and for other sub-problems T_i (i>1), the initial stored electricity is the remaining electricity at the end of the previous sub-problem. Sub-problems T_i (i>1) are defined by Equation (3).

$$\max R_{y,k} = \begin{cases} \sum_{t=T_{k-1}}^{T_k} e_t p_t + (S_{T_k} - S_{T_{k-1}})\overline{p}_{T_{k-1}} & \text{if } S_{T_k} \le S_{T_{k-1}} \\ \sum_{t=T_{k-1}}^{T_k} e_t p_t + (S_{T_k}\overline{p}_{T_k} - S_{T_{k-1}}\overline{p}_{T_{k-1}}) & \text{if } S_{T_k} > S_{T_{k-1}} \end{cases} \tag{3}$$

While the majority of conventional electric systems run on alternating current (AC), batteries deliver electricity as direct current (DC), which means an AC-DC converter is required for an energy storage battery to pass through electricity to the power grid. Therefore, both efficiencies of the battery and of the inverter need to be considered in the charging and discharging process. The state of the system is determined by the quantity of stored electricity S_t and the corresponding cost $\overline{p}_t$, which can be calculated by Equation (4) and Equation (5), respectively.

$$S_t = \begin{cases} S_{t-1} - e_t\eta_{inv} & \text{if } \mathrm{e}_t < 0 \\ S_{t-1} - e_t / (\eta_{bat}\eta_{inv}) & \text{if } \mathrm{e}_t \ge 0 \end{cases} \tag{4}$$

$$\overline{p}_t = \begin{cases} (\overline{p}_{t-1}S_{t-1} - p_t e_t \eta_{inv}) / S_t & \text{if } \mathrm{e}_t < 0 \\ \overline{p}_{t-1} & \text{if } \mathrm{e}_t \ge 0 \end{cases} \tag{5}$$

Where, η_{bat} is the efficiency of the battery and η_{inv} is the efficiency of the inverter. Constraints are given by Equations (6)-(8).

$$0 \le S_t \le C_t \tag{6}$$

$$-Pow \le e_t \le Pow \tag{7}$$

$$Pow = \lambda C_t \tag{8}$$

Where C_t denotes the remaining capacity of the battery, Pow is the power constraint for charging or discharging and λ is power-to-energy ratio. For Equation (6), the quantity of stored electricity S_t is subject to the battery capacity C_t; for Equation (7), the amount of electricity charged or discharged is subject to the power limitation; for Equation (8), the acceptable power for charging or discharging is usually a proportion of the battery capacity.

The energy storage system is designed to be operated based on two threshold values: an upper threshold p_{thr_h} and a lower threshold p_{thr_l}, which are subject to Equation (2) and (3), as described in (Lin et al., 2019). The operation mode is defined by Equation (9): the energy storage system will sell electricity when the electricity price is higher than p_{thr_h} (discharging), and buy electricity when the electricity price is lower than p_{thr_l} (charging).

$$e_t = \begin{cases} Pow & \text{if } \mathrm{p}_t \geq p_{thr\_h} \\ -Pow & \text{if } \mathrm{p}_t \leq p_{thr\_l} \\ 0 & \text{if } p_{thr\_l} < \mathrm{p}_t < p_{thr\_h} \end{cases} \tag{9}$$

Hence, the total profit during the lifetime of the second life battery can be calculated by Equations (10) and (11).

$$R_y = \sum_{k=1}^{n} R_{y,k} \tag{10}$$

$$R = \sum_{y=1}^{lifetime} R_y / (1+r)^y \tag{11}$$

Where, R denotes the potential total profit from energy arbitrage during the lifetime; R_y is the potential profit at year y; and r is the discount rate.

The value for the second life battery can therefore be estimated based on how much profit the energy storage system generates, given by Equations (12) and (13).

$$\begin{aligned} R &= C_{bat} + C_{inv} \\ &= P_{bat} C_0 + P_{inv} \lambda C_0 \end{aligned} \tag{12}$$

$$P_{bat} = (R - P_{inv} \lambda C_0) / C_0 \tag{13}$$

Where, C_{bat} and P_{bat} is the acquisition cost and unit cost for the used battery, respectively; while C_{inv} and P_{inv} is the installation cost and unit cost for the inverter, respectively.

2.2 Battery degradation model

A number of previous studies have considered the impact of battery degradation. However, the majority carried out their analysis by making simple assumptions on the number of years that batteries will last (Madlener and Kirmas, 2017; Neubauer et al., 2015). The service life is assumed to be ten years in most studies, see e.g. Millner (2010), Wankmüller et al. (2017) and Han et al. (2018). For second life batteries used in energy storage systems, their cycle life is recognized as one of the main factors for evaluating their value for energy storage applications. The battery degradation model has been widely discussed in recent studies. For example, Millner (2010)built an aging model for Lithium Ion batteries based on theoretical models of crack propagation and showed that the service life in PHEVs could barely meet expectations with batteries at that time (in 2010) and that cycle life improvements were needed. Pelletier et al. (2017) summarized different battery degradation models and argued that due to the complex nature of electrochemical models which rely heavily on theory to understand the actual reactions that cause degradation within the battery, empirical and semi-empirical models that aim to estimate relationships between battery degradation and certain factors by using experimental data are more preferable. Uddin et al. (2017) proposed a battery degradation model based on ageing data collected from more than fifty long-term degradation experiments on commercial Lithium-ion batteries. In this paper we use the laboratory results reported by Yang et al. (2018), that are based on aging tests of lithium ion phosphate (LFP) batteries which are commercially popular in a number of EVs including BYD e5, BYD e6, and JAC iEV6 series. Their results showed that LFP presents a steady-speed irreversible energy loss, under a constant temperature of 45°C. As a result, the battery degradation model for LFP can be expressed by Equation (14):

$$C_k = \eta^k C_0 \tag{14}$$

Where, k is the number of cycles, η denotes the battery degradation rate, C_0 is the initial capacity of the battery, and C_k is the remaining capacity of the battery at cycle k.

When a battery has reached EOL (defined in this example as when the remaining capacity has dropped below 80% of the rated capacity), the corresponding cycles can be estimated by Equation (15).

$$k_r = \ln(C_k / C_0) / \ln \eta = \ln(0.8) / \ln \eta \tag{15}$$

When operating in energy storage applications, batteries are assumed to maintain this degradation. In order to learn the dynamic change of battery capacity, Equation (16) describes the relationship between battery capacity and accumulated discharge capacity.

$$\sum_{e_t>0} e_t / (\eta_{bat}\eta_{inv}) = \sum_{s=k_r}^{k} \eta^k C_0 = \eta^{k_r} C_0 (1-\eta^{k-k_r}) / (1-\eta) \tag{16}$$

Although it is not possible to find an analytical solution for k, a numerical solution can be obtained based on the accumulated discharge capacity, according to which the remaining battery capacity can be estimated.

2.3 Assessment of market price for second life batteries

In this paper, we assess the market price for second life batteries by providing an estimation range, with the lower limit being the 'willing to sell' price from the perspective of EV owners and the upper limit being the 'market evaluation' price calculated based on battery condition and market price for a new battery.

(1) The 'market evaluation' price

The 'market evaluation' price is determined by both the State of Health (SOH) of the used battery and the market price for a new battery. Following the research framework proposed by Neubauer et al. (2012) and Neubauer et al. (2015), the 'market evaluation' price for a second life battery can be calculated by Equation (17).

$$P_{used} = K_h * CP_{new} \tag{17}$$

Where, P_{used} denotes the market price for used batteries, K_h is the SOH factor of the used battery, and CP_{new} is the current market price for a new battery.

The SOH factor is estimated using the method of Present Value of Throughput (PVT), which compares the value of a used battery relative to a new one by measuring the ratio of remaining PVT of a used battery to that of a new battery of the same capacity providing an identical service, and it can be written as Equation (18).

$$\begin{aligned} K_h &= PVT_U / PVT_N \\ &= \left(\sum_{t=1}^{T_U} \frac{R_t}{(1+r)^{t/8760}}\right) \Big/ \left(\sum_{t=1}^{T_N} \frac{R_t}{(1+r)^{t/8760}}\right) \end{aligned} \tag{18}$$

Where, PVT_U and PVT_N is the present value of throughput for a used battery and a new battery of the same capacity, respectively. T_U is the remaining lifetime for a used battery, T_U represents the lifetime for a new battery, R_t measures the value that a battery's owner can obtain for each unit of throughput processed by the battery today, while r is the discount rate.

(2) The 'willing to sell' price

Under China's current policies, EV manufacturers are responsible for the recycling of retired batteries. From the perspective of EV manufacturers, the battery recycling market is usually considered to be an oligopoly, however, the EV sales market is under monopolistic competition. As a result, an ideal market price for a used battery would be a price that enables the use costs of EVs not exceeding that of conventional vehicles, to encourage customers' purchase of EVs. This can be expressed by Equation (19)-(20).

$$P_{new} - P_{used} + EV_e * P_e \leq V_g * P_g \qquad (19)$$

$$EV_e = \mu V_g \qquad (20)$$

Where, P_{new} is the price for a new battery; EV_e and V_g denotes the amount of electricity and gasoline that has been consumed, respectively; while P_e represents the charging price of electricity and P_g is the price for gasoline. μ is an energy conversion coefficient.

The 'willing to sell' price for a used battery can therefore be written as Equation (21).

$$P_{used} = P_{new} + EV_e * P_e - V_g * P_g \qquad (21)$$

3. Results

Four scenarios are modelled, with batteries removed from EV after having 90%, 80%, 70% and 65% of the original capacity remaining. The batteries are then used in a stationary energy storage system where they continue to degrade according to Equation (14).

3.1 Simulation of energy storage operations

To illustrate the operation of the battery as energy storage according to Equation (9), Fig. 1 shows the simulation results for a typical day (48 half-hours) according to the Guangzhou industrial tariff in 2018,[2] based on a 1MWh[3] second life battery energy storage system.[4] The electricity stored fluctuates due to the activities of arbitrage: during off-peak hours when the electricity price reaches the low threshold, a charging decision will result in an increase in storage; while during peak hours when the electricity price reaches the high threshold, a discharging decision will result in a decrease in storage. The charging/discharging is also subject to the remaining capacity of the second life battery.

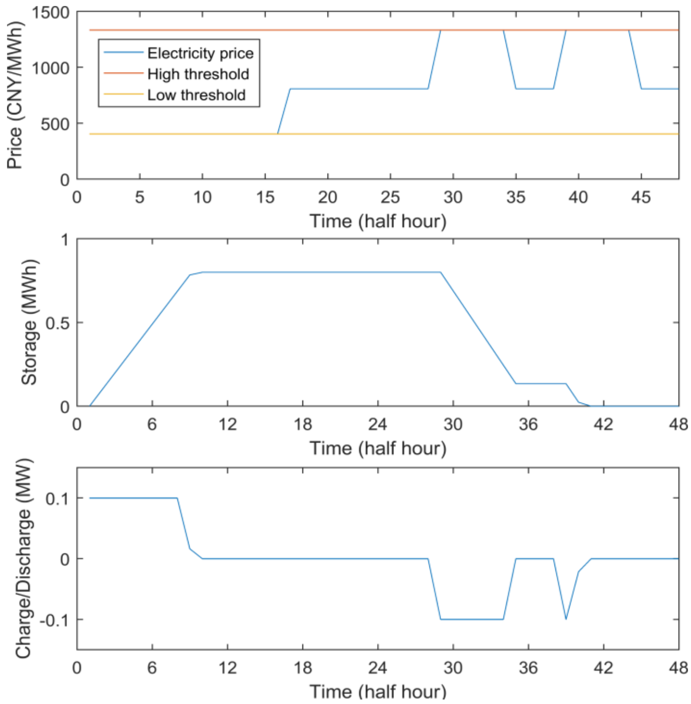

Fig. 1. Operating schedule for a typical day (48 half hours)

3.2 Value and service lifetime for energy storage applications depending on remaining energy capacity in retirement and abandonment

The potential value for energy storage applications using second life batteries is closely related to the remaining capacity in retirement, which will impact the service lifetime. Fig. 2 summarizes the value and service lifetime for the energy storage of second life batteries based on various scenarios of their remaining capacity in retirement from EV use and in abandonment after its application as stationary energy storage.

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2 Data from China Southern Power Grid (https://95598.sz.csg.cn/help/wzcx.do).

3 Charge/discharge power rating is 0.25MW.

4 Simulations are run in Matlab.

It can be seen from the sub figure (a) that the value for energy storage applications would be higher when the second life battery is retired with high remaining capacity and abandoned with low remaining capacity (the cost for buying the second life battery is not considered at this point and will be discussed in the following section). In the baseline scenario that the battery is retired with remaining capacity of 80% and is abandoned with remaining capacity of 50%, it would have a potential value of 785 CNY/kWh (116USD/kWh) and a service lifetime of 4.5 years. This potential value generating from second use is about 1/3 of the price for a new battery (in 2015). When a battery is retired with remaining capacity of 65-90% and is abandoned with remaining capacity of 50%, it could achieve a value of 375-1,045 CNY/kWh (56-155 USD/kWh), with a service lifetime of 2.8-5.3 years. If the remaining capacity in abandonment can be lower, for example, to 20%, the potential value for energy storage could increase to 1130-1724 CNY/kWh (167-255 USD/kWh). In reality, there is no conclusive evidence that second life batteries with 20% of remaining capacity can still be used as energy storage, still it is a scenario to be considered in investment decision-making.

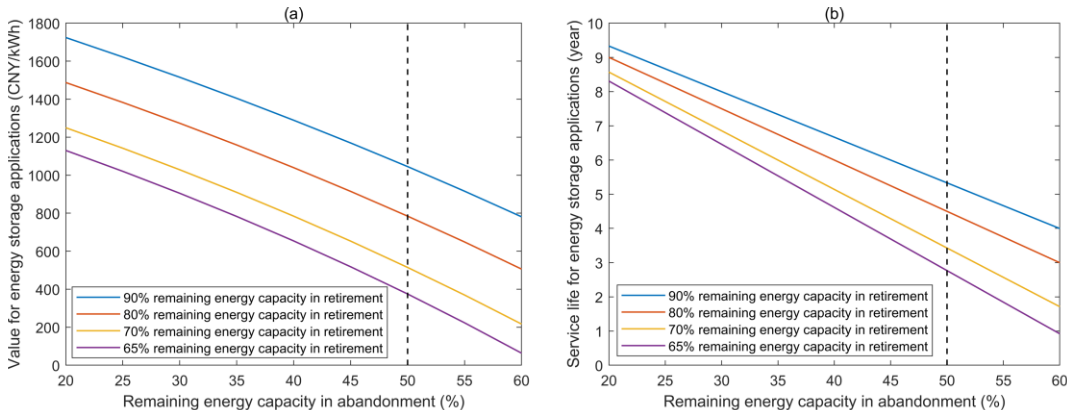

Fig. 2. Value and service lifetime for energy storage applications (discount rate: 6%)

3.3 Sensitivity analysis for discount rate and battery degradation rate

The potential profit of using second life batteries for energy storage can be affected by many factors, most importantly discount rate and battery degradation. When interest rate changes in reality, we may need to adjust the setting of discount rate accordingly in the model. Also, there are uncertainties in the battery degradation rate. The baseline degradation rate in the model is obtained during tests under constant conditions in the laboratory, which could be very different from the operating environment of EVs in use and vary from different battery manufacturers. As a result, there is need to carry out the sensitivity analysis to make the model results more robust.

Fig. 3 shows the impact of discount rate and battery degradation for a battery retired with 80% remaining capacity. Fig. 3.(a) describes the impact of different discount rates on the value for energy storage applications using second life batteries. As expected, decline of discount rate will improve the application value of the second life battery.

In the baseline scenario that the battery is abandoned with remaining capacity of 50%, the service lifetime of second life batteries used for energy storage is around 4.5 years, and the impact of discount rate on the value for energy storage applications is limited, with a potential value of 745-864 CNY/kWh (111-128 USD/kWh) when discount rate ranging from 8%-2%. However, as the service lifetime of second life batteries extends (abandoned with remaining capacity of lower than 50%), the impact of discount rate on the application value of the second life battery increases.

The changes of battery degradation rate will have a larger impact on the value for energy storage applications using second life batteries. In our battery degradation model, the remaining capacity of a new battery will reduce to 71% after 1500 cycles of usage. In the sensitivity analysis, we consider different battery degradation rates, ranging from 61% to 81% remaining capacity after 1500 cycles of usage, shown as Fig. 3.(b). Results suggest in the baseline scenario that the second life battery is abandoned with remaining capacity of 50%, it could achieve a value of 529-1245 CNY/kWh (78-184 USD/kWh) for energy storage applications. In reality, there could be a big difference in the degradation rates of a variety of batteries. For higher-quality batteries with slower degradation rate, they could serve a longer lifetime in EVs before retirement and bring in higher value when used for energy storage after retirement, and we need to take that into account when accessing their market values.

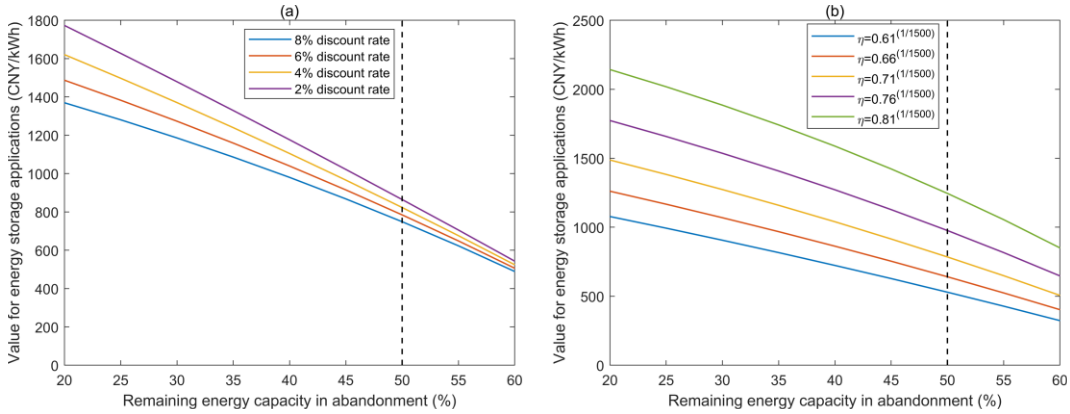

Fig. 3. Sensitivity analysis for discount rate and battery degradation rate

4. Market price for second life batteries

In the above analysis, the potential profit from using second life batteries for energy storage applications has been estimated. To allocate profit among different parties including battery recycling enterprises, energy storage plants and second life battery owners, it is important to assess the price for used batteries.

As mentioned before, in this paper we provide an estimation price range for the market price for second life batteries, with the lower limit being the ‘willing to sell’ price and the upper limit being the ‘market evaluation’ price.

(1) The ‘market evaluation’ price

The ‘market evaluation’ price can be regarded as the highest price that the market would accept for buying the used battery, which is mainly determined by the condition of the battery and the current market price for a new battery.

In light of the 2018 semi-annual report of Contemporary Amperex Technology Co. Limited (CATL),[5] the world’s largest provider of EV batteries followed by Panasonic (Sanyo) and BYD,[6] the market price for a new EV battery was about 1,106 CNY/kWh (164 USD/kWh) in 2018. By adopting the method of PVT and based on the market price for a new battery, Fig. 4 shows the SOH and the corresponding ‘market evaluation’ price for a second life battery based on its remaining capacity in retirement.

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5 http://static.cninfo.com.cn/finalpage/2018-08-24/1205321523.PDF.

6 https://en.wikipedia.org/wiki/Contemporary_Amperex_Technology.

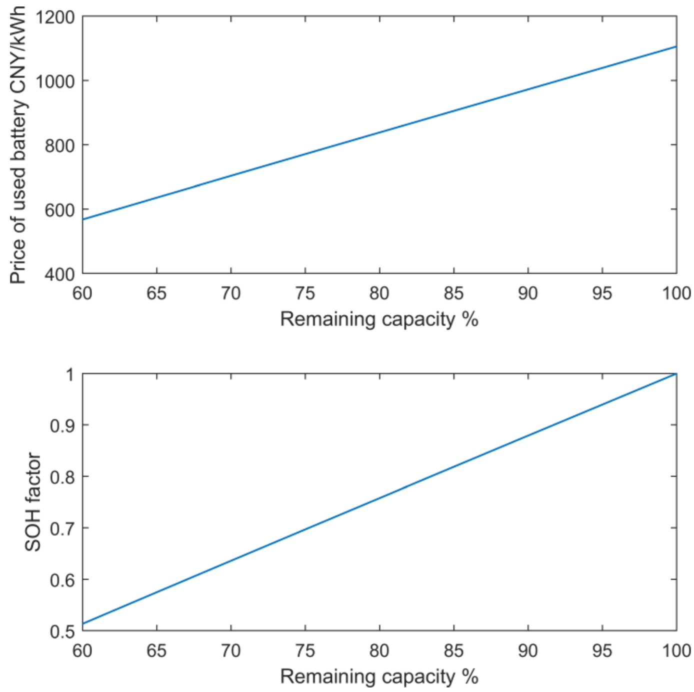

Fig. 4. SOH factor and 'market evaluation' price for a second life battery

(2) The 'willing to sell' price

The 'willing to sell' price can be regarded as the lowest price that the battery owner would accept for selling the used battery, which is estimated based on the residual value for a used EV and using an equivalence approach. As in reality, the residual value for a used EV battery depends on how the EV owner values it, so it could be very different even for those used EVs of similar condition. As a result, we estimate the residual value for a used EV battery by considering the lifecycle use costs of the EV and assume that the EV owner will take the lifecycle use costs of a conventional internal combustion engine vehicle as reference. To simplify our analysis, we do not consider maintenance costs, so the use costs for an EV mainly include battery degradation costs and electricity costs; while the use costs for a conventional vehicle are the fuel costs. So 'willing to sell' price will be a price that enables the use costs of EVs not exceeding that of conventional vehicles, for a given total mileage.

According to the "General principles for calculation of the comprehensive energy consumption (GB/T 2589-2008)", the calorific values of petrol is 43070 kJ/kg.[7] The normal density of petrol is 0.74 kg/L (ranging from 0.71 kg/L to 0.75 kg/L for various petrol types with different octane

[7] http://www.fjyc.gov.cn/upload/content/file/20131210/20131210144611_9407.doc.

rating), reported by the SinoPec.[8] And currently most petrol engines are working with an overall efficiency in the range of 20-22% (Patel and Molvi, 2017). Ingram (2014) also argued the average thermal efficiency for most petrol engines is about 20%. The above-mentioned numbers suggest that 1 L of petrol could produce useful work of around 6.37 MJ for gasoline vehicles. Considering energy consumption for EVs, an electric motor is generally believed to have an efficiency between 85% and 90%.[9] This means, the energy conversion coefficient μ in Equation (20) is assumed to be 2.1 kWh/L, i.e., 2.1kWh of electricity would be needed to produce useful work of 6.37 MJ. For the gasoline prices, the average market price of CNY6.457/L (USD0.955/L) between January 2010 and August 2018 is used; while for electricity price, the average commercial tariff of CNY0.769/kWh (USD0.114/kWh) between January 2010 and August 2018 is used.[10]

The price for a new battery (P_{new}) refers to the market price for a new battery at the time when an EV was just bought (as a part of the EV purchase price), rather than the current (at the time of intending to sell a used battery) market price for a new battery (CP_{new}). Again, an assumption of 2,285 CNY/kWh (338 USD/kWh) is made according to annual reports of Contemporary Amperex Technology Co. Limited (CATL).[11]

Fig. 5 shows the 'willing to sell' price for a second life battery based on its remaining capacity in retirement. Results show that, when remaining capacity of a battery falls below 77% of its rated capacity, the 'willing to sell' price for the used battery will be no more than 0, and its value will be determined by the business models for batteries. If the battery is bought by the EV owner (together with the EV), then the 'willing to sell' price for the used battery will be 0 for any remaining capacity below 77% (shown as the red line in Fig. 5). However, if the battery is leased by the EV owner (from EV manufactures), which means the EV manufactures can benefit from leasing the battery and the 'willing to sell' price for the used battery will be negative for remaining capacity below 77% (shown as the blue line in Fig. 5). The negative 'willing to sell' price from another sense, means the profit that EV manufactures could obtain

[8] http://www.sinopec.com/listco/products_services/for_consumers/oil_products/.

[9] https://cleantechnica.com/2018/03/10/electric-car-myth-buster-efficiency/.

[10] https://insights.ceicdata.com/.

[11] http://static.cninfo.com.cn/finalpage/2018-05-29/1205010303.PDF.

through leasing batteries to EV owners.

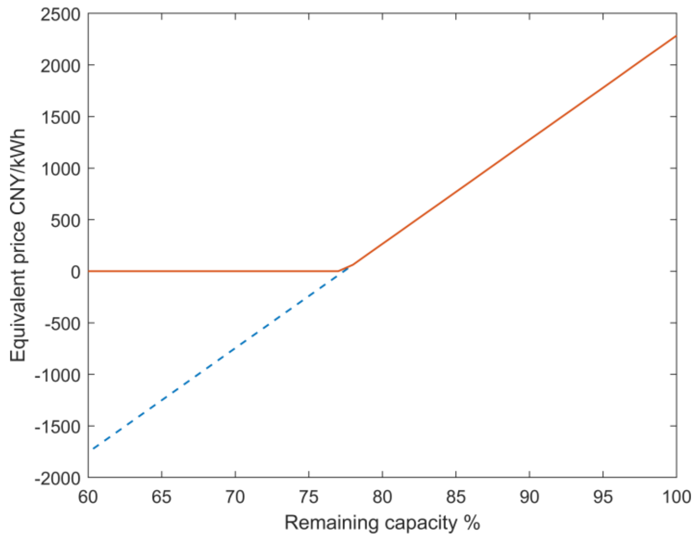

Fig. 5. 'Willing to sell' price for a second life battery

Fig. 6 shows potential profit of reusing second life batteries for energy storage (remaining capacity is assumed to be 50% in abandonment), based on the above-mentioned estimation on value for energy storage applications and market price for second life batteries. When the remaining capacity in retirement is above 85%, the 'willing to sell' price would be higher than the 'market evaluation' price for a second life battery. As the EV owners will not accept a buying price for their used batteries lower than the 'willing to sell' price, the potential profit of reusing second life batteries for energy storage would be the value for energy storage applications minus the 'willing to sell' price for second life batteries.

When the remaining capacity in retirement falls below 85%, the 'willing to sell' price would be lower than the 'market evaluation' price for a second life battery. If the price for second life batteries is determined by the 'market evaluation' price, the profit of reusing second life batteries could achieve a maximum value of 113 CNY/kWh (17 USD/kWh) and the optimal remaining capacity in retirement would be 85% (as illustrated by Fig. 6., grey area means the potential profit for the second use of EV batteries when their price is determined by the 'market evaluation' price, with the maximum profit showing as 'BC'). However, if the price for second life batteries is determined by the 'willing to sell' price, the profit of reusing second life batteries could achieve a maximum value of 674 CNY/kWh (100USD/kWh) (showing as 'DE' in Fig.

6), and the optimal remaining capacity in retirement would be 77%. This will also enable the maximum total surplus of economic welfare from reusing EV batteries for energy storage, therefore, 77% is regarded as the ideal remaining capacity for EV battery retirement.

It is worth mentioning that, the 'market evaluation' price is estimated mainly base on the SOH of the used battery, however, in reality the market price for used batteries can be affected by many other factors such as supply and demand, as well as market mechanism. But in any case, if the market price is somewhere within the grey or bule area in Fig. 6 where the remaining capacity is below 87%, the reusing of second life battery will enhance the welfare and achieve Pareto improvements.

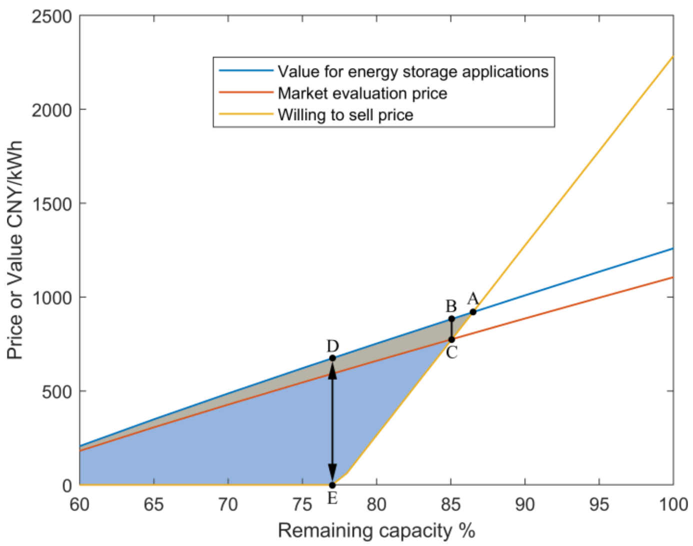

Fig. 6. Potential profit of reusing second life batteries for energy storage

5. Discussion

Many studies have argued that the high costs of EV batteries impede the market adoption of EVs, as nearly half of their costs coming from the expense of the battery. By reusing these batteries under certain business operations, potential profits can be created, and therefore the value of EVs can be higher by extending the service lifetime of their batteries (Lih *et al*., 2012). In light of the "Interim measures for recycling management of EV batteries for new energy vehicles"[12] released in February 2018, China's EV manufacturers need to take responsibility for collecting used batteries. That means EV manufacturers are required to establish channels and networks for collecting EV batteries and sharing these recycling channels with EV battery manufacturers and battery recycling companies. As a result, those companies will be the main suppliers for second life batteries in the future.

To improve the cascade utilization of EV batteries, we suggest a business model that illustrate as Fig. 7. In our model, EV manufacturers provide EV batteries to EV owners through selling or leasing, and take responsibility for collecting those used batteries when they reach their retirement phase. It is reasonable to make EV manufactures responsible for used battery collecting in practice for two reasons. First, EV manufactures can connect and communicate directly with EV owners, which makes it convenient for them to collect those used batteries. Second, when EV manufacturers are responsible for collecting the used batteries it enables them to create a unified specification and dimensions for EV batteries, which will help greatly with their integration into energy storage applications. To promote the cascade utilization of EV batteries, EV manufactures can then sell second life batteries to energy storage operators.

In turn, energy storage operators are then able to lease these second life batteries as part of an energy storage system to end-user energy storage units and reclaim the abandoned batteries when they can no longer be used for the purpose of energy storage. Leasing is likely to be more preferable than selling in this case, as there may be a difference in performance for second life batteries when they are retired from EVs with different remaining capacities. Generally speaking, customers have limited information to make an accurate judgement on the conditions of batteries which may therefore impede the market adoption of second life batteries. However, through leasing, the problem of asymmetric information can be overcome effectively as energy storage operators are taking the risk of performance inconsistency for second life batteries. On one hand, energy storage operators have better information on battery performance and that would give potential customers confidence on battery quality. Equally, customers can request a replacement when there is a quality issue on a second life battery, or terminate the lease contract easily when the energy storage system falls short of their expectations. After service

[12] http://www.miit.gov.cn/n1146290/n4388791/c6068851/content.html.

in energy storage applications, the abandoned batteries are reclaimed and handed over to battery recycling companies.

At the recycling stage, the retrieved raw material from abandoned batteries can be sold to EV battery manufactures for producing new EV batteries. Though raw material recycling could potentially increase the residual value of batteries, the cost of recycling needs to be taken into account. Due to the lack of data regarding relevant costs in large-scale battery recycling, the residual value of abandoned batteries has not been evaluated in this paper and remains a topic for future research.

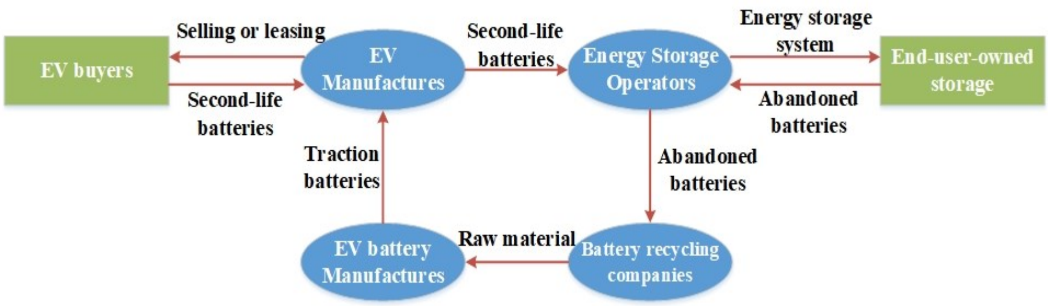

Fig. 7. Business model for cascade utilization of EV batteries

If this business model is to be implemented, the market value of second life batteries and the potential value from their use in energy storage applications could improve EV price competitiveness through a reduction in the cost of EV ownership. Based on our results described in Fig. 6, assuming the market price for second life batteries is determined by the 'willing to sell' price and these second life batteries are retired at the optimal remaining capacity of 77%, Table 1 shows potential profit of reusing second life batteries for energy storage applications and its impact on EV price, which is represented by the ratio of the potential profit for energy storage applications to vehicle price. It can be seen that, for these top ten best-selling models in China's EV market in 2017, the potential profit of reusing second life batteries for energy storage applications ranges from CNY 24,000 (USD 3,551) to CNY 82,000 (USD 12,132) depending on the capacity of their batteries, and it accounts for 14.3%-36.3% of the upfront EV price. These results show that there is considerable room for improving EV competitiveness through establishing business models for cascade utilization of EV batteries.

Table 1. The value of retired EV batteries from the top ten best-selling models in China

Vehicle model	Average capacity (kWh)	Vehicle average price (thousand CNY)	Profit for energy storage applications (thousand CNY)	Profit /vehicle price
BAIC EC series	20.3	158	27	17.3%
Know beans D2	18	170	24	14.3%
Chery eQ series	23	166	31	18.7%
JAC iEV6 series	30.6	139	41	29.7%
BYD e5	60.48	225	82	36.3%
Geely Emgrand EV	47.8	216	65	29.9%
Zotye E200	31.9	126	43	34.2%
JMC E200	23.3	87	31	36.2%
Changan BenBen EV	31	130	42	32.2%
BAIC EU series	48.2	228	67	29.4%

6. Conclusions and policy implication

This paper builds an operational optimization model to evaluate the maximum potential profit for using second life batteries from EVs to serve as energy storage systems, with the aim of providing some reference for policy makers evaluating policies for supporting EV related industries, EV manufactures designing their business strategies around used EV batteries and consumers making their purchase decisions on EVs.

Results show that there is potential for considerable profit from energy storage applications and the value would be higher when the second life battery is retired with a higher remaining capacity and abandoned with low remaining capacity (the cost for buying the second life battery is not considered). Under the baseline scenario that battery is retired with remaining capacity of 80% and is abandoned with remaining capacity of 50%, it could achieve a value of 785 CNY/kWh (116 USD/kWh), and the service lifetime of the retired battery is 4.5 years. If a battery is retired with remaining capacity of 80% and is abandoned with remaining capacity of 20%, it could achieve a value of 1,487 CNY/kWh (220 USD/kWh).

However, this profit will fall if we consider the acquisition cost of second life batteries. As a result, we estimate a market price range for second life batteries, with the lower limit being the 'willing to sell' price from the perspective of EV owners and the upper limit being the 'market evaluation' price evaluated based on health condition of the used battery and the current market price for a new EV battery. Results suggest that when the remaining capacity in retirement falls below 87%, the value of energy storage application is higher than the "willing to sell" price, and the reuse of second life battery can achieve a Pareto improvement. When the remaining capacity in retirement falls below 85%, the 'willing to sell' price would be lower than the 'market evaluation' price for a second life battery. The profit of reusing second life batteries for energy storage could achieve a maximum value of 674 CNY/kWh (100USD/kWh) with an optimal remaining capacity of 77% in retirement. This will also enable the maximum total surplus of economic welfare from reusing EV batteries for energy storage, therefore, 77% is regarded as the ideal remaining capacity for battery retirement.

For the top ten best-selling models in China's EV market in 2017, the potential profit of reusing second life batteries for energy storage applications accounts for 14.3%-36.3% of the upfront EV price, suggesting that there is considerable room for improving EV competitiveness through establishing business models for cascade utilization of EV batteries and building a market for used batteries.

To encourage reusing second life batteries for energy storage applications, we make the following policy suggestions.

First, battery standardization is important for second life batteries serving as stationary energy storage systems. To date, there is no universally accepted manufacturing and recycling standards, and EV manufactures often opting to cooperate with different battery suppliers, which presents a challenge for battery reuse. Therefore, to promote EV battery reuse and recycling, national standards on specification of EV batteries and requirements on the test of residual capacity, dimension, coding regulating should be established.

Second, our model results suggest that battery degradation could have a big impact on potential profit from reusing EV batteries for energy storage applications. The battery degradation could be affected by many factors including the battery quality and operating environment in use. And due to asymmetric information, potential customers for used batteries may have concerns on their quality and this could impede the market adoption of second life batteries. Therefore, there is need for a transparent tracing and evaluating mechanism on battery quality to reassure consumers and reduce unnecessary concerns. In addition, policies should focus on supporting the implementation of finance lease to increase market adoption of second life batteries, and encourage applications of user-side energy storage.

Third, China has made EV manufacturers responsible for setting up facilities to collect used batterie through battery recycling regulations. In the meanwhile, many EV manufacturers have offered EV battery warranties which cover repair service or guarantee a replacement, in order to offset some of the range concerns raising from potential EV consumers. According our model results, the optimal remaining capacity in retirement would be 77%. EV manufacturers could consider making it as a criterion for battery replacement.

Finally, consumers may have concerns about economic feasibility of a new technology and application. To demonstrate the viability of the business model, pilot projects in selected cities would provide valuable learning. Such pilot projects could be located in load centers such as Guangdong or Shanghai, where a large part of electricity demand is met by imported energy, and both their electricity prices and peak-valley differences are higher, which would enable greater profit from energy storage applications.

On the other hand, this study also has some limitations.

First, will the energy storage market be large enough for using these retired EV batteries in China? A study by Lin and Wu (2017b) argued that the ideal ratio of energy storage to daily electricity consumption should be ranging between 4.6% and 7.4% in China. Which means, potential energy storage capacity could reach 1 TWh in China.[13] This demand for energy storage may become even larger as the penetration of renewable energy increases. Given China's goal of 5 million New Energy Vehicles by 2020, and an overall average rated capacity for EV batteries of around 29.5 kWh, assuming EV batteries retire at 80% of rated capacity (i.e., 23.6 kWh) and an annual increment of 1 million in EV sales, the potential capacity of retired batteries is 23.6 GWh per year, which only accounts for a small share of China's potential energy storage capacity. However, more detailed analysis is needed to investigate the

[13] China's total electricity consumption was 6,307 TWh in 2017. Assuming a ratio of energy storage capacity to daily electricity consumption of 6%, it implies that energy storage capacity of about 1 TWh is needed.

relationship between growing retied EV batteries and the emerging energy storage market. Second, if retired EV batteries are massively used in energy storage applications, will that dramatically affect the potential profit? When large-scale of retied EV batteries are deployed for energy storage, it could change the load characteristic of the power grid and therefore have an impact on the peak and valley electric prices. But as mentioned above, for the power grid, there could be a significant room for energy storage applications and large market potential for reusing EV batteries for energy storage, and the potential capacity of retired batteries is considered to be rather small for China's electricity market, which means our model results are convincible at least in the short term. In the longer term, as China's electricity demand keeps rising rapidly, besides revenue from arbitrage, energy storage could also play an important role in reducing the grid infrastructure costs. Nevertheless, as the EV market further expands and battery technology improves, the potential profit from reusing EV batteries for energy storage will change for sure. We will follow market trends and improve our analysis in the future research.

Acknowledgment

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