Estimating the Availability of Energy Storage Capacity from Used Electric Vehicle Batteries on a National Scale

Narjes Fallah[a], Colin Fitzpatrick[a]
a) Dept of Electronic & Computer Engineering, University of Limerick, Limerick, Ireland.

Keywords: Electric Vehicle Battery; Circular End-of-Life Management; Life Cycle Assessment; Battery Degradation; Capacity Estimation.

Abstract: Moving toward a zero-carbon transport system accelerates the diffusion of batteries in society through electric vehicles. This so-called “clean transport”, as kind as it is to the environment during its lifetime, could be a burden for waste management at end of life if not managed properly. A circular waste management system, alternatively, suggests exploring the appropriate actions and policies to create the right environment for the second use of end-of-life batteries. A temporal estimation of the remained capacity in end-of-life electric vehicle batteries enables us to find the fitting second-use applications. This paper will present a model which has been developed for Ireland which combines (i) predictions for the adoption of electric vehicles by class, (ii) vehicle lifetime estimates based on a combination of current EV & ICE vehicles, and (iii) estimation of end-of-life battery generation and associated reuse capacity. The model computes a range of scenarios to estimate the potential availability of EV batteries for secondary use in Ireland out to 2050. Our estimation shows that a scale of several ten, several hundred, and a few several thousand megawatt-hour energy capacities would be available by 2050 in small, medium, and large class vehicles.

Introduction

Electrifying the transport sector is a promising movement for vehicle technology which is accelerated by authorities to meet the green transportation agenda. Different policies are primarily implied to encourage the uptake of Electric Vehicles (EVs), while their End of Life (EOL) management is not fully comprehended yet. Enacting new legislation and schemes toward circular waste management would address some of these EOL concerns. (Baars et al., 2021) narrates some of the strategies for circular waste management by evaluating different scenarios and anticipating the outcomes. Among these, a longer lifetime of EOL EV Batteries (EVBs) is likely when their second use is feasible in less demanding applications. Yet the techno-economic viability of repurposing strategy is not clear.

The key measures to address some of the technical burdens in EVB reuse are their scale and the State of Health (SOH) at EOL. The former further depends on the EV adoption rate in the vehicle technology transitioning period and the survival age of EVs themselves on the road. Several works in the present literature developed different models to estimate the scale of EOL EVBs either for recycling or reuse. (Ai et al., 2019) conducted a material flow analysis to develop a timely projection of EOL EVBs on a state and national scale. A regional reuse planning of EVBs is suggested by authors in (Ai et al., 2019) to match the energy storage requirement in renewable energy facilities in the state of California.

(Moore et al., 2020) estimated the number of available Li-ion batteries from EOL EVs by 2040 and discovered the strategic locations in Berlin, Germany that best suits for the second use of these batteries as back up supply for critical infrastructures in power system or emergency traffic signals. (Wu et al., 2020) provide a spatial and temporal estimation of EOL EVBs in 32 states of China from 2020 to 2036 and compared the results for every state with their number of collection station and recycling facilities. Recommendation on EOL management are then provided based on their predictions. (Castro et al., 2021) explored the EOL EV generation in Brazil by predicting the EV uptake considering three different scenarios. (Cusenza et al., 2019) assessed the impact of reusing EVBs in stationary storages in residential buildings on enhancing the environmental sustainability of the two systems. This work aims to project the volume of EOL EVB that are going to be disposed of during the next 30 years up to 2050 on a national scale in Ireland. This projection is broke down into an estimation of the sale of EVs and the survival age of EVs on the Irish road.

The rest of the paper is as follow: The methodology is discussed in the next section, followed by the result and discussion. A conclusion of the findings of this work is discussed in the conclusion section.

Methodology

The methodology in this work is approached through several steps. First, a model is developed to predict the sale of EVs in Ireland by considering the Total Cost of Ownership (TCO) of EVs that customers have to pay. TCO comprises the vehicle's capital cost including VRT, fuel cost, and operation & maintenance cost including the annual motor tax and insurance. Finding the relative cost of EV to traditional vehicles, the S-shaped EV growth curve is modelled (Kwon, 2012) using the well known logistic function as the following equation indicates:

$$\boldsymbol{MS_j} = \frac{\mathbf{1}}{(\mathbf{1} + \boldsymbol{e}^{(\propto * (\boldsymbol{RC_j} - \mathbf{1}))})}$$

Equation 1

Wherein, *RC* is the relative cost of EVs and ∝ is the parameter indicating the market sensitivity of the new technology to the cost.
Moreover, to include the impact of customer behaviour into the market diffusion model (*MS* model), we categorized the vehicle owners by their driving profiles based on the vehicle kilometre travelled. The rationale behind this categorization is that customers decision on purchasing a vehicle with a specific fuel technology depends on their travel needs. In another word, customers who travel higher distances may prioritise their purchase based on the fuel economy rather than other factors and might have more tendency toward buying EVs to reduce their fuel costs. Therefore, more similarity in decisions can be observed between customers with similar travel distances. Consequently, the *MS* model has been developed for three types of drivers naming mild, medium, and frequent drivers recognized by the vehicle class. Thus, the mild, medium and frequent driving profile is assigned to the owner of vehicles in mini & small class, compact, medium & executive class, and SUV & MPV class, respectively. *j* in Equation 1 is indicative for the customer category.

After finding the EV share in the market, the survival rate of these vehicles is explored through an EOL assessment. Two datasets are accessed for EOL estimation: one is the EOL data for private passenger cars gathered from the National Motor Tax Office which issues certificates of destruction for EOL vehicles, and the other is the MOT test result from the UK (Department-of-Transport, n.d.) in which the specifications of vehicles are recorded either failing or passing the test. The survival age of vehicles in Irish roads is extracted from the first dataset and modelled by a distribution function. However, the number of BEVs in this dataset is not high enough to conclude, thus the number of EOL BEVs are extracted from the MOT dataset due to the similar availability of vehicle models, environmental conditions as well as ELV legislation. The distribution of EOL BEVs are modelled using the Weibull function as indicated in Equation 2, wherein α and β, known as scale and shape parameters, indicate the peak life of a vehicle and upper limit of lifespan, respectively.

$$\boldsymbol{EOL\_dist}(\boldsymbol{n}) = \mathbf{1} - \boldsymbol{exp}[-(\boldsymbol{n}/\propto)^{\boldsymbol{\beta}}]$$

Equation 2

Having the annual number of EV sale and their EOL distribution, a material flow analysis is conducted to estimate the number of EOL EVB packs that are going to be disposed of over the years, as the following equation indicates:

$$N_{EOL\_EVB}(t) = \int_{\acute{t}=1}^{t} Sale(t) * L(t - \acute{t})$$

Equation 3

Wherein, the number of EOL EVB packs $N_{EOL\_EVB}(t)$ is calculated by summating the distributed return (L) of EVs that have been sold from year 1 to year t.
The available energy capacity of these EOL packs depends on their SOH at end of life. The ones with above 80% remained capacity can be reused, whereas the rest are directly recycled. However, testing and monitoring the EOL batteries are not effectively facilitated at the current leading to a low rate of reuse. This work assumes an increasing linear growth of 10% and 20% per decade reuse rate in a high and low reuse scenario, respectively. We also assumed

an average 80% remained capacity for batteries that fit a second life. Subsequently, the available reuse capacity of EOL EVBs is calculated according to the following equation:

$$R\_Cap_{Wh}(t) = \int_{\acute{t}=1}^{t} Sale(t) * L(t-\acute{t}) * C_{EOL}(t-\acute{t}) * RR(t-\acute{t})$$

Equation 4

Wherein, the reuse capacity at year t ($R\_Cap_{Wh}(t)$) can be calculated by multiplying the EOL capacity C_{EOL} and the reuse rate RR to Equation 3.

Results and Discussion

EV market share has been estimated by *MS* model and using the projected relative cost of EV listed as percentage change from ICE (ICE=100) in Table 1. A cost parity occurs roughly in the year 2040, 2035, and 2027 in small, medium and large class categories as Table 1 shows. The higher decrease rate in the relative cost of EV in the large category is partly due to the huge difference in the fuel cost between EV and ICE vehicles as well as a more noticeable decrease in motor tax and maintenance cost comparing to other categories.

Results of the *MS* model for three vehicle categories are illustrated in Figure 1. A different range of values for the ∝ parameter is considered in each category, as the legends in Figure 1 indicates, by matching the historical market share to the prediction curves.

The results in Figure 1 suggest an earlier full-electric market overtake in the large class in which above 80% market share is expected after 2030. Whereas, a lower slop in EV market growth is estimated in the medium and small class. In medium class, a range of nearly 60% to 80% market share is estimated by 2040, while the same range of market share is estimated to

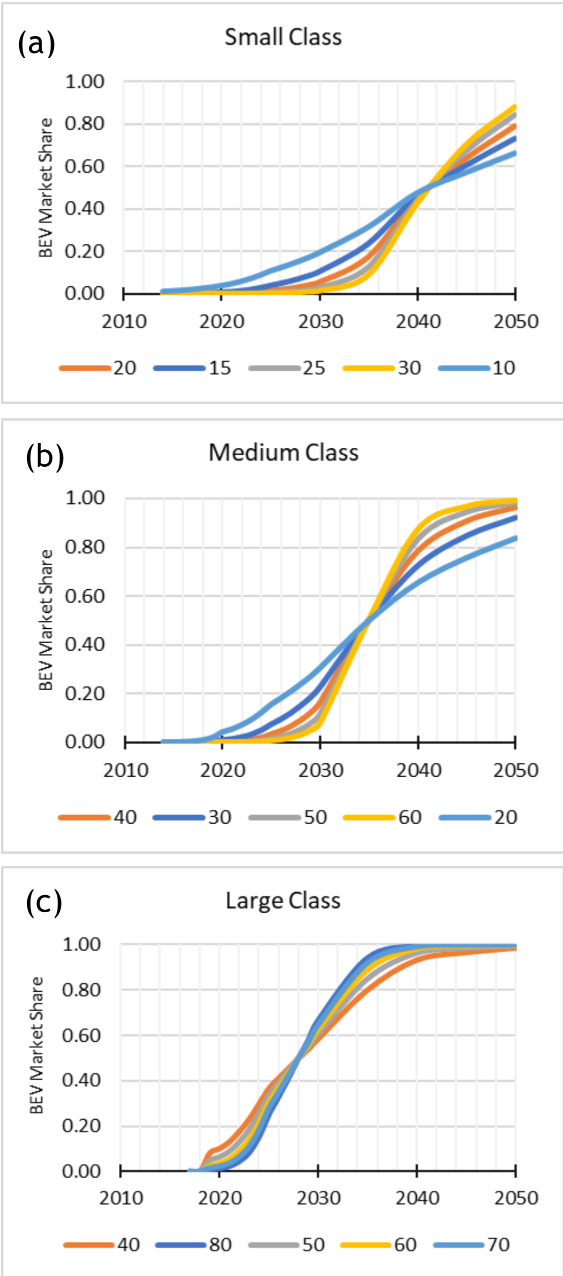

Figure 1. EV market share estimation for (a) small (b) medium, and (c) large class vehicles.

Year / Vehicle Class	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050
Small	45	43	41	39	37	34	32	30	28	26	23	21	20	18	17	16	14	8	1	-3	-7
Medium	39	35	31	27	23	19	16	14	13	11	10	8	8	7	6	5	4	0	-3	-6	-8
Large				21	19	6	5	5	4	3	2	1	1	0	0	0	-1	-3	-7	-8	-10

Table 1. Percentage change in the relative cost of EV over the years (ICE=100).

happen a decade later by 2050 in the small class.
The result of modelling the distribution of survival age of vehicles in Ireland using the Weibull distribution function is illustrated in Figure 2(a). The histogram and Weibull distribution of EOL BEV from UK data are also shown in Figure 2(b).
Comparing the parameters and distribution of these two figures, It can be comprehended that most vehicles on Irish road reach EOL at 17 years after their first registration, while for BEVs this happens 9-10 years after first registration. However, since the EOL distribution for BEV are only valid for vehicles that have been registered before 2005, and considering the technology developments in battery manufacturing and their increasing capacity in EVs, we expect that EOL distribution parameters also change over the years and be more similar to the EOL distribution of traditional vehicles. The logic behind this expectation is that at the moment the life of the electric vehicle is mainly driven by battery performance and lifetime, while in the future by decreasing the probability of battery failure, the EV EOL status is expected to be similar to the traditional vehicles. A series of evolutionary EOL curves are created by interpolating the Weibull parameters of electric and ICE vehicles as Figure 2(c) indicates.

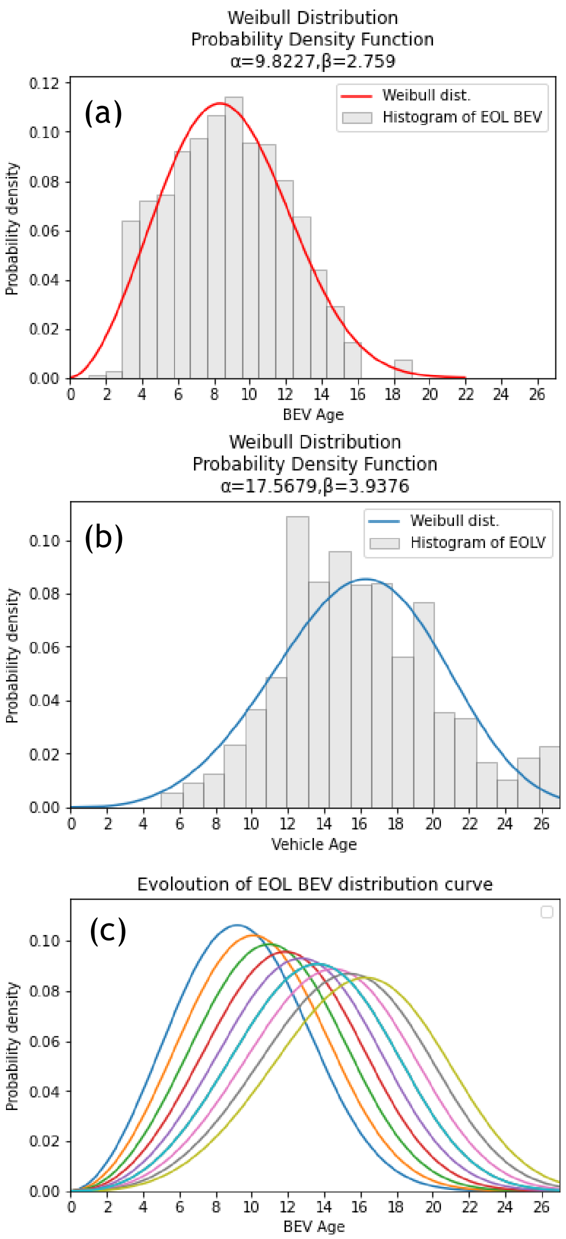

Figure 2. EOL distributions (a) Weibull distribution of EOL vehicles in Ireland (b) Weibull distribution of EOL electric vehicles in UK (c) predicted evolution of EV survival rate.

Having the results of EV market share in Figure 1 and the EOL distribution in Figure 2, the numbers of EOL battery packs disposed of are estimated using Equation 3. Results are illustrated in Figure 3 in units of thousand for three classes of vehicles. According to Figure 3, this number is estimated to rise to a range of 2-4.5, 15.2-15.8, and 42-48 thousand units by 2050 for small, medium and large class vehicles, respectively.
The reuse capacity of these EOL EVBs is further estimated using Equation 4. Results for the low and high scenario are indicated in Figure 4 and Figure 5, respectively. It can be observed that in the small class, the reuse capacity is estimated to grow around several ten megawatt-hours in 2045 and further rise to 37-90 and 60-143 megawatt-hours by 2050 in low and high reuse scenarios, respectively. Whereas in Medium class, the available reuse capacity starts to be noticeable by 2040 from few several hundred megawatt-hours and grows up to around 400 and 700 megawatt-hours by 2050 in low and high reuse scenarios, respectively. In the large class, on the other hand, a major arrival of EOL EVBs to the waste suggests an earlier availability of reuse capacity on a considerable scale by 2035, rising to a range of approximately two to three megawatt-hours capacity by 2050.

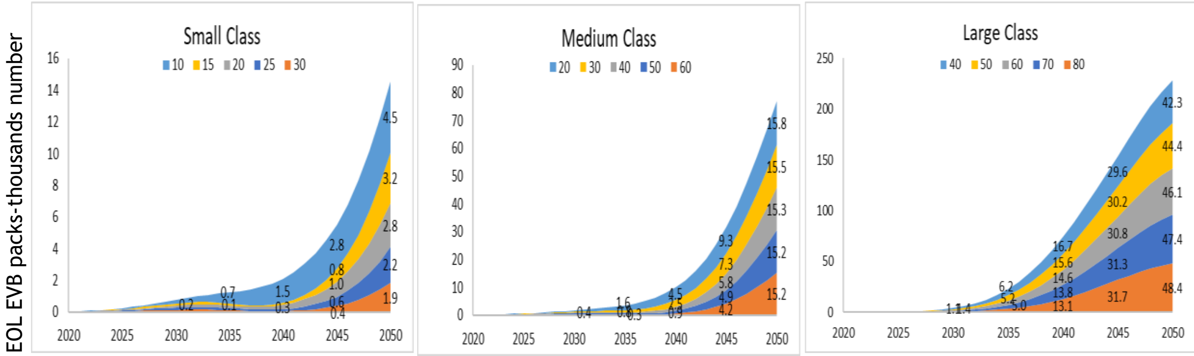

Figure 5. EOL EVB packs disposed of – thousand units

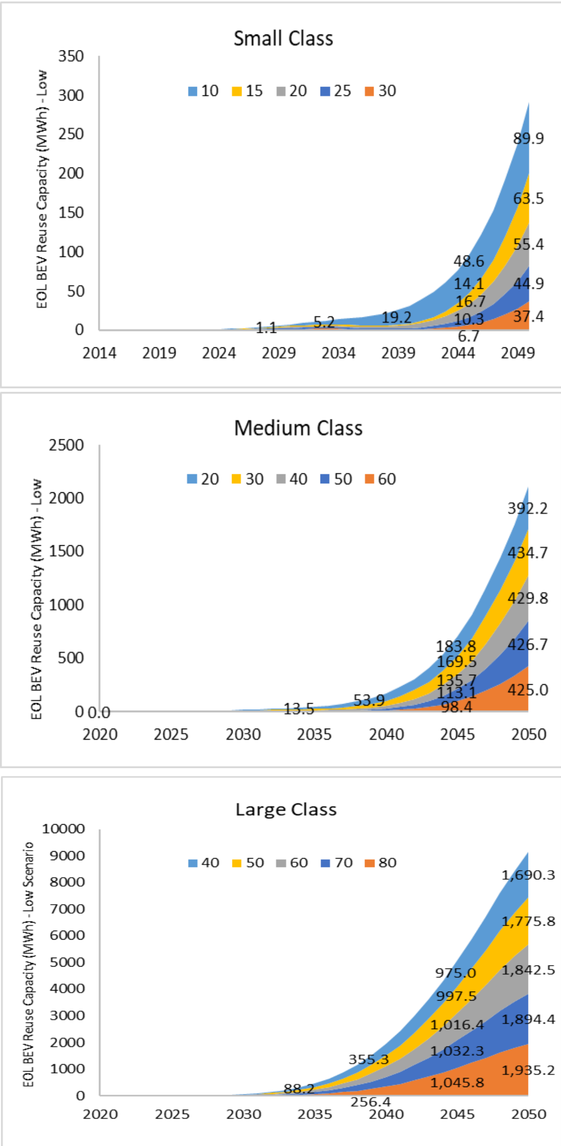

Figure 3. Estimated EOL EVB reuse capacity (MWh) in low scenario.

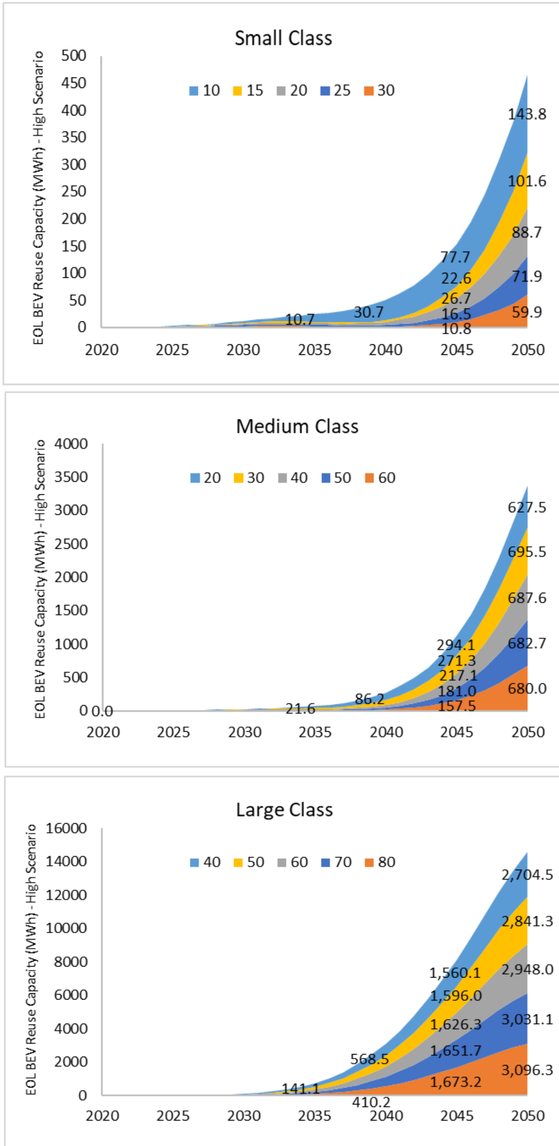

Figure 4. Estimated EOL EVB reuse capacity (MWh) in high scenario.

Conclusions

This work aimed to estimate the reusable capacity of EOL EVBs locally in Ireland. A material flow analysis was conducted in which the market share of EVs are simulated using an S-shaped curve with different growth rate. The survival rate of these vehicles on the road are modelled using the historical EOL data in Ireland and UK. Results indicate a considerable availability of reuse capacity after 2035, 2040, and 2045 for large, medium and small class vehicles. Our estimation shows more than fifteen hundred up to three thousand megawatt-hours battery capacity would be available by 2050 in EOL large class EVs. For medium class vehicles, a range of four to seven hundred megawatt-hours is estimated by 2050, whereas in the small class, this is ranged in between a few ten up to less than one hundred and fifty megawatt-hours capacity, based on different reuse support scenarios and EV market growth rate.

This substantial battery capacity can be reused in less demanding applications comparing to EVs such as stationary storages. Finding the fitting applications locally in Ireland is recommended for future works

Acknowledgements

This work was supported by the Environmental Protection Agency (Ireland) (Project Codes 2019-RE-DS-14 & 2019-RE-PhD-3) and EU H2020 project Si-Drive (Grant Agreement 814464).

References

Ai, N., Zheng, J., & Chen, W.-Q. (2019). US end-of-life electric vehicle batteries: Dynamic inventory modeling and spatial analysis for regional solutions. Resources, Conservation and Recycling, 145, 208–219.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H. E., & Heidrich, O. (2021). Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nature Sustainability, 4(1), 71–79. https://doi.org/10.1038/s41893-020-00607-0

Castro, F. D., Cutaia, L., & Vaccari, M. (2021). End-of-life automotive lithium-ion batteries (LIBs) in Brazil: Prediction of flows and revenues by 2030. Resources, Conservation and Recycling, 169, 105522.

Cusenza, M. A., Guarino, F., Longo, S., Ferraro, M., & Cellura, M. (2019). Energy and environmental benefits of circular economy strategies: The case study of reusing used batteries from electric vehicles. Journal of Energy Storage, 25, 100845.

Department-of-Transport. (n.d.). Anonymised MOT tests and results (2020th ed.). https://data.gov.uk/dataset/e3939ef8-30c7-4ca8-9c7c-ad9475cc9b2f/anonymised-mot-tests-and-results

Kwon, T. hyeong. (2012). Strategic niche management of alternative fuel vehicles: A system dynamics model of the policy effect. Technological Forecasting and Social Change, 79(9), 1672–1680. https://doi.org/10.1016/j.techfore.2012.05.015

Moore, E. A., Russell, J. D., Babbitt, C. W., Tomaszewski, B., & Clark, S. S. (2020). Spatial modeling of a second-use strategy for electric vehicle batteries to improve disaster resilience and circular economy. Resources, Conservation and Recycling, 160(December 2019), 104889. https://doi.org/10.1016/j.resconrec.2020.104889

Wu, Y., Yang, L., Tian, X., Li, Y., & Zuo, T. (2020). Temporal and spatial analysis for end-of-life power batteries from electric vehicles in China. Resources, Conservation and Recycling, 155, 104651.