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The potential energy output and GHG emissions reduction in the second life of retired Li-ion batteries with different capacity

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Abstract. The retired lithium-ion batteries from varied electric vehicle platforms may differ in their potentials to store and deliver energy in the second life, as well as the possibilities to avoid greenhouse gas emissions. In this paper, we simulated the batteries from four typical platforms of electric passenger vehicles. The potential energy output (PEO) and potential greenhouse emission reduction (PGR) of these batteries were calculated. Then a sensitivity analysis was conducted to assess the impacts of the key parameters, such the cycling life, vehicle mileage, end-of-life capacity retention threshold and the battery efficiency fading. It is found that the larger batteries tend to retain a higher potential after their usage in vehicles, which also make it possible to avoid more GHG emissions by replacing the fossil-fuel-sourced electricity during peak load period. Additionally, PGR of PEO of the larger batteries would be less affected by variation of the key parameters.

Key words. Electrical vehicle, Lithium-ion battery, Greenhouse gas emissions, Second-life, Battery degradation.

1. Introduction

Electric vehicles (EV) are regarded as one of the key ways to mitigate the global warming problem (Chu and Majumdar, 2012), however, whose energy storage systems, the traction batteries, may not be environmental-friendly or sustainable (Bossche et al., 2006). It is widely accepted that due to the variation in electricity sources, EV could be more or less cleaner in its use stage than the inner combustion engine vehicle (ICEV). However, in the production and end-of-life stages, EV is usually

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more energy and GHG emissions intensive than its conventional-fuel counterparts, mainly because of the battery (Notter et al., 2010; Majeau-Bettez et al., 2011; Dunn et al., 2015; Ellingsen et al., 2016; Kim et al., 2016). In short, battery may be one of the key components which determine the overall environmental performance of EVs.

There have been several assessment studies (Zackrisson, et al., 2010; Amarakoon et al., 2013; Ellingsen et al., 2014; Li et al., 2014; Oliveira et al., 2015) about the battery's cradle to gate or life cycle energy demands, GHG emissions and other impacts, which reported many findings about the EV or PHEV batteries with different size, cathode or anode chemistry and other variations. Through these studies, cognitions and knowledge of the EV or PHEV batteries have been greatly widened.

However, there lies another question. It is known to all, a battery is deemed to be no longer fit for vehicle use once its capacity degraded to 80% of the initial valve, which would have it retired immediately. Also, it is possible that a battery has to be removed from the vehicle before its capacity retention fell to 80%, for the vehicle itself has reached the end of life. Both cases may left batteries which still remain part, even most of its designed capability to store and deliver energy, and what's more, the chance to reduce GHG emissions in other applications, such as energy storage system (ESS) (Genikomsakis et al., 2013; Heymans et al., 2014), etc. Thus, those potentials should be assessed and estimated before battery is dismantled and recycled, since an extended usage of this battery could bring more benefits, functionally and environmentally. Several studies focused on this issue have been carried out, for example, Ahmadi et al. (2014) examined the potential GHG reduction by the extended EV batteries using in grid storage system; Faria et al. (2014) conducted an impacts assessment about the first (in EV) and second use (in residential energy storage) of batteries under a series of variations; Casals et al. (2015) assessed the life cycle GHG emissions per unit energy output of EV battery's second use; Sathre et al.(2015) predicted the potential GHG reduction by utilizing the second-life EV batteries in California; Ahmadi et al. (2015) carried out a complete life cycle impact assessment of battery in EV and extended use, 6 categories of impacts covering global warming, environmental degradation and resource depletion were assessed and compared between different scenarios. All these studies validated the potential benefits of second use of EV batteries and their results are relatively encouraging.

Nevertheless, it's obvious the potentials could be quite different, since there are too many relating factors, e.g. the chemistry and specifications of the batteries, the charging and discharging patterns in their first lives and working environments. Though several studies have been carried out in this field, few have focused on this spot. Therefore, modeling some batteries working on different vehicle platforms with various conditions would be an efficient way to identify and evaluate those potentials.

In this study, the potential energy output (PEO) and potential GHG emissions reduction (PGR) of the retired batteries in their second life use were assessed. Accordingly, the residual value of batteries retired from different electric vehicle platforms or working conditions could be compared and analyzed. The results could be utilized in the pricing strategies for the retired EV batteries, and to support the policy making in EV battery related industries.

2. Method

2.1. *Specifications of the vehicles and batteries*

(1) Vehicle platforms

Four classes of vehicles were chosen as the working platforms of batteries' first life use, which are platform A for mini cars, C for medium cars, D for large cars and F for luxury cars. Detailed specifications of these vehicles are cited from the early study (Ellingsen et al., 2016), as demonstrated in table 1.

Table 1. The specs of batteries and their vehicle platforms

Specs	Unit	A	B	C	D
vehicle class	/	mini	medium	large	luxury
energy efficiency	Wh/km	133	155	169	189
battery capacity	kWh	17.7	26.6	42.1	59.9
all electric range	km	133	172	249	317
vehicle curb weight	kg	1100	1500	1750	2100
mass of battery	kg	177	253	393	553
specific energy	Wh/kg	100	105	107	108

(2) Batteries

All the batteries are not real but simulations of EV battery technologies nowadays. The cathode active material is lithium nickel manganese cobalt oxide (NMC). The mass and specific energy of the battery packs are also showed in Table 1. Some key parameters of the batteries were discussed below.

Cycling life

The cycling life of a battery was identified as the number of cycles in the given working conditions (environment temperature, depth of charge, rate of charging & discharging current, etc.) till the energy capacity falls below 0.8 of its initial value. Nominal cycling life of a battery is usually obtained through standard testing procedures, however, in practical use the real cycling life would differ quite much. For NMC Li-ion batteries, the cycling life is ranged from 500 $\sim$ 3000 (Omar et al., 2011; Wood et al., 2011; Ellingsen et al., 2016). In this study, we assumed the cycling life is 2000 in the base-case. Due to the uncertainties in this assumption, we also examined the outcomes when the cycling life is 1500 and 2500 in the sensitivity analysis, respectively.

Capacity fading

Once a battery starts its charge/discharge cycles, the capacity fading is unavoidable, i.e., as the result of the consumption of Li-ion in the electrolyte and the growing of solid-electrolyte-interphase (SEI), the battery's available capacity would gradually decline (Wood et al., 2011). For simplicity, we assumed the battery capacity was to decrease in a linear function of the cycle times, i.e., the degradation rate is constant, and could be obtained through dividing capacity loss by the cycling life, e.g., when a battery's cycling life is 2000, its degradation rate of capacity is 0.2/2000

= 0.0001 per cycle.

Efficiency

Efficiency matters in every energy conversion system, so does the battery. In this study, we mainly concern the efficiencies exists in two parts, the charger and the battery, as showed in Figure 1.

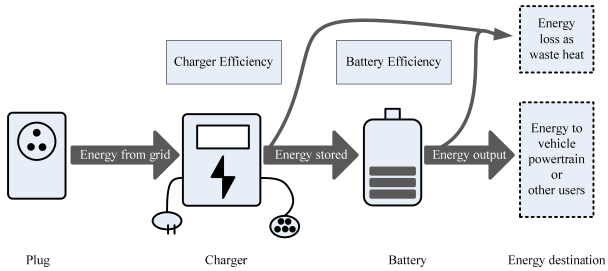

Fig. 1. Efficiencies of charger and battery

The charger matched for EV is usually a rectifier and transformer, in which the alternating current (AC) from grid (plug) was turned into direct current (DC) with a voltage adjustment, in this process, a portion of energy was lost as waste heat, the rest was transferred to the battery and regarded as the energy stored, the efficiency of the charger is identified as the ratio of the latter to the energy from the grid, whose value was set at 96% constantly (Ellingsen et al., 2016). The second part is the battery efficiency (BE), which is the ratio of energy output from the battery to the energy it stored. The initial BE was set to be 95% (Ellingsen et al., 2016).

Here we considered two scenarios, without or with BE fading. If there is no BE fading at all, the BE would remain 95% constantly. In the other scenario, BE would gradually decline in a linear function of its cycle times, when capacity of the battery falls to 50% of its nominal value, its BE degraded to 70% (Ahmadi et al., 2015).

Therefore, the degradation rate of BE is also assumed to be constant. The value was obtained through dividing 0.25 (which is the difference between the initial efficiency 0.95 and the end-point value 0.7) by the number of total cycles of its two usage stages. All the related details of the BE in the scenarios without or with fading are listed in Table 2.

Table 2. The specifications of BE

Specification	without fading	with fading
BE (initial)	0.95	0.95
BE (end point)	0.95	0.7
degradation rate per cycle	0	0.00005

2.2. Life cycle stages

The typical cascaded life cycle of a traction battery could be demonstrated in Figure 2, including production, the first life use, re-purposing, the second life use and end of life. (Ahmadi et al., 2015)

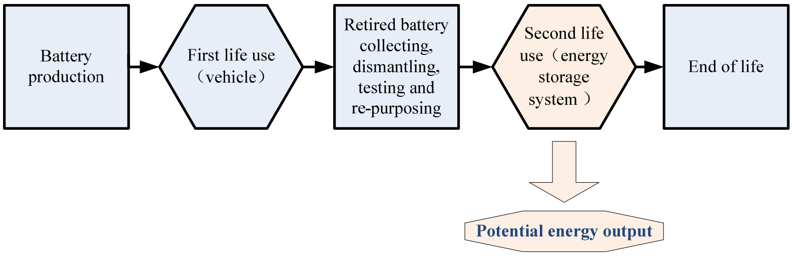

Fig. 2. Life cycle stages of batteries

Production

Production of a battery including the material extraction, preparation, components manufacture, battery assembly and transportations, all of these processes would generate GHG emissions. Since the second life use is the primary concern in this study, we collected the related data from the work of Ellingsen et al. (2016).

First life use

In order to make the comparison possible, we assumed a relatively fixed scenario for the batteries' first life use. Uncertainties such as user's driving style, charging pattern, climate of the travelling region were ignored.

The annual mileage of the vehicles is 12500 km and the total mileage is 125000 km after a ten-year service, the annual range was assumed based on a prior research of private passenger vehicles' daily mileage in Beijing from 2012 to 2013 (Wang et al., 2013), which reported an average daily travel range of 33.5 km (equals to an annual mileage around 12 200 km) from all of the private passenger vehicle samples.

The vehicle platforms with different battery capacity varied in their available all-electric ranges (AER), which may lead to different frequencies of charging. In order to limit these variations, we assumed that for a certain vehicle platform, the distance travelled between charging is identical all through the first life use stage, which is 0.75 of its initial AER, thus the depth of discharging (DOD) would be restrained in a limited range, e.g., to the mini cars (platform A), with an initial AER of 133 km, the distance it travelled between charging is 133*0.75 = 100 km, dividing the annual mileage by this value, we can obtain the annual charging times, i.e. the annual cycles. Unavoidably, the DOD of the battery would be 75% at the beginning and increased gradually as the capacity fades.

Regarding the uncertainty in the assumptions above, we examined the outcomes with annual range being10000 km and 15000 km respectively, in the sensitivity analysis.

Re-purposing

The re-purposing process including the collecting of the retired batteries, dismantling, testing, re-assembly of the battery, disposing the failed cells, replacing or adding some necessary parts. Due to the lack of detailed data, we assume that the energy demand and GHG emissions in this process is as more as 30% of the first production stage (Ahmadi et al., 2015).

Second life use

Once installed into the ESS, the re-purposed batteries were then to be charged by wind power, and discharged in the peak load period of the day. The frequency of charge/discharge is one cycle per day, i.e. 365 cycles per year. The service-year of this stage is dependent on the available cycles of the battery before its capacity falls to 50% of the initial value.

The energy output per cycle of the battery from a certain vehicle platform is determined by the DOD, the BE and the capacity retention after its first life use. In base-case, we assume the BE and the DOD remain 95% and 80% respectively all through the second life use, as the capacity retention keeps falling down, the energy output per cycle would also decrease gradually. Such settings make the comparison possible since batteries from different platforms could work in a similar pattern.

End of life

After the capacity retention falls below 0.5, the batteries would be uninstalled and sent to the recycling facilities. We assumed a hydrometallurgical process for the disposed batteries, which required some reaction agents and out-sourced energies (Ellingsen et al., 2016). By modelling this process in LCA software, the GHG emission intensity for every kilogram of disposed battery was obtained. Besides, the materials and components needed in re-purposing should also be recycled, being lack of detailed data, we assumed an extra 30% GHG emissions were discharged from their end of life processes.

The uncertainty arose from the capacity retention threshold of battery's end of life should not be underestimated. Thus we examined 0.4 and 0.6 as the two alternative values in the sensitivity analysis.

2.3. potential energy output (PEO)

The PEO is the product of the battery's energy output per cycle and the total cycle times in its second life use, as Equation 1.

$$PEO = EO_{percycle} \cdot TC\,. \tag{1}$$

where $EO_{percycle}$ and TC are the average energy output per cycle and total cycles, respectively, which could be obtained through Equation 2 and 3.

$$EO_{percycle} = DOD \cdot C_{initial} \cdot CR_{avg} \cdot \eta_{battery}\,. \tag{2}$$

$$TC = N \cdot SY\,. \tag{3}$$

where DOD, $C_{initial}$, CR_{avg}, $\eta_{battery}$, N, SY, are depth of charge, initial capacity of the battery, BE, number of annual cycles, service years and average capacity retention, respectively.

Since the capacity retention of battery declines with every working cycle, the

CR_{avg} should be obtained through Equation 4,

$$CR_{avg}{=}SY^{-1} \cdot \int_{0}^{\text{service year}} (CR - DR_{capacity} \cdot N \cdot SY)\mathrm{d}t\,. \tag{4}$$

whereCR, $DR_{capacity}$ are the capacity retention (after first life) and degradation rate of capacity, respectively.

Taking the efficiency degradation into account, $\eta_{battery}$ would decrease after each charge/discharge cycle with a constant rate as mentioned above, hence the $\eta_{battery}$ in Equation 2 should be replaced by the average BE in second life, which can be obtained through Equation 5,

$$\eta_{battery,avg}{=}SY^{\text{-}1} \cdot \int_{0}^{\text{service year}} (BE - DR_{battery} \cdot N \cdot SY)\mathrm{d}t\,. \tag{5}$$

where $\eta_{battery,avg}$, BE and $DR_{battery}$ are the average BE, battery efficiency (after first life) and degradation rate of BE, respectively.

Due to the difference in the batteries' capacity, the specific PEO is necessary for the comparison under a normalized functional unit, i.e. the PEO per each kWh of initial capacity of the battery. In this case, we identify the PEO' which can be calculated as Equation 6,

$$PEO' = PEO/C_{Initial}\,. \tag{6}$$

2.4. potential GHG emissions reduction (PGR)

The amount of PGR in the second life use stage is strongly dependent on the scenarios in which the comparison is carried out. As mentioned before, we assumed the retired batteries were installed in the ESS, charged by wind power and discharged in peak load period of the day, in this scenario the retired EV batteries and renewable energy source were incorporated. In another conventional scenario where there is no ESS, we assumed that the same amount of peak load of the power grid is satisfied by the natural gas fire plant, which usually takes part in the grid's load adjusting for its instant reaction and high flexibility. Hence, the PGR of retired battery could be identified as the difference between the GHG from the wind-ESS system and that from a natural gas-fired plant which delivers a same amount of energy to the end users, as showed in Figure 3. It should be noted that the energy loss in electricity transmission exists in both scenarios, differences in these losses were omitted for simplicity.

The $GI_{balance}$ is the difference between the GHG emissions intensities of the electric energy from natural gas fired power plant and the ESS (with retired battery)-wind system, which could be calculated though Equation 7,

$$GI_{balance} = \ GI_{natural\ gas} - GI_{ESS-wind}\,. \tag{7}$$

where, $GI_{naturalgas}$ is the GHG intensity of electricity from the natural gas fired

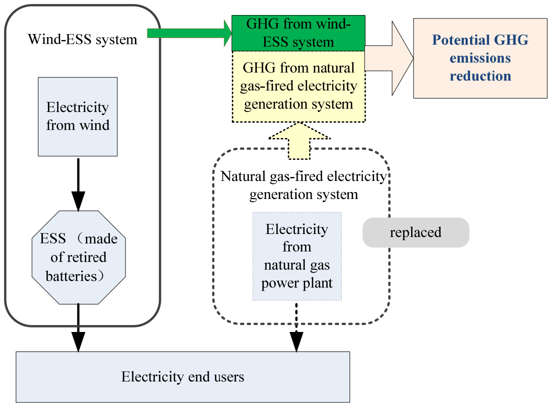

Fig. 3. The PGR of retired batteries

power plant, which is 0.51 kg CO_2 eq/kWh (O'Donoughue et al., 2014), while $GI_{ESS-wind}$ is the GHG intensity of the energy output from the ESS (with retired batteries) charged by wind power. Since there is some energy loss due to the efficiency of the charger and battery in that process, the $GI_{ESS-wind}$ should be calculated as Equation 8,

$$GI_{ESS-wind} = GI_{wind}/(\eta_{charger} \cdot \eta_{battery}) \,. \tag{8}$$

where GI_{wind} is the GHG intensity of the electricity from the wind power farm, $\eta_{charger}$ is efficiency of charger, which were assumed to be constant in the base-case scenario.

Then, we can have PGR as Equation 9,

$$PGR = GI_{balance} * PEO - GHG_{rp} \,. \tag{9}$$

where GHG_{rp} represents the extra $GHGs$ emitted in the re-purposing and end-of-life process, but excludes GHGs emitted in its original production and end of life, the unit is tonne carbon dioxide equivalent (CO_2 eq), the data was quoted from the prior study (Ellingsen et al., 2016). The PGR could be obtained by taking Equations 1 to 4 into Equation 9. If BE fading was considered, then Equation 5 is added to calculate the $\eta_{battery,avg}$ to replace the constant $\eta_{battery}$, in Equation 2.

Dividing the PGR from batteries by their initial capacity in kWh, we can have the PGR', in the unit of 'tonne CO_2 eq per kWh initial capacity of battery'.

3. Results

3.1. PEO and PGR

In the base-case scenario, we assume a nominal cycling life of 2000 cycles, a total vehicle mileage of 125000 km in the first life use stage. Under these preconditions and other assumptions mentioned above, we obtained the PEO as showed in Figure 4 and PGR in Figure 5 in the unit of 'per battery', where batteries with or without BE fading were represented in solid and dashed lines respectively.

As a result, batteries from vehicle platforms A, C, D and F would delivery 34.1-147.4 Mega-Watt-hours (MWh) energy in the extra 10.3-12.3 years of service as their second life uses if no BE fading occurred, whereas, if BE fades during its cycling, under the same conditions, the PEO and PGR of batteries from A to F platforms would be 29.3-127.8 MWh, which can be observed in Figure 4.

Meanwhile, batteries without BE fading would potentially reduce the GHG emissions by 16.3-70.4 tonne of CO_2 eq, whereas 13.6-60.4 tonne of CO_2 eq from the batteries with efficiency degradation, as showed in Figure 5. The service years have remained the same no matter BE faded or not, for which has nothing to do with the available working cycles.

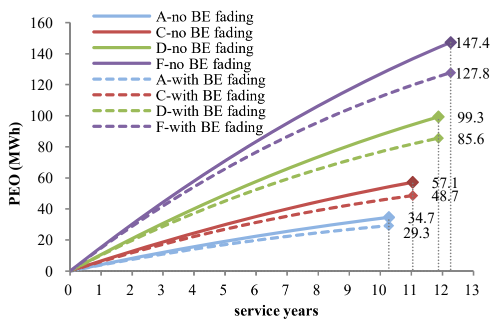

Fig. 4. The PEO of batteries

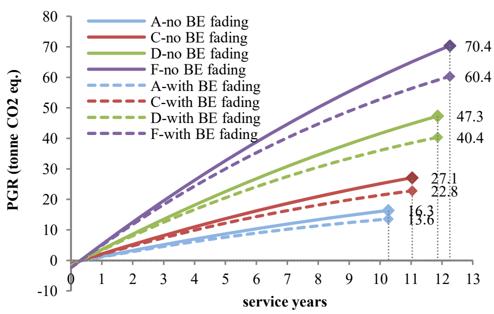

Fig. 5. The PGR of batteries

It should be noted that the PGR in the beginning of battery's second life is below zero, indicating that the initial PGR is actually a GHG emission increase due to the extra energy demand of re-purposing, etc., however, these negative values would turn to positive in less than a year, i.e., suggesting the eventual potential of reducing GHG emissions.

As demonstrated in Figures 4 and 5, PEO and PGR of those retired batteries would continually grow as the service years went by, while the growth speed is slowing down due to the capacity fading, if BE fading was considered, the climbing curve would be even more placid. Meanwhile, since the PGR has linear relationship with PEO, the evolutionary curves of the PEO and PGR versus the service years have shown little difference between Figure 4 and Figure 5 except the numbers on the y-axis.

3.2. PEO' and PGR'

Comparing batteries from different vehicle platforms under a normalized unit, we can find that, as the battery becomes bigger, its PEO' and PGR' also showed a same trend of increasing, with or without BE fading, e.g., if there is no BE fading, battery from the vehicle platform F (luxury car) showed the highest PEO' and PGR', which is 2.5 MWh and 1.2 tonne CO_2 eq per kWh of initial capacity, as light blue column and deep blue diamonds in Figure 6, more than those of the battery from platform A (mini car), C (medium car), D (large car) by 25.7%, 14.6%, 4.3% and 27.3%, 15.4%, 4.5%, respectively. Taking BE fading into account, the PEO' of battery from F platform is 2.1 MWh per kWh of initial capacity, more than that of A, C and D by 22%, 13% and 4%, respectively, meanwhile the PGR' is 1.0 tonne CO_2 eq per kWh of initial capacity, more than that of A, C and D by 24%, 14% and 4%, respectively.

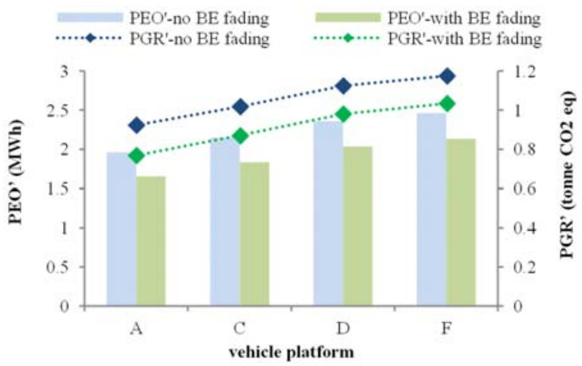

Fig. 6. The PEO' and PGR' of batteries

3.3. Sensitivity Analysis

Since PGR' is in a linear relationship with PEO', we only examine the PGR' in the sensitivity analysis. Figure 7 showed the possible PGR' coverage of batteries from different vehicle platforms, which were resulted from the variation of three parameters in two scenarios: (a) without or (b) with BE fading, these parameters includes cycling life (CL), vehicle mileage (VM) and capacity retention threshold of end-of-life (RT), whose ranges have been presumed above and could been found in the statement below the figure.

*CL = cycling life, ranges from 1500 to 2500; VM= vehicle mileage, ranges from 100 000 km to 150 000 km; RT=capacity retention threshold, ranges from 0.4 to 0.6. The white bar means the PGR' would increase when the value of parameter

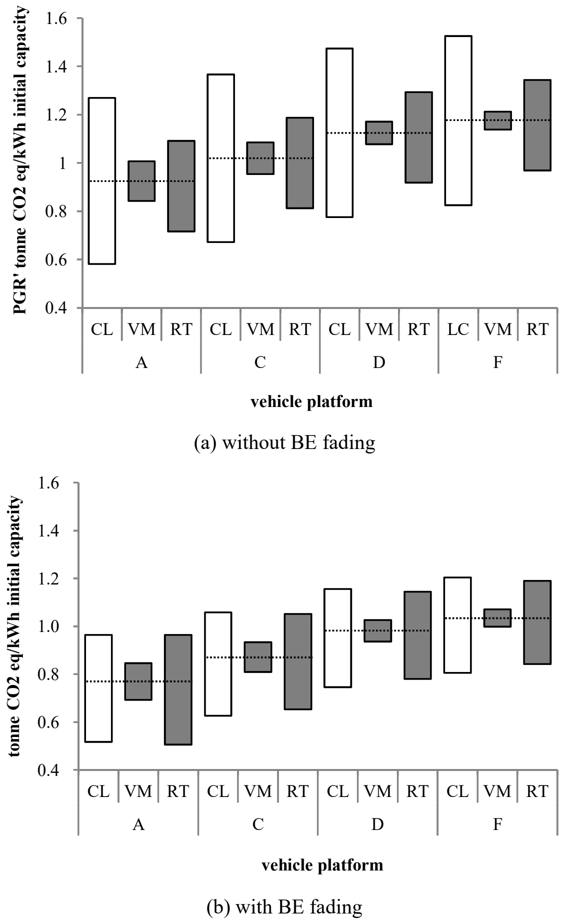

Fig. 7. The PGR' variation in sensitivity analysis*

becomes larger, whereas the dark gray bar means the opposite trend. The dash line represents the base-case PGR'.

Cycling life

More charge/discharge cycles available would mean more energy output and consequentially, more PGR possible. Hence, the variation of cycling life could affect the battery's PGR' significantly. Through sensitivity analysis, it was found that the variation of CL by ±500 times would lead to fluctuations of 0.7 tonne CO2 eq per kWh capacity for any of the batteries from A, C, D and F vehicle platforms when there is no BE fading taken place. With BE fading, the difference between the upper and lower value of PGR' of all the batteries become approximately 0.4 tonne CO_2 eq per kWh capacity, as showed in figure 7 (a) & (b).

Vehicle mileage

Vehicle mileage is another key factor in the first life use of the batteries. Increasing vehicle mileage requires more energy output, which 'consumes' more charge/discharge cycles, therefore leads to a decrease of the available cycles and consequentially, the PEO and PGR in battery's second life use. On the contrary, an increase of PGR could be expected. We examined the scenario in which the total vehicle mileage was increased or reduced by 25000 km (±20% of the original value), as results, the fluctuation of PGR' of the batteries were 0.1-0.2 tonne CO_2 per kWh capacity for all batteries in both scenarios with or without BE fading, as shown in Figure 7 (a) & (b).

Capacity retention threshold

Disposing the batteries sooner or later could also bring discrepancy on their PGR', when capacity retention threshold was set at 0.4 and 0.6 (0.1 less or more than the base-case), the fluctuation of PGR' of batteries from vehicle platform A, C, D and F would be approximately 0.4 and 0.3-0.5 tonne CO_2 per kWh capacity respect to scenarios without or with BE fading, also shown in figure 7 (a) & (b). It can be observed that when BE fading was taken into account, the smallest battery shows the greatest fluctuations on PGR', indicating that, smaller the battery is, more sensible its PGR' is to the threshold variation. However, this phenomenon doesn't occur when there is no BE fading.

BE fading

The BE fading has a negative effect on the PEO and PGR, so for the PEO' and PGR'. In detail, we could find that when the BE fading was taken into account, the PGR' of different batteries in the base-case conditions would decrease by 12%-16.8%, the decreasing range may vary significantly under different parameter settings, e.g., in the scenario where batteries have a cycling life of 1500 times (500 times less than that in base-case) while other conditions remain the same, their PGR' would only decrease by 2.4-11% if BE was considered, which indicates that the BE fading would impact the PGR' more or less, but also depends on many other parameters.

Another phenomenon we found is that when the battery becomes bigger, its PGR's seem to be less affected by the BE fading in most scenarios. As demonstrated in Figure 8, battery from platform F, which owns the biggest initial energy capacity, is usually with the least fluctuation among the 4 batteries, except when the retention threshold becomes 0.4 from 0.5.

4. Discussion

4.1. About the findings

As we've seen in the results, the batteries retired from vehicle usage can potentially work much longer and bring notable environmental benefits, which has also been proved by previous studies made by Ahmadi et al. (2014, 2015), Casals et al. (2015) and Sathre et al. (2015), etc.

In this study, we further the knowledge by studying the difference among the batteries from varied segments of passenger vehicles from mini cars to luxury ones. The results suggest that there are obvious differences among the potential abilities of these batteries to deliver energy and reduce GHG emissions, no matter in the perspective of the battery or each kWh of their initial capacity. Moreover, those

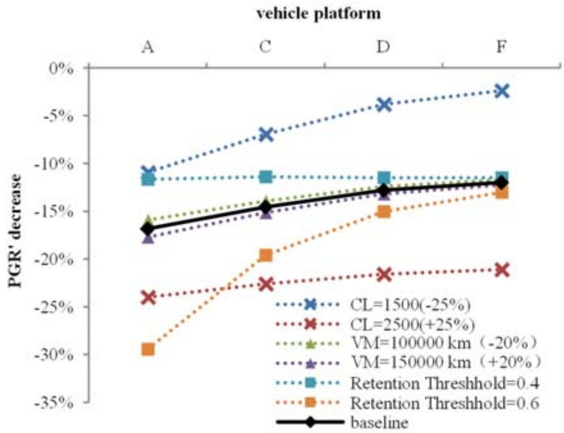

Fig. 8. The decrease of PGR' when BE fading took place

differences may differ as the parameters vary, which include the cycling life, vehicle mileage, retention threshold in this study, besides, the BE fading has also been considered.

With the base-case assumptions without BE fading, second life use of the batteries retired from cars small or large could avoid dozens to over a hundred tonne of GHG emissions, e.g. the PGR of the smallest battery (17.7 kWh) in this study is 16.3 tonne CO_2 eq, which basically consists with previous findings by Ahmadi et al. (2014), who reported a potential reduction of 24 tonne CO_2 eq (Ahmadi et al., 2014), from the 16 kWh pack retired from a plug-in hybrid electric vehicle, notably there are some difference between the assumptions in this study and theirs. In detail, Ahmadi et al. assumed an 8-year service life and 160 000 km total mileage in the vehicle use stage and another 10-year service life in the ESS for the battery, which provides a fixed amount of energy daily, rather than a gradually decreasing value in this study, which may make their results higher than that in this study. Besides, Casals et al. (2015) reported a maximum of 65 tonne GHG reduction by the second use of EV battery in stationary system, from an extra 20 years service life, by replacing the diesel-fueled generator, though the energy capacity of the battery was not mentioned. Since the GHG intensity of diesel fueled electricity (0.78 kg CO_2 eq per kWh according to the Chinese Life Cycle Database, v0.8) is 53% higher than that of electricity powered by natural gas, it can be inferred that their result also agree with what's found in this study if the battery size is similar.

Meanwhile, we found that the largest battery in our cases not only has the biggest PEO and PGR, but also advances most in PEO' and PGR', i.e., suggesting the largest residual value in single kWh capacity. We postulate that the least cycles 'consumed' in first life use may leave the most remained available cycles for its second life use, which made the PEO' and PGR' biggest in all of the batteries. Hence, this advancement may narrow if the batteries' cycling life extends, or the vehicle mileage reduces, so as retention threshold comes later, for which all lead to more available cycles in second life use. This finding suggests that the bigger battery tends to retain a higher per-kWh value after the same mileage of vehicle usage, especially when batteries' cycling life was relatively short. It can be expected that the healthier state of the retired vehicle battery would lead to a higher price for repurchase, which would compensate the owners of the larger EVs economically better.

Furthermore, we compare the GHG emissions reduction between the batteries' first and second life, the results are presented in Figure 9. The empty columns with black frame represent the GHG reductions in the vehicle use stage, which is the difference between life cycle GHG emissions from the conventional vehicles and same size EVs all through their life cycles (including production, use and end-of-life), by normalizing the results from Ellingsen et al. (2016) based on the total mileage (from 180 000 km to 125 000 km). The columns filled with dark grey stand for the PGR of batteries in this study, just from the same vehicle platforms, while the error bars located above or below the top of the column of PGR represent the lower and upper value under different parameters settings, which include LC and BE fading (VM has been fixed at 125 000 km).

It can be observed that, for the battery from any vehicle platform, its PGR of second life is bigger than GHG reduction in the vehicle use stage, and as the vehicle platform becomes larger, the gap turns more significant. It should be noted that the GHG reductions from Ellingsen et al. (2016) were obtained based on the assumption of charging the EV with the average European electricity mix, with a GHG intensity of 521 gram CO_2 eq per kWh, which is far more than that of Chinese power grid mix (about 900 gram CO_2 eq per kWh according to the Chinese Life Cycle Database, v0.8), thus the GHG reduction would be much less if those vehicles were deployed in China and charged by the Chinese power grid mix. It is predictable that the GHG reductions may vary greatly if the vehicles were charged by electricity from different sources, however, those scenarios are beyond the scope of this study, since our primary concern in this comparison is the difference across the vehicle platforms. As we can see, with the same mileage in vehicle use stage, the larger car's retired battery tends to bring an impressive GHG reduction in its second life, which may be several times more than that of its first life use.

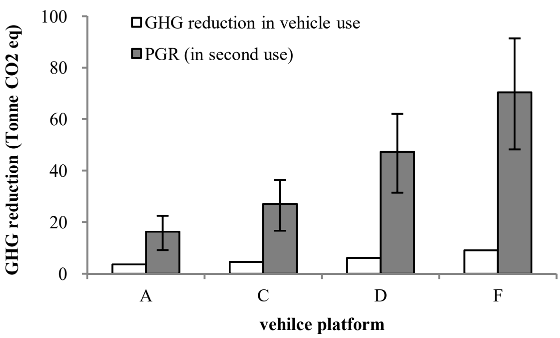

Fig. 9. The GHG reduction in vehicle use and PGR in second life

All these findings above strongly suggest the importance of second life use of retired traction batteries form EVs, not only for the sizable amount of avoidable GHG emissions, but also for the benefits cover a wide range from electric-mobility to renewable energy utilization, especially for those bigger batteries from larger cars.

4.2. Limitations

In this study, we compared the PEO, PGR of batteries from different segments of vehicles, the results showed that larger the battery is, the greater potential (to transmit energy and reduce GHG emissions) it may possess. However, it should be noted that these results were based on a number of assumptions and preconditions, including the parameters mentioned above such as cycling life, vehicle mileage, threshold of end-of-life capacity retention and BE fading, since their influences has been examined in the sensitivity analysis, we focused on the limitation arose from other preconditions.

Firstly, we assumed that all the vehicles would follow a same pattern of charging-driving-charging and maintain this pattern all through their usage life, which may not accord with the reality, since small EV (e.g. Benz Smart) and luxury EV (e.g. Tesla Model S) are designed to meet the demands of different consumers, whose using habits, driving style and infrastructures may differ quite much. However, there are few studies or surveys about those differences in the practical situation, without reliable data it is hardly to cover the possible variations in this study.

Secondly, the concept of PGR could be regarded as a relatively optimistic prediction of the retired batteries' potentials, for there are many obstacles may lower the availability in practice, especially the average battery fading rate (both in capacity and efficiency), which may be higher than what we assumed in this study. This deficiency could weaken the batteries' ability to reduce GHG emissions. However, as mentioned before, though much efforts has been devoted on the mechanism of decaying of battery (Han et al., 2014), there is still a huge uncertainty, especially when the battery capacity has already been less than 80% of its original value and even much lower in the up-coming service years, thus, we assumed a linear way of the decaying, which may not be that accurate, but accord with its unavoidable trend in some extent. Also, in our presuppositions, there are some other possible negative factors ignored such as the failure of battery cell, energy consumption in battery thermal management system and logistics, etc, base on the findings of a prior study (Sathre et al., 2015), we assumed that these factors only have a relatively small, even negligible effect on final results.

The last but not the least, part of key data applied in this study, mainly about the batteries and vehicle platforms, was directly drawn from prior studies, mostly from the work completed by Ellingsen et al.(2016), which has saved us a lot of efforts to model such a complicated system. However, it should be noted, that data only reflects the results from a series of assumptions, e.g. the energy requirements of vehicles were obtained through the NEDC test, the inventory of batteries' production was based on another previous study (Ellingsen et al., 2014). Thus, the uncertainties and limitations in prior results were inevitably inherited in this study. Moreover, applying the existed data, rather than model the whole process of battery and vehicle ourselves, narrowed our choice in parameters for a wider sensitivity analysis which covers the different cathode material of battery, the energy requirements of vehicle usage, the energy consumption in end-of-life process, etc. It is important to complement those studies in future work.

4.3. Prospectives

As the technologies of EV and battery advances rapidly, we may expect EVs with lower energy requirements and batteries with longer lifespan and higher specific energy in the near future, which would inevitably modify what we've found in this study, and should be adjusted in accordance with the new findings in future related studies.

Moreover, with implementation of the intelligent power grid and more durable batteries, the vehicle to grid technology would make a much bigger GHG reduction possible during its vehicle use stage by shifting the peak load (Marongiu et al., 2015), as the electricity from fossil-fuel generators could be replaced by renewable energies. The impact of this technology to batteries from different vehicle platforms ought to be comprehensively assessed in future studies.

Meanwhile, the progress of knowledge about the battery's chemistry, mechanism of decaying and techniques of manufacture, re-purposing and recycle would also bring some more possibilities, e.g. the variation trend of key parameters such as capacity fading or efficiency fading could be more accurately described, the energy consumption of re-purposing would be more precise and detailed, all of which could lead to results with a higher reliability.

Finally, findings obtained through this study are mainly from the perspective of environment benefits. This feasibility could be further validated if the economic and social factors were taken into account.

5. Conclusion

We assessed the different potentials to output energy and reduce GHG emission of batteries from vehicle platform from mini cars to luxury ones, confirmed a positive result that any of the retired batteries, with no matter small or big capacity, would continue to store and delivery energy in their extended usage life in the ESS, which make it possible to avoid sizable tonnes of GHG emissions by replacing fossil-fuel electricity during peak load period.

The findings of this study could be summed as follows. Firstly, as the battery capacity becomes larger, the potential of energy out and GHG emission reduction would be higher, in all scenarios, battery from the biggest vehicle platform showed the highest potential to bring those benefits mentioned before, in both units of per battery and per kWh capacity. Additionally, with a larger capacity, the battery's potential to output energy and reduce GHG emissions would be less affected by variation of the cycling life and vehicle mileage, as well as BE fading. What's more, the possible GHG emission reduction in batteries' second life would be no less than that in their vehicle use stage, and the gap would be more obvious for the bigger batteries from relatively larger vehicles.

In all, it can be conclude that, according to the state of the art of the technologies of battery and EV, the importance of second life use of retired traction batteries form EVs should not be underestimated, especially for the large batteries, which could not only offset the extra GHG emissions from production and end-of-life, but also bring much more environmental benefits.

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