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Forecasting the EU recycling potential for batteries from electric vehicles

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ABSTRACT

Managing the waste stream of lithium ion batteries from electric vehicles is an emerging challenge. Therefore, a distribution delay forecasting model is developed considering multiple end-of-life options for battery applications; including replace, reuse, repurpose and recycle. This model is used to forecast the characteristics of the waste stream. Results of the presented model forecast a waste stream of 120 thousand and 1.8 million batteries to be recycled in 2030 and 2040 respectively. The results also demonstrate that retired batteries can potentially contribute to stationary energy storage markets by providing 8 GWh storage capacity in 2030, and 92 GWh in 2040.

1. Introduction

1.1. Background

Europe has established a leading position among producers of motor vehicles. The automotive industry is the largest private investor in research and development in the EU, and provides 6.1% of total employment opportunities (European Commission). However, emissions from the transportation sector represent 25% of Europe's greenhouse gas emissions (European Parliamentary Research Service, 2019). Therefore, the EU is committed to reducing emissions from its transportation sector to 60% of 1990 levels by 2050 (European Parliamentary Research Service, 2019). Electric vehicles (EVs) are thus promoted as alternative to internal combustion engine vehicles. Electricity, powering this type of vehicles, is directly stored in an on-board battery for later traction use with minor conversion losses to mechanical energy.

The expected superior environmental performance of EVs as compared to internal combustion engine vehicles is, however, subject of fierce debate and scientific study. Study from Ellingsen et.al shows that the production phase of EVs is more emission intensive than of conventional vehicles (Ellingsen et al., 2016). Moreover, EV battery production requires raw materials, including nickel, copper, and aluminium, the mining and processing activities of which are associated with significant environmental impact (Peters and Weil, 2018). Other raw materials on the EU critical raw material list, such as cobalt, graphite, silicon, magnesium, and rare earth elements, are also involved in the production of EV batteries (European Commission, 2018). The eventual environmental lifetime greenhouse gas emission reductions of EVs and lightweight electric vehicles (LEVs) over conventional vehicles depend on multiple variables, including the driving range of the battery, the share of renewables in the electricity mix used in charging, the driving pattern, and the climatic conditions (Ellingsen et al., 2016; Egede, 2017).

The share of annual EV sales in the EU is forecasted to reach 23% of global EV sales by 2030, which is equivalent to roughly 5 million vehicles per year (International Energy Agency, 2018). In response, the EU is promoting battery recycling through directives 2006/66/EC (batteries directive) and 2013/56/EU that impose minimum collection rates for retired batteries, and guide the calculation of recycling efficiencies. Moreover, the European Commission inaugurated the European Battery Alliance in 2017 with the objective of establishing a competitive and sustainable battery manufacturing sector in Europe. Within the strategic action plan of this policy, access to secondary raw materials from recycling is pursued with the aim of securing future supply of raw materials for batteries.

1.2. Goal and scope

In this paper, a forecasting model for the battery waste stream from plug-in passenger EVs in the EU is presented. A distribution

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Nomenclature

B2U	battery second use
BEV	full battery electric vehicle
DOD	depth of discharge
EoL	end of life
EV	electric vehicle
LEV	lightweight electric vehicle
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
SoH	state of health
WEEE	waste electrical and electronic equipment

delay method is used for modelling different use phases during battery lifetime. The model moreover takes into account different End-of-Life (EoL) options for batteries retiring from EV use. The output of the model is an estimation of the yearly number of batteries that will reach their end-of-life in Europe for the next 20 years. The battery waste stream is characterised in terms of number of retired battery units, as well as their lifetime applications. Estimates for future size of end-of-life markets (battery second use (B2U), and recycling) are hence given.

The scope of study includes the battery waste stream from plug-in passenger and light commercial electric vehicles in the EU; including both Plug-in Hybrid (PHEV) and full battery (BEV) electric vehicles. The study is constrained to lithium ion batteries, since these are widely used for plug-in EV applications. Nickel metal hydride batteries, which are more suited for Hybrid Electric Vehicles, are excluded. The study considers available EV sales from 2010 till 2018, and outlook studies on EV sales for forecasting annual battery sales until 2030.

2. Literature review

2.1. Lifetime stages of an EV battery

Fig. 1 depicts the subsequent use stages that EV batteries can go through prior to eventual recycling. The first stage following production concerns usage in an EV. The majority of commercial EV models on the market provide an eight year warranty for the batteries. Nevertheless, early failures can occur. Accordingly, batteries are either remanufactured and reinstalled in an EV (remanufacture), or replaced by a new battery (replace) depending on the severity of the failure.

Most battery manufacturers mark the end of the EV use stage when available battery capacity fades to 70–80% of its nominal maximum capacity (Millner, 2010). At present, EV batteries retiring from EV use stage are either directed to immediate recycling or prior use in less demanding stationary energy storage applications. New markets for EV battery second use (B2U) applications are prospering owing to the improved environmental performance of second use applications for EV batteries versus immediate recycling, and the residual capacity inside the battery at the end of EV use stage (Canals Casals et al., 2016). Consequently, B2U applications are promoted by different stakeholders to be included in the next revision of the Batteries Directive (Bobba et al., 2018).

A study for the European Parliament states that EoL vehicles in the EU represent around 50% of deregistered vehicles (Schneider et al., 2010). This may imply that the collection rate of EoL electric vehicles and retired EV batteries may not exceed 50% as well. Nevertheless, Gattiglio from EUROBAT argues that the collection rate of decommissioned industrial and EV batteries is in the high 90% (Gattiglio, 2019). The complex technology of the batteries, small market niche for EVs in Eastern Europe and Africa, nascent recycling technologies for EV batteries, and hazards linked with transportation and storage of EV batteries can all be contributing to this high collection rate. Because of these reasons, the model assumes the collection of all EV batteries within Europe.

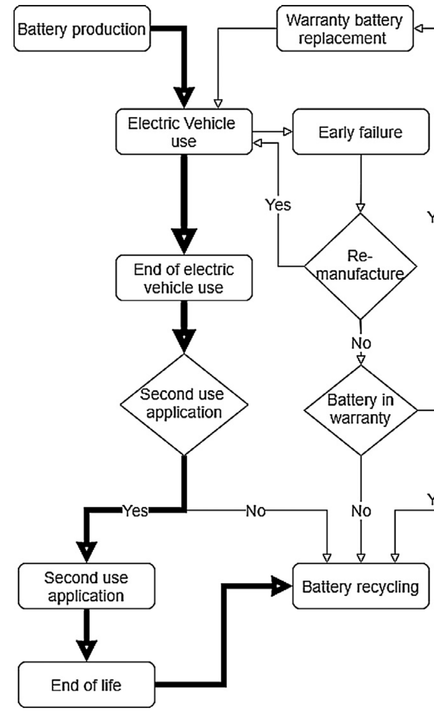

Fig. 1. The modelled life stages of an EV battery.

2.2. Modelling the lifetime of electronics and EV batteries in literature

In the work of Chancerel, a number of parametric and non-parametric methods for “Substance flow analysis” in various waste electrical and electronic equipment (WEEE) streams were reviewed (Chancerel, 2010). These include: sales method, simple delay, distribution delay, time step, Carnegie Mellon, batch leaching, and econometric analysis methods. Unlike parametric methods, non-parametric methods do not assume statistical distributions for the product lifetime. With the exclusion of the econometric analysis method, all methods listed require knowledge of either sales data, lifetime data, or both (Chancerel, 2010). Similarly, substance flow analysis models for tracing lithium and cobalt flows in EVs were developed in recent studies (Bobba et al., 2019; Ziemann et al., 2018).

Different estimates for battery lifetime in EV use have been reported in previous studies. Drabik and Rizos’ study on EV batteries circular economy indicates 8 years only (Drabik and Rizos, 2018). In addition, the study by Canals Casals and the International Energy Agency (IEA) Outlook on EVs estimate it to range from 8 to 10 years (Canals Casals et al., 2019; International Energy Agency, 2018). Ellingsen calculated the lifecycle greenhouse gas emissions of an EV battery based on an expected lifetime of 12 years (Ellingsen et al., 2016). Finally, the highest lifetime estimate is from the work of Neubauer et.al at 15 years (Neubauer et al., 2015).

Duration of the B2U stage is a parameter of high uncertainty as well. Studies report durations from as low as 3.6 years, to 29 years depending on the type of application, the state of health of the battery, and the residual capacity available from first use (Canals Casals et al., 2019; Bobba et al., 2018). Neubauer’s work on B2U modelling shows the strong correlation between used EV battery lifetime in B2U stage, the state of health (SoH) of the battery coming from the EV use stage, and the depth of discharge and cycling rates applied during this stage (Neubauer et al., 2015). Results from this study show that used EV batteries are capable of delivering from 6 to more than 10 years of operation in B2U applications, following a 15 year duty in EV, at 50% and 60% Depth of Discharge (DOD) rates.

A number of studies addressed waste generation of EV batteries for the USA, China, and the EU (Drabik and Rizos, 2018; Xu et al., 2017; Richa et al., 2014). However, these studies assumed either a fixed EV battery life stage (typically around 8 years), truncated lifetime functions, or fitted a normal distribution with a population mean of 10 years only. Second use applications (B2U) were either not modelled, or modelled with a fixed lifetime assumption (10 years). Therefore, the present paper introduces a more refined waste stream forecasting method based on the work of Melo (1999).

Building on the battery lifetime model proposed, the generation of EV battery waste is derived from two statistical models. In the first model, the battery lifetime in the EV stage is simulated. This model accounts external failures due to road accidents, successful repair of early failures, and replacements for batteries underperforming during warranty period as well. The output of this model is then allocated to one of the EoL markets (recycling or B2U) according to allocated market shares for second use applications for used EV batteries at the year of waste return, as explained in detail in Section 3.2. In the second model, the battery lifetime in a stationary B2U is simulated. Finally, returns to recycling output from the second model are added to direct returns to recycling from the first model of the same year.

3. Methodology

3.1. Formulation of lifetime models

Due to the high uncertainty in estimates for the duration of use stages and allocation to second use, three scenarios for the battery lifetime model are developed. As such, estimates from the three scenarios for waste stream returns shall provide the upper and lower bounds for the amounts that will actually return in the future. The first scenario, termed Recycling scenario, is characterized by rapid growth of product waste stream heading for recycling. It considers battery recycling as the main EoL market for retiring EV batteries. The scenario assumes high learning curves for EV batteries, together with consumers with a variety seeking behaviour. This will result in low prices for EVs and frequent replacement of EV models by their owners. Recycling activities are the highest in this scenario, together with a short battery lifetime, lower battery SoH after EV application, and a short B2U lifetime.

The second scenario, referred to as Baseline, is the best practice scenario. The scenario is in line with most outlook studies and expert views on exploiting full battery potential in EV use and B2U stages. The baseline scenario assumes long durations for EV use stage, in addition to high allocation rate of retired Ev batteries to second use applications. As a result, the waste stream growth rate estimated from this scenario should be the most realistic.

The third scenario, referred to as Repurpose scenario, is the scenario with longest lifetime assumptions, and slowest growth rate of waste stream. The scenario considers the highest product repairability and the best conditions for vehicle operation and second life applications that result in the longest vehicle lifetime, high battery SoH after EV application, and the longest lifetime for B2U application.

Based on the assumptions listed for the three scenarios, values are assigned to parameters like the mean and standard deviation values of the EV lifetime distributions. The share of products failing during warranty period that are remanufactured and reused again in EV is based on the 40% estimate from Fredrik Andresen from BatteriRetur, Norway (Andresen, 2019). Estimates for the percentage of retired EV batteries with potential for second use applications, depth of discharge and cycling rate applied in B2U, and the duration of these applications are derived from the study of Neubauer et.al (2015). The values assumed are indicated in Table 1.

For the first year following production, the probability of product failure $D_{(s,\,w)}$ in the EV use stage during the first year of operation is given by Eq. (1), in which s is the year of production, w is the year of waste return, μ is the mean value of the normal distribution, and σ is its standard deviation. External failure due to road accidents is given by the constant d. Constant failure rate d is given a value of 0.65% for the EV application to account for road accidents, and assumed 0 for stationary energy storage applications (Neubauer et al., 2015).

$$\textbf{\textit{First year}}: \; D_{(s,w)} = \Phi\left(\frac{(w-s)-\mu}{\sigma}\right) + d \tag{1}$$

Where:

$$\Phi\left(\frac{(w-s)-\mu}{\sigma}\right) = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{(w-s)-\mu}{\sigma\sqrt{2}}\right)\right]$$

Subsequent to the first year of battery lifetime, the probability of battery failure from the second year onwards is given by Eq. (2).

$$D_{(s,w)} = \Phi\left(\frac{(w-s)-\mu}{\sigma}\right) - \Phi\left(\frac{(w-1-s)-\mu}{\sigma}\right) + d \tag{2}$$

From the probability failure function developed, the quantity of EoL batteries going to recycling or B2U can be determined by Eqs. (3) and (4). The number of EoL batteries going to recycling directly from EV use within a certain year w is denoted by ($FQ_{recycling(w)}$), and the number of EoL batteries heading to B2U is given by ($Q_{B2U(w)}$).

$$FQ_{recycling(w)} = \sum_{1}^{s=w-1} QP_{(s)} * D_{EV\,(s,w)} * \left(1-r_{(s)}\right) * S_{(yw)} \tag{3}$$

$$Q_{B2U\,(w)} = \sum_{1}^{s=w-1} QP_{(s)} * D_{EV\,(s,w)} * \left(1-r_{(s)}\right) * (1-S_{(yw)}) \tag{4}$$

where $QP_{(s)}$ is the total number of vehicles produced in year s, $S_{(yw)}$ is the share of EoL EV batteries heading to recycling, and $r_{(s)}$ is the share of early failures that can be remanufactured.

The second use phase (B2U) is then modelled with a similar failure function as for the first EV use, as shown in Eq. (5). $FQ_{EoL,B2U(w)}$ denotes the quantity of EoL batteries from B2U returning for final EoL in recycling, and $D_{B2U(s,\,w)}$ denotes the probability of product failure in B2U.

$$FQ_{EoL,\;B2U\,(w,s)} = \sum_{1}^{s=w-1} Q_{B2U\,(s)} * D_{B2U\,(s,w)} \tag{5}$$

Replacements for damaged batteries or batteries with excessive capacity loss are offered by electric vehicle Original Equipment Manufacturers (OEMs) (Berman, 2018). Replacement batteries can thus be expected to operate within the same lifetime model proposed earlier. Estimation for the quantity of these batteries is given in Eq. (6).

$$QR_{(s)} = \sum_{1}^{s=w-1} QP_{(s)} * D_{EV\,(s,w)} * \left(1-r_{(s)}\right) * R_{(yw)} \tag{6}$$

Where R(yw) is the fraction of retired EV batteries during a standard 8 year warranty period that are replaced by new batteries by the OEM.

Table 1
EV and B2U lifetime distribution parameters for three scenarios.

	Remanufacture percentage of failures during warranty r [%]	Replacement percentage of un-repaired batteries in warranty $R_{(yw)}$ [%]	Mean (EV) μ_{EV} [years]	Standard deviation (EV) σ_{EV} [years]	Share of EoL batteries in direct recycling $S_{(yw)}$ [%]	Mean (B2U) μ_{B2U} [years]	Standard deviation (B2U) σ_{B2U} [years]
Recycling Scenario	30	100	11.27	1.63	50	3.35	0.65
Baseline Scenario	50	80	13.70	2.86	20	5.35	2.65
Repurpose Scenario	70	50	14.53	3.27	10	6.35	3.65

3.2. Forecasting product sales

The annual number of EV batteries put on the market is directly related to annual EV sales. Annual EV sales in Europe are readily available and reported for EU countries only, or with EFTA countries and Turkey. For the forecasting study, sales of EU together with EFTA countries and Turkey are used. EV sales data were gathered and confirmed from European Alternative Fuels Observatory database (EAFO) and EV volumes annual reports (EAFO 2019; Irle, 2019). Outlook studies predict an average annual growth rate of global EV sales at 24%, with global EV sales reaching 4, 12, and 21.5 million vehicles by 2020, 2025, and 2030 respectively (International Energy Agency 2018; Walton et al., 2019). Based on these parameters, third order polynomial regression is used to derive Eq. (7) for estimating the annual global EV sales. The EU market share of annual global EV sales is taken as 22%. The EU has a current market share of 20%, and the IEA predicts a 23% market share for EV sales in Europe by 2030 (International Energy Agency 2018).

$$S = -6508*(Y-2016)^3 + 187837*(Y-2016)^2 + 106076*(Y-2016) + 1E06 \quad (7)$$

where Y is the year of production studied, and S is the annual global EV sales in year Y.

The study aims to examine waste stream characteristics from 2010 till 2040. This timeline of the results goes beyond forecasted sales to examine the effect of second use markets and products sold close to the year 2030 on the waste stream. Product sales beyond 2030 should constitute a minor part of the waste stream between 2030 and 2040. Hence sales data beyond 2030 are given the same value as the year 2030.

Determining the market average battery capacity in EV models is important for estimating the capacity of EoL markets (recycling and B2U). Based on IEA outlook study, the average capacities for BEV and PHEV are modelled to increase from a current average of 43 and 9 kWh to 60 and 15 kWh by 2030 for BEV and PHEV respectively (International Energy Agency, 2018). Furthermore, the share of BEV sales in total EV sales is modelled to increase from 56% in 2018 to 70% in 2030 based on the outlook study by Walton et.al (Walton et al., 2019).

4. Results and discussion

Fig. 2 shows the amount of retired EV batteries returning to recycling from the three scenarios. All three scenarios forecast high annual waste stream returns after 2030, indicating high potential for scaling up of recycling facilities thereon.. For administering the recycling of the whole waste stream within, annual recycling capacity of 12 GWh (18 kton/year), and 138 GWh (150 kton/year) are needed for the years 2030 and 2040 respectively.

For the time span of the study, the Baseline scenario gives the highest estimates for retired EV batteries which could be potentially used in a second lifetime application. In 2030, the amount of retired batteries that will be directed to B2U should be in the order of 350 thousand batteries, possibly providing an 80% residual storage capacity of 8 GWh from an initial capacity of 10 GWh. The figures significantly increase in 2040 to 4 million batteries with a residual storage capacity of 92 GWh from an initial capacity of 115 GWh. Prior research shows that the EU grid needs 3 TWh storage capacity for an 80% share of electricity generation from variable renewable energy sources, such as wind and PV (Cebulla et al., 2018). Hence, used EV batteries can potentially fulfil 15% of the energy storage capacity demand for this sector, with no additional need for virgin raw materials.

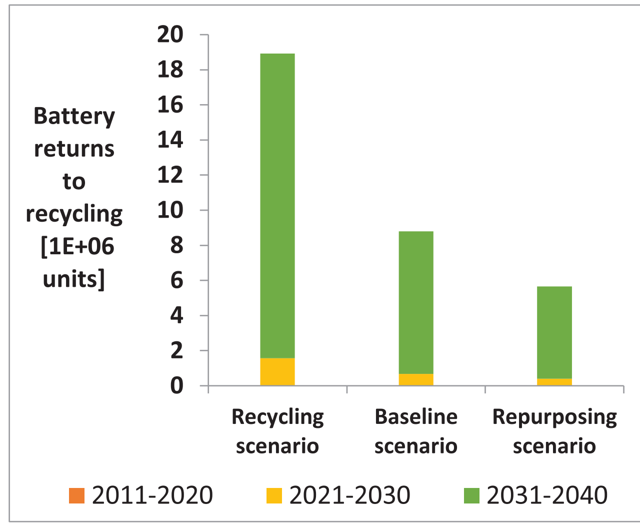

Fig. 2. Retired EV batteries returning to recycling from the three scenarios.

The widespread of second use applications for EV batteries shall delay the return of batteries to eventual recycling. Furthermore, the Baseline scenario indicates that in 2036, more than half of the retired EV batteries available for recycling will be coming from B2U applications. This event is forecasted to take place starting from 2031 and 2043 in the Repurpose and Recycling scenarios respectively. Hence, the value chain of retired EV batteries will grow more complex, and will necessitate proper management of product transportation between several stakeholders; including, EoL vehicle treatment facilities, second lifetime users and recyclers.

The study of Drabik and Rizos, on the circular economy of EV batteries in the EU, defines fixed lifetime assumptions for an EV battery of 8 years in the EV use, and 10 years in B2U stages (Drabik and Rizos, 2018). Thus, they forecast 1.1 million batteries reaching end of life in 2030. The Recycling scenario, with the shortest lifetime assumptions of the three scenarios proposed, forecasts 386 thousand batteries to reach their end of life in the same year. The differences get bigger by 2040, where the study forecasts 5.4 million battery units reaching end of life, compared to 3.2 million battery units from the Recycling scenario.

With the possibility of two lifetime uses for EV batteries, applying fixed lifetime assumptions constrains the amount of EoL product returns per year exclusively to the sales in two former years. Hence, fixed lifetime assumptions cannot accurately estimate the size of the waste stream, nor can they convey its growth rate either. On the other hand, the uncertainty in this study is that the model developed applies the same lifetime distributions, reuse, and recycling parameters to all battery technologies put on market in a time frame of 20 years.

The high potential for employing EV batteries in second use applications can also be argued. The economic and safety disadvantage aspects for this application comes from the chemistries used in EV batteries that demand expensive and critical raw material for their synthesis, in addition to employing flammable organic electrolytes (Ritchie, 2004).

5. Conclusion

The presented methodology forecasts EV battery waste stream characteristics. The lifetime model used considers different lifetime applications of EV batteries. Results show that the waste stream size is dependent on the battery lifetime in the EV phase. Other factors define the size and growth rate of the emerging waste stream, such as successful repair of failed products, EoL criteria for the EV use phase, and the collection rate for and duration of B2U.

The study demonstrates a huge potential from employing retiring EV batteries in second lifetime applications. This shall result, as a rebound effect, in delaying the return of EV batteries to recycling significantly until 2030. From 2030 onwards, all scenarios developed forecast exponential growth in recycling capacity needed for the emerging waste stream. With most recyclers operating the sorting and dismantling activities of EV batteries manually, Automated sorting and dismantling systems should aid recycling facilities efficiently process waste stream returns, and readily expand existing capacities.

The study concludes that batteries in EVs sold between 2010 and 2030 will represent the major part of the waste stream until 2040. Past studies assumed fixed waste stream composition on the basis of fixed market shares for battery technologies or content per MWh basis (Drabik and Rizos, 2018; Neubauer et al., 2015; Richa et al., 2014). However, the market is shifting toward higher energy density technologies. The first generation of EV batteries is characterized by a relatively high cobalt content, whereas subsequent generations are trending toward minimal cobalt content.

Finally, using a wide spectrum of battery technologies will affect the type and amount of materials recovered by recycling. Shifting from the weight-based criteria for amount of recycled material defined in the Batteries Directive to specifying relevant metals for recycling shall help recyclers operate their process in an economically feasible manner, with maximum recovery for these metals. It is, therefore, crucial to quantify these metals in waste batteries, and how can recycling contribute to relieving stress on metal resources and mining activities. Following future studies based on the presented methodology will serve this purpose.

Declaration of Conflict Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mohammad Abdelbaky: Conceptualization, Software, Writing - original draft. **Jef R. Peeters:** Methodology, Writing - review & editing. **Joost R. Duflou:** Supervision, Writing - review & editing. **Wim Dewulf:** Supervision, Validation, Writing - review & editing.

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References

Andresen, F., 2019. 24th International Congress for Battery Recycling ICBR 2019. Lyon.
Berman, B., 2018. What you need to know about electric car battery warranties, [Online]. Available: https://www.plugincars.com/what-you-need-know-about-electric-car-battery-warranties-132884.html. [Accessed 30 September 2019].
Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenze, M.A., Podias, A., Pfrang, A., 2018. Life cycle assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage 19, 213–225.
Bobba, S., Mathieux, F., Blengini, G.A., 2019. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. Res., Conserv. Recycl. 145, 279–291.
Canals Casals, L., Amante García, B., Canal, C., 2019. Second life batteries lifespan: Rest of useful life and environmental analysis. J. Environ. Manag. 232, 354–363.
Canals Casals, L., Amante García, B., González Benítez, M.M., 2016. A cost analysis of electric vehicle batteries second life businesses. In: Capuz-Rizo, S. (Ed.), Project Management and Engineering Research. Springer, Cham, pp. 129–141.
Cebulla, F., Haas, J., Eichman, J., Nowak, W., Mancarella, P., 2018. How much electrical energy storage do we need? A synthesis for the US., Europe, and Germany. J. Cleaner Product. 181, 449–459.
Chancerel, P., 2010. Substance flow analysis of the recycling of small WEEE. Institut für Technischen Umweltschutz Berlin, Berlin.
Drabik, E., Rizos, V., 2018. Prospects for electric vehicle batteries in a circular economy. European Union, Brussels.
EAFO, "Vehicles and fleets," 2019. [Online]. Available: https://www.eafo.eu/vehicles-and-fleet/m1 . [Accessed 29 April 2019].
Egede, P., 2017. Environmental Assessment of Lightweight Electric Vehicles. Springer International Publishing, Switzerland.
Ellingsen, L.A.-W., Singh, B., Strømman, A.H., 2016. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ. Res. Lett. 11 (5), 054010.
European Commission, "Automotive industry," [Online]. Available: https://ec.europa.eu/growth/sectors/automotive_en . [Accessed 7 August 2019].
European Commission, 2018. Report on Raw Materials for Battery Applications. Brussels.
European Parliamentary Research Service, "Electric road vehicles in the European Union: Trends, impacts and policies," 2019.
Gattiglio, F., 2019. 24th International Congress for Battery Recycling ICBR 2019. Lyon.
International Energy Agency, 2018. Global EV Outlook 2018. IEA.
Irle, R., 2019. Europe EV sales for 2018, [Online]. Available: http://www.ev-volumes.com/country/total-euefta-plug-in-vehicle-volumes-2/. [Accessed 22 April 2019].
Melo, M.T., 1999. Statistical analysis of metal scrap generation: the case of aluminium in Germany. Res., Conserv. Recycl. 26 (2), 91–113.
Millner, A., 2010. Modeling Lithium Ion battery degradation in electric vehicles. In: 2010 IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply. Massachusetts.
Neubauer, J., Smith, K., Wood, E., Pesaran, A., 2015. Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries. NREL, Denver.
Peters, J.F., Weil, M., 2018. Providing a common base for life cycle assessments of Li-Ion batteries. J. Cleaner Product. 171, 704–713.
Richa, K., Babbitt, C.W., Gaustaf, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. Res., Conserv. Recycl. 83, 63–76.
Ritchie, A.G., 2004. Recent developments and likely advances in lithium rechargeable batteries. J. Pow. Sources 136 (2), 285–289.
Schneider, J., Karigl, B., Neubauer, C., Tesar, M., Oliva, J., Read, B., 2010. End of life vehicles: Legal aspects, national practices and recommendations for future successful approach. European Parliament, Brussels.
Walton, B., Wu, H., Alberts, G., Hooper, J., 2019. New market. new entrants. new challenges. Battery electric vehicles. Deloitte LLP.
Xu, C., Zhang, W., He, W., Li, G., Huang, J., Zhu, H., 2017. Generation and management of waste electric vehicle batteries in China. Environ. Sci. Pollut. Res. 24 (26), 20825–20830.
Ziemann, S., Müller, D.B., Schebek, L., Weil, M., 2018. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach. Res., Conserv. Recycl. 133, 76–85.