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Prospects on end of life electric vehicle batteries through 2050 in Catalonia

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ABSTRACT

As electric mobility gains prominence, the demand for electric vehicle batteries is rapidly rising. Although the amount of these batteries reaching their end of life is presently negligible, studies to quantify their flows and stocks will progressively gain importance as they have a high potential for reuse and contain some economic valuable materials. This study aims at forecasting the number of batteries due to be collected yearly from 2020 to 2050 in Catalonia (Northeast Spain). Product flow analyses are developed considering two different future electric vehicle sales, and two lifespan scenarios for batteries, assuming they follow a Weibull lifetime probability distribution. The volume of batteries reaching their first-use end of life will not reach significance until 2050, however strategies to optimise their use can be placed earlier to get prepared to the coming influxes. If future electric vehicle sales are to meet the Spanish Climate Change Law, influxes of batteries can increase up to 25-fold in 2030 and 72-fold in 2040. Under the extended battery service scenarios, the storage capacity is estimated to be 4 to 5 times larger than in scenarios where batteries are recycled earlier. The potential supply of secondary materials from end of life batteries will increase up to 80% of cobalt, copper and nickel, and 60% of lithium in 2050. The results urge to place proper management strategies for batteries in the coming years to help optimising their use and their potential recovery.

1. Introduction

Electric mobility has become a hotspot for European Union's green policies (Niestadt and Bjornavold, 2019) and will play a crucial role in the implementation of the European Green Deal (European Commission, 2019). For example Spain approved the Plan MOVES II - a nationwide grant scheme incentivising the purchase of electric vehicles - soon after the release of the spring 2020′s lockdown (BOE, 2020). The outcome of the Plan MOVES II can be observed through the change in the share of newly registered vehicles corresponding to electric vehicles (EVs). In 2019, battery electric vehicles (i.e. BEVs or pure-electric vehicles) and plug-in hybrid electric vehicles (PHEVs) only accounted for 0.8% and 0.6% of the total newly registered cars, respectively (European Alternative Fuels Observatory EAFO, 2021). However, the share of newly registered BEVs and PHEVs increased towards 2.1% and 2.8% respectively in 2020 (EAFO, 2021). The number of electric vehicles on the Spanish roads are set to keep on increasing in the coming years as Spain has set a target of 100% new electric passenger car and light commercial vehicle sales by 2040 as part of its Law on Climate Change and Energy Transition (now onwards referred to as the Spanish Climate Change Law), approved in April 2021 (BOE, 2021a).

Nation-wide shifts towards electric mobility will result in a higher demand for high-performance traction batteries for electric vehicles across Europe (Bobba et al., 2019), including Spain. Lithium-ion based batteries - particularly lithium-cobalt batteries - are currently dominating the market for EV batteries (Cusenza et al., 2019), and are set to keep dominating it in the following 30 years (Zubi et al., 2018). As electric mobility continues gaining momentum, the demand for the raw materials needed for the manufacturing of EV batteries will certainly increase. This is an issue particularly concerning the EU as some of these materials - like lithium and cobalt - are considered Critical Raw Materials for the EU (European Commission, 2020a) because of their large quantities needed and/or the concentration of their supply sources (European Commission, 2018). In 2006, the EU set up the Waste Battery Directive, requiring member states to properly collect and recycle industrial and automotive batteries no longer in service (European Parliament and European Council, 2006). Therefore, producing secondary raw materials that re-enter the manufacturing process and reduce the need for primary raw materials (Mathieux et al., 2017). The role of battery recycling has been reinforced by the European

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Commission's Strategic Action Plan on Batteries, which aims to ensure a sustainable battery value chain within Europe in line with the 2015 and 2020 Circular Economy Action Plans (CEAPs) (European Commission, 2020b, 2018, 2015).

Extending the lifespan of products is considered one of the main strategies to achieve the reduction of material consumption required by the circular economy (Mesa et al., 2020). Under the current scenario, EV batteries are considered to reach their end-of-life (EOL) once they are no longer capable of powering an EV, when they are then sent back to its manufacturer to recycle its components (European Parliament and European Council, 2006). At this point, a lithium-ion battery still retains a residual capacity between 60% and 80% of its nominal capacity (Bobba et al., 2019). Therefore, the lifespan of these batteries could be easily prolonged by assigning them a second life use in a less energy-demanding application. This is one of the points targeted by the new proposal for Regulation 2020/353 - aiming to revoke and update the Waste Battery Directive - which includes guidelines to manage the second life of batteries (European Commission, 2020c). Recent research efforts have found promising results in coupling retired EV batteries with renewable energy sources (Koch-Ciobotaru et al., 2015; Zubi et al., 2018), particularly in residential household solar energy systems (Bobba et al., 2018a, S. 2018b), for their second life uses. In this scenario, the batteries can be used for photovoltaics firming, photovoltaics smoothing, primary frequency regulation and energy time shift and peak shaving (Bobba et al., 2018a; DigiPrime project, 2020).

As more EV batteries reach their EOL, infrastructure to collect, select and prepare the batteries for their second life use needs to be made available in Spain. Understanding the temporal characteristics of EOL batteries can guide the implementation of policies that effectively deal with these batteries. However, data on the quantity or volume of retired batteries, battery type, technology availability and demand for recycled products is very limited (Ai et al., 2019). Previous studies have used different models to project the number of retired EV batteries in the coming years at a national level in China (Wu et al., 2020), the US (Richa et al., 2014) and at a regional level in the state of California (Ai et al., 2019). National-level studies of this type predominate the literature. However, regional analyses have a bigger capacity to connect EOL EV batteries management with urban and regional planning (Ai et al., 2019).

This study aims at forecasting the number of EV batteries reaching their EOL yearly from 2020 to 2050. This information is key to help optimise the service life of EV batteries as well as to estimate the potential secondary materials (i.e., cobalt, copper, lithium, and nickel) at their EOL. To do so, the study focused on the Spanish region of Catalonia which accounts for over 16% of vehicle registrations in Spain (Idescat, 2021a). The study is performed using a product flow analysis considering two future EV sales scenarios and modelling the lifespan of EV batteries using a Weibull lifetime probability distribution function. The educated guess for EOL EV batteries is later used to predict the number of batteries that could be available for second use as energy storage equipment and then to calculate the quantity of materials contained within the batteries that can be possibly recovered. Results are given for the yearly generation of treated batteries, the potential energy storage capacity if reused and the potential secondary material production for the four defined scenarios. In the discussion the significance of the results and suggestions to better guide decision makers to setup of regional management strategies for EOL EV batteries are proposed.

2. Methods and data

This paper uses Product Flow Analyses (PFAs) to quantify the number of EV batteries that will reach the end of their first life use in EVs. Based on this information, it provides estimates of the amount of EV batteries available for second life and the material recovery potentials for a number of materials (cobalt, copper, lithium and nickel). The results of PFAs are used to characterise the stocks and flows of EOL EV batteries according to different lifetime patterns, which can contribute in finding proper management strategies for EOL EV batteries in Catalonia.

2.1. Modelling the EV batteries reaching the end of life

The number of batteries reaching their EOL is quantified using a Product Flow Analysis (PFA). PFA is a type of Material Flow Analysis (MFA) widely used to model the stocks and flows of different products across their life cycles given some established system boundaries (Ai et al., 2019; Magalini et al., 2012; Wu et al., 2020). PFAs often focus on the consumption stages of commodities, allowing examining how differences in the lifetime and disposal rates of a product can affect the amount of waste generated (Wernick and Irvin, 2005). Few studies have used PFAs to quantify the number of EV batteries reaching the end of their first life in a region, which can later guide better EOL EV batteries management (Ai et al., 2019; Wu et al., 2020).

This study follows the Brunner and Rechberger (2004) guidelines to conduct two PFAs to quantify the total amount of EV batteries that need to be to be checked to be reused, recycled or discarded (Ai et al., 2019) in Catalonia each year, following Eq. (1).

$$W(n) = \sum_{t=t_0}^{n} POM(t)\cdot L^{(p)}(t,n) \quad (1)$$

In which (Magalini et al., 2012; Melo, 1999; Oguchi et al., 2010):

is the quantity of batteries reaching their EOL in evaluation year *n*.

is the amount of EV batteries entering the market in any historical years *t* prior to year n

$t_0$is the initial year a product was put on the market

$L^{(p)}(t,n)$ reflects the probable obsolescence rate in evaluation year n.

Two PFAs are conducted. The first PFA quantifies the number of EV batteries reaching their first EOL. The second PFA quantifies the number of EV batteries going to second life uses will reach their EOL yearly. Combining these two PFAs results in the total amount of EV batteries needing to be treated yearly. In these PFAs we assume that batteries are treated the same year they reach their EOL, that all EV batteries purchased in Catalonia are treated within the Catalan administrative borders and that no batteries purchased elsewhere need to be treated. The following sections illustrate the procedures to calculate the two main variables affecting the quantity of batteries reaching their EOL: the number of batteries put on the market and their lifespan.

2.1.1. EV batteries put on the market in Catalonia

EV battery inflows into the Catalan market come from the sale of new EVs and the sale of replacement batteries. As replacement batteries represent only a very small proportion of the total EV batteries market (Ai et al., 2019), we assume that EV sales determine the historic and projected EV battery sales volumes.

There are data of EV registrations since 2013 (ICAEN, 2017), however these data do not classify EVs into their type and technology classes, thus impeding a more accurate analysis. The Catalan Energy Institute (ICAEN) has compiled EV registrations data since 2017 in the 'Dades obertes' in a more detailed form which also includes the typology of the vehicle (ICAEN, 2021). As result, we use EV registrations data from the latest dataset to represent historical EV sales, assuming that EV registrations match EV sales in Catalonia. Therefore, this study counts with the EV registration data between 2017 and 2020, and with the predictions of future EV registrations until 2040, following three different sales scenarios. We assume that all the batteries within the sold vehicles consist of lithium-ion based technologies.

2.1.1.1. Data gathering of EV historical sales. The EV registration data from the Catalan Energy Institute (ICAEN) includes information for BEV, PHEV, HEV and MHEV vehicles, which are described in Table A.1 of the Supplementary information. These EV types differ in many architectural aspects, being their battery capacity the most notorious one. Although battery capacities change vastly between car models, BEVs are the vehicles with a bigger energy storage capacity, starting from 40 to 80 kWh. PHEVs are the second type with a bigger capacity, with up to 15 kWh of storage (ICAEN, 2021). PHEV sales in Catalonia follow a similar trend as in the rest of Europe where, as described by Tsiropoulos et al., 2018, PHEV battery capacities and mileage efficiencies have been decreasing in recent years in favour of an increase of vehicles' power with larger internal combustion engines. HEVs and MHEVs have smaller batteries with a lower energy storage capacity, with capacities of 8kWH and 1 kWh or less respectively (APTIV, 2021). As smaller batteries degrade faster than bigger batteries, they are not as useful for second life uses (Barré et al., 2013). For this reason, we have only considered BEVs, as they are the most relevant for the purpose of this study. Details about the registration for all typologies of vehicle are available in Table A.2 of the Supplementary information.

Catalan and Spanish policies and incentives promoting electric mobility exist for different types of vehicles but focus especially on passenger cars (BOE, 2020, 2021a; GENCAT, 2019). In fact, passenger cars are the second type of vehicle with the most EV registrations in 2020, right after mopeds (Table A.2 in supplementary information). However, the battery of an electric moped is smaller (2–5 kWh) than that of an electric passenger car. Thus, it degrades faster, limiting their suitability for second life uses. Consequently, electric passenger cars will provide the highest volume of EOL EV batteries available for a second life use. For this reason, this study models the EOL EV batteries of passenger cars.

HEVs currently dominate the market of EVs in Catalonia but MHEVs are gaining importance as observed in the annual registrations of passenger cars for each type of EV technology between 2017 and 2020 (table A.3 of supporting information). Car registrations for PHEVs are also increasing, reaching an all-time maximum in 2020 (Table A.3). However, BEVs are the category set to dominate the market in the following years as the Spanish Climate Change Law has established, via the Integrated National Plan on Energy and Climate (PNIEC), that by 2030 there must be a fleet of three million electric vehicles in Spain. It has also set that by 2040 no more cars with internal combustion engines are to be sold (BOE, 2021a; MITERD, 2020b). It is to be noted that this database does not include data entries for hydrogen-fuelled vehicles (FCEVs), which are also all-electric vehicles. However, this type of vehicles is set to play a major role in the electrification of mobility in the future decades. In fact, there are roadmaps to foster hydrogen-based transportation both at the Catalan (ICAEN et al., 2020) and Spanish level (MITERD, 2020a).

2.1.1.2. Definition of EV future sales. To forecast future EV sales data, we modelled the predicted EV registrations in Catalonia from 2021 to 2040 according to two different scenarios:

- **Scenario A**: EV passenger car sales follow the current sale trend, increasing linearly until 2040 following the 2017–2020 trend.
- **Scenario B**: Several assumptions are made in this scenario. First, regarding the EV car sales in Catalonia according to the targets set by the Spanish Climate Change Laws, and the EV market share in Catalonia. Passenger car sales increase to reach Spanish Climate Change Law targets, which sets three million cars must have been sold by 2030 and that no more internal combustion engine cars are set to be sold after 2040. We assume that the proportion of cars sold in Catalonia respect to Spain by 2030 remains the same as it has been during the last five years (15%) (Idescat, 2021a). The second assumption taken is on trend of BEV sales in Catalonia. We also assume that BEV yearly sales in Catalonia increase linearly from 2020 sales to reach the target of cumulative sold cars by 2030 including sales since 2017. Third, we assume that from 2030 to 2040 yearly BEV sales will linearly increase to match passenger cars sales volumes predicted by the Spanish Association of Automobile and Truck Manufacturers (ANFAC) (ANFAC, 2020) in which yearly passenger car sales in Spain are predicted to be 1.4 million by 2040. Finally, despite the uncertainties regarding vehicles sales, we extended the study until 2050 assuming EV sales will remain constant to be able to evaluate the effect on the possible storage capacity of repurposed batteries and the potential materials recovered from batteries put on the market between the years 2030 and 2040.

2.1.2. Modelling the lifespan of ev batteries

Battery lifespan is a crucial factor in PFA models estimating EOL EV battery flows. In general, it is assumed that the lifespan of an EV battery ends when it can no longer power a car, approximately when they only retain an 80% of their original capacity (Neubauer et al., 2015; Richa et al., 2014). Three main factors are affecting the EV battery lifespan: (1) battery capacity and degradation rate, which are related to the type of EV technology (smaller batteries need to be recharged more frequently and have greater degradation rates); (2) technology and battery materials (newer batteries have upgraded technologies that allow longer lifespans); and (3) the consumer usage pattern, which includes factors such as driving and recharging behaviours and road conditions (Ai et al., 2019). These factors imply that EV battery lifespans do not follow a normal but a Weibull distribution, which is later described in this section.

EV batteries are under constant technological advances that prolong their lifetime (Ai et al., 2019). Currently, EV batteries are considered to last between 5 and 15 years (Bobba et al., 2019), and most EV manufacturers include battery warranties spanning for 8–10 years (Ai et al., 2019). Continuous innovations on batteries, such as battery performance management (BPM), optimisation approaches and new structure and materials, are expected to carry on prolonging the EV battery lifetime (Cano et al., 2018) reaching 15 years by 2030 (EUROBAT, 2015).

As there is wide variability in the lifetime of batteries and many variables are affecting their lifespan, there is no consensus on EV battery lifetime amongst literature analysing the inventory of EOL EV batteries in a region. Some studies have used a constant (Ai et al., 2019) while others an increasing battery lifetime along the years studied (Ai et al., 2019; Wu et al., 2020). In this study, we aim at examining the first EOL EV battery generation in Catalonia according to two different battery lifespan scenarios. The 'reduced battery service' scenario considers that batteries have a constant lifetime of 10 years, the current average EV battery lifespan (EUROSTAT, 2020). The second scenario referred to as 'extended battery service' follows that of Ai et al. (2019), in which battery lifetimes increase over time from an average lifespan of 10 years in 2017 to 16 years in 2035–2040 (Table B.1 of supplementary information). In total, we will examine four different scenarios with different

Table 1
Summary of the four scenarios defined for this study.

Scenario name	Future sales scenario (POM)	Lifetime assumptions (L)		
		First life	Reuse rate	Second life
A.1	Based on the 2017–2020 EV sales trend	Reduced service: 10 years	From 10% (2017) up to 25% (2030)	Reduced service: four years
A.2	Based on the 2017–2020 EV sales trend	Extended service: from 10 to 16 years	From 10% (2017) up to 75% (2030)	Extended service: from four to 12 years
B.1	Reach Spanish Climate change Law's targets	Reduced service: 10 years	From 10% (2017) up to 25% (2030)	Reduced service: four years
B.2	Reach Spanish Climate change Law's targets	Extended service: from 10 to 16 years	From 10% (2017) up to 75% (2030)	Extended service: from four to 12 years

EV sale and battery lifetimes values, all summarised in Table 1.

Each individual EV battery has its own lifespan, which may differ from the average EV battery lifespan assumed. Probability distribution functions for EV battery lifespans are used to represent the variety in each single battery lifespan and to predict the generation of EOL EV batteries (Wu et al., 2020). This study uses the Weibull distribution function, which considers different product life behaviours to model realistic product lifetime distributions (Ai et al., 2019). The Weibull distribution has been widely used in the analysis of e-waste (Magalini et al., 2014, 2012; Polák and Drápalová, 2012) and in the analysis of EOL EV batteries (Ai et al., 2019; Richa et al., 2014; Temiz and Guven, 2016; Wu et al., 2020; Xu et al., 2020).

In this study, we adopt a Weibull probability density function defined by two parameters: the *shape* α(t) and the *scale* β(t). The Weibull distribution adopted in this study is defined by Eq. (2) (Magalini et al., 2014):

$$L^{(p)}(t,\ n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-[(n-t)/\beta(t)]^{\alpha(t)}} \quad (2)$$

Eq. (2) is one of the parameters of Eq. (1), and the *shape* and *scale* parameters. The *shape* parameter α refers to the technical failure rates of the batteries (Schuster et al., 2015) and determines the shape of the probability density function (Wu et al., 2020). Based on the studies done by Ai et al. (2019) and Wu et al. (2020), we adopt the *shape* parameter of 3.5. We assume the *shape* parameter does not change during the years considered in our study, as it hardly varies over time (Wang et al., 2013). The *scale* parameter β represents the average lifetime of EV batteries (Barré et al., 2013). We have employed different β values in our Weibull distributions, according to the lifespans indicated in Table 1. Additionally, we also assume that EV batteries are sent for EOL management the same year they reach their EOL.

Finally, we combined the values obtained with this function with the number of EV batteries put on the market (POM) following Eq. (1), as done by (European Commission, n.d.). Therefore, obtaining the total amount of EV batteries reaching their end-of-life each year in Catalonia from 2017 to 2050.

2.2. Estimates of EV batteries available for second life

The quantity of EV batteries put on the market (POM) and the different lifetime scenarios described are combined following Eq. (1) to obtain the total amount of EV batteries reaching their first EOL in Catalonia from 2017 to 2050. Once EV batteries are collected, they can have a second life in stationary storage applications. The number of EV batteries available for second life will be determined by the number of EV batteries reaching the end of their first life and the collection rate. This study assumes a 95% collection rate for the two scenarios as EV batteries collection ranges between 90 and 100% in Europe (Abdelbaky et al., 2021; Bobba et al., 2020; S. 2018b). Out of the collected batteries, Bloomberg New Energy Finance (Curry, 2017) estimated that in 2025, 27% of these batteries will have a second life in stationary storage units, whereas the remaining 73% will be available for recycling. Neubauer et al. estimated availability for recovery around 80% (Neubauer et al., 2015). As result, we assumed an initial reuse rate of 10% out of the collected batteries for both scenarios. Then, we assume that the improvement in management strategies will help these percentages to increase linearly until 2030 up to 25% for the battery ‘reduced service’ scenario and 75% for the battery ‘extended service’ scenario. After 2030, the reuse rates remain constant until 2050. These percentages are employed to calculate how many of the EV batteries reaching the end of their first life use each year will go onto second life uses as storage systems for PVs. EV batteries reused for other applications other than powering electric cars will ultimately be recycled to recover the materials within them. Hence, we perform a PFA of the EV batteries with a second life use to quantify the number of batteries will reach the end of their second life use every year. The PFA is performed analogously as for the first life but using a different *scale* parameter, that is a different average lifetime. Bobba et al., 2018a and Neubauer et al., 2015 estimated an average second lifetime of three to four years. Other estimations considered the possibility to reuse batteries during 10 to 13 years (Assunção et al., 2016; Neubauer et al., 2015). Hence for the second life forecast, the battery ’reduced service’ scenario sets a constant average lifetime of four years while in the battery ’extended service’ scenario the average lifetime increases linearly from four years to 12 years for batteries starting their reuse in the year 2030.

After the second life, all EV batteries are assumed to be collected for recycling. The number of EV batteries reaching yearly the end of their first and second life is added up resulting in the total number of EV batteries due to be treated. Batteries reaching their end of lives are further analysed to quantify the potential for secondary materials.

2.3. Estimates of potential secondary materials from EV batteries

A preliminary step to estimate the potential quantity of secondary materials from EV EOL batteries is to investigate further the chemical composition of these batteries. There are multiple types of battery chemistries that differ in properties such as safety, stability, energy density, lifetime and, importantly, material requirements (Campagnol et al., 2019). Lithium nickel manganese cobalt oxide (NMC) chemistries currently dominate the EV battery market due to their long cell durability, high performances and relatively low cost (Azebedo et al., 2018). However, they require cobalt, considered an EU critical raw material due to its high economic importance and a high supply risk potential (Greenwood et al., 2021). For this reason, nickel-rich formulations of NMC, such as NMC-622 and NMC-811, are gaining grounds in the EV market, especially in the EU. In fact, McKinsey (Campagnol et al., 2019) estimated that NMC chemistries would represent 72% of all EV batteries by 2020 but 93% by 2030 (see Figure B.1 of supplementary information). Other studies, such as that of Zubi et al. (2018) include different battery chemistry mix forecasts that estimate that NMC chemistries will have a market share of a 35% while lithium iron phosphate (LFP) and lithium nickel-cobalt-aluminium oxide (NCA) chemistries will have a 40% combined market share. In this study, we assume that the battery chemistry distribution mix follows McKinsey’s forecast, as it includes estimates of the market share occupied by each of the different types of NMC cathodes (i.e. NMC-111, NMC-622 and NMC-811)(Campagnol et al., 2019). McKinsey’s forecast includes estimates of the battery chemistry mix until 2030, and we assume that it remains constant from 2030 to 2050 in order to be able to estimate secondary material recoveries from 2030 to 2050. Nonetheless, it needs to be acknowledged that this assumption is limited by the fact that new battery technologies – such as NMC-955, NMC-9525, NCA-955 and beyond lithium-ion batteries – are likely to disrupt the EV battery market once they become commercially available (Abdelbaky et al., 2021; Greenwood et al., 2021; Mauler et al., 2021).

This study estimates the content of relevant materials (i.e. cobalt, copper, lithium and nickel) within EV batteries as defined per kWh basis based on projected yearly energy capacities. Lithium-ion battery capacities for BEVs and PHEVs are set to increase to meet EV range goals (Greenwood et al., 2021). IRENA (2017) estimate that BEV battery capacities will increase from 40 kWh in 2017 to 52 kWh in 2025 and 60 kWh from 2030 onwards. The requirement of cobalt, copper, lithium, and nickel per kWh for every battery chemistry type considered in the study is detailed in Table B.2 of the supplementary information.

To estimate the potential for secondary materials out of the batteries, it is important to understand the functionalities of the relevant materials. For example, cobalt, lithium, and nickel constitute parts of the cathode of the batteries. Lithium is also used as a salt in the electrolyte in Li-ion batteries while copper is used as the current collector foil at anode side, in wires and other conductive parts (Bobba et al., 2020). All these materials are in a chemical form that is potentially recyclable. However, at present EV batteries mainly undergo pyrometallurgical processes that only target metals with high economic value such as cobalt, copper and nickel (European Commission, 2020d; Mossali et al., 2020). Indeed, it was estimated that in 2015 no lithium recycling took place in Europe (European Commission, 2020d). Pilot plants have proven possible to apply a hydrometallurgical process or a sequence of a pyrometallurgical and hydrometallurgical processes and achieve a recycling efficiency over 50% for lithium and 90% for cobalt, copper and nickel (Lebedeva et al., 2016).

In this study, we assumed a unique scenario, determined by the targets in the new draft European Batteries Regulation proposal on recycling efficiency (European Commission, 2020c – Annex XII), which seeks drastic improvements in lithium recycling efficiency. The recycling efficiency of lithium is set to increase from 0% to 35% in 2025 and to 70% in 2030. For copper, cobalt and nickel, we assumed efficiencies starting from 80% in 2017, increasing up to 90% in 2025 and 95% in 2030. There are some other materials contained in EV batteries that were not considered in this study. The recycling of natural graphite is assumed to remain negligible throughout the studied period as result it was not included in the study. For manganese, another material contained in batteries, the new battery regulation does not define recycling efficiencies, probably because it is not classed as a EU Critical Raw Material. The materials recovered are assumed to be potentially reusable into batteries, as recently demonstrated by Ma et al., 2021.

3. Results and discussion

As the number of EV batteries starts to gain importance in the transition to a lower carbon economy, analyses that help envision possible strategies to optimise their lifetime of EV batteries and to quantify their potential contribution to the supply of materials are in order. To account for the EV batteries reaching their EOL, two main variables are modelled: the amount of EV batteries put on the market, and their lifetime. The following section shows the results of the estimated EV batteries reaching their EOL, the quantity of batteries available for second life and the potential production of secondary materials in four possible scenarios.

3.1. EV batteries reaching the end of their life

The quantity of EV batteries reaching their EOL can be calculated with information about the number of EV batteries put on the market and the modelling of their lifespan. With the Spanish Climate Change Laws assumed for scenarios B, the amount of EV batteries POM will be significantly greater than in the EV sales-as-usual for scenarios A. Table C.1 of the supporting information shows the amount of EV batteries put on the Catalan market from 2020 to 2050. By 2030, 80 thousand EVs will be sold in scenario B while only 11 thousand EV will be sold under scenario A. By 2040, 19 and 230 thousand car sales are forecasted under scenarios A and B respectively. This means that the sales of EVs can increase up to 25-fold in 2030, and up to 72-fold in 2040. These results are relevant to predict the role that EV batteries can play in future energy transition and waste scenarios.

Based on the quantity of EV POM, Fig. 1 shows the results for the diverse EV sales and battery lifespan scenarios. By 2030, 2.4 and 8.4 thousand batteries are expected to reach their first-use EOL under scenarios A and B. By 2040, these figures will rise to 7.4 and 55 thousand units and by 2050 to 14.3 and 151 thousand units. The results show that even though there is still time until a large volume of EOL EV batteries reach the Catalan market, reuse and recycling strategies for EV batteries should be set up soon to prepare for the coming influxes, particularly if the Spanish Climate Change Law is to be met. Further information is available in Table C.2 of the supporting information.

Although assumptions have been cautiously chosen, there are still some uncertainties remain in this study, particularly in those variables related to forecasts on future sales and battery technology advancements. Decision-makers looking at this paper for guidance on the application of suitable EV battery reuse and recycling strategies in Catalonia should take into account that our long-term estimates are less reliable than our short-term ones. The result about the potential reused and recycled batteries are commented in the next sections.

3.2. EV batteries available for second life

Assuming the respective reuse rates described in table 1, the number of EV batteries reaching their EOL in Catalonia during selected years from 2020 to 2050 suitable for second life uses as stationary energy storage units were accounted for. By 2050, under scenarios B1 and B2,

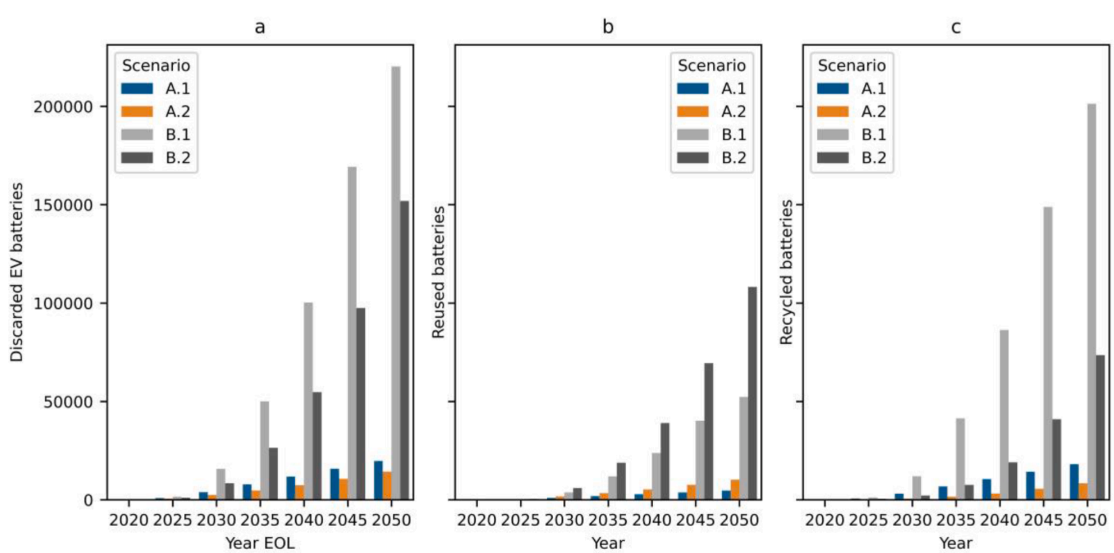

Fig. 1. Yearly generation of first life EOL EV batteries (a), the potential reused batteries (b) and the potential recycled batteries (c) in Catalonia from 2017 to 2050 according to the four different scenarios: A1 - EV sales as usual and reduced EV battery service life, A2 - EV sales as usual and extended EV battery service life, B1 - EV sales to meet the Spanish Climate Change Law and reduced EV battery service life, B2 - EV sales to meet the Spanish Climate Change Law and extended EV battery service life.

the quantity of EV batteries suitable for reuse is an order of magnitude higher than that of the A1 and A2 scenarios – showing that the number of batteries put on the market will have a big influence on the EV batteries that can be reused as stationary storage systems. Scenarios A1 and B1 with a reduced lifespan (10 years for the first life) will generate nearly double the amount of EOL EV batteries after first use in the mid-term than scenarios with extended lifespan. However, because in scenarios A1 and B1 most batteries are diverted from second uses to recycling, the actual number of batteries for second life uses installed every year after 2030 would be nearly half of that in the extended battery service scenarios (i.e. A.2 and B.2). As prior to their second life use, batteries need to be checked and, if necessary, repurposed to meet the requirements to become reliable stationary storage units. Centers that specialize in the preparation for reuse of EV batteries are needed in Catalonia. Currently, the influx of retired EV batteries needing to be prepared for reuse is negligible but, by 2030, around 150–1100 units will be suitable for reuse and will need to be processed.

The nominal storage capacity at a given year for the two EV sales scenarios is accounted for considering that new batteries' capacity increases as stated in Table 1, repurposed EV batteries retain 80% of their nominal capacity and that EV batteries have a second lifespan in accordance with the scale factors of scenarios 1 and 2. The installed energy storage rated capacity from repurposed batteries, increases every year, reaching maximum values of 700 kWh to 35 MWh by the year 2050 (Fig. 2). The amount of EV batteries put on the market highly influences the total storage capacity of second-life batteries, as the scenarios with larger forecasted EV sales (i.e. B.1 and B.2) will have a potential storage capacity an order of magnitude higher than on the other scenarios. Besides, in extended service scenarios it was obtained a storage capacity of 4 to 5 times larger than in scenarios where batteries are recycled earlier (Fig. 2). Extending the service of EV batteries through second life uses as stationary energy storage to support the further implementation of stochastic renewable technologies aligns with PNIEC (MITERD, 2020b). The storage capacity provided by second-life batteries can help achieve this goal. However, depending on the lifespan these batteries reach, the difference in installed storage capacity at a given moment can vary by more than 50%.

3.3. Potential secondary materials from EV batteries

An educated guess about the potential production of cobalt, copper, lithium and nickel from EOL batteries is performed. Fig. 1 shows estimates of how many batteries will be available for recycling annually under the four different scenarios. Out of the recycled batteries, we measured the potential material recoveries in Catalonia taking into consideration the year these batteries were put on the market to determine their capacity and composition. The analysis also considers the year the batteries are recycled to determine the recycling efficiencies. In line with previous results, under reduced battery lifespans and larger influxes of batteries put on the market, the number of materials available for recovery is higher (see Fig. 3). Besides, under extended lifetime and higher reuse rates scenarios, secondary sourced materials will be able to supply a smaller proportion for the manufacturing of new batteries (Fig. 3). We also find that the higher the increase in EV batteries put on the market every year, the smaller proportion of recovered materials in new products will be achieved. In the case of scenario B2 while there is a fast increase in new BEVs yearly sales before 2040, the recovered proportion does not exceed 10% for any metal, being insufficient to meet the recycled content set in the draft of the New EU Battery Regulation. After 2040, the proportions of recoverable materials increase rapidly for both scenarios B1 and B2 (Fig. 3). It should be noted, however, that long-term estimates of materials' demand present large uncertainties. The reduction in the use of cobalt rich cathodes can explain the higher proportion of recoverable cobalt in all scenarios despite having the same recycling efficiency as copper and nickel (Fig. 3). It must be noted, however, that in our scenarios, we did not consider the influence of the extended service and promotion of reuse of batteries in the demand for new batteries in both vehicles and stationary energy storage applications.

Discussion

Understanding the number of batteries reaching their EOL yearly is key to define a more optimal management and ensure their recycling. Similar to findings by Ai et al. (2019), we find that under extended lifetime scenarios the annual EOL EV batteries increases at lower rate than when a reduced lifespan is assumed. Extending EV battery lifespans reduces significantly the total batteries needing to be treated every year. We find that, for the year 2030, 37% and 46% less batteries need to be

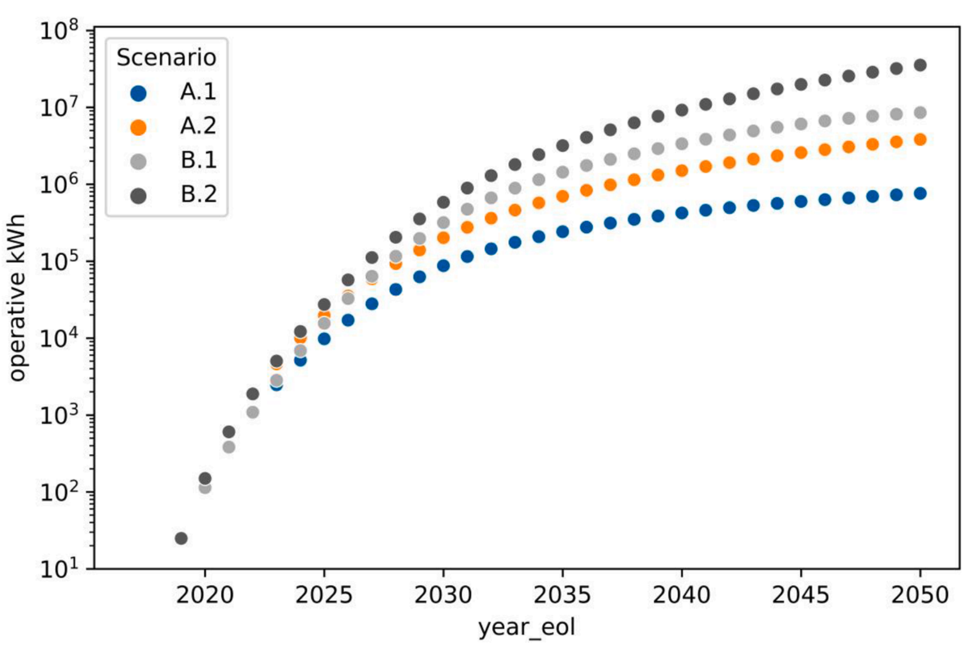

Fig. 2. Potential storage capacity (in kWh) available from the EOL EV batteries reused as stationary storage units in Catalonia. Values are represented in logarithmic scale to illustrate the exponential growth from present to 2050.

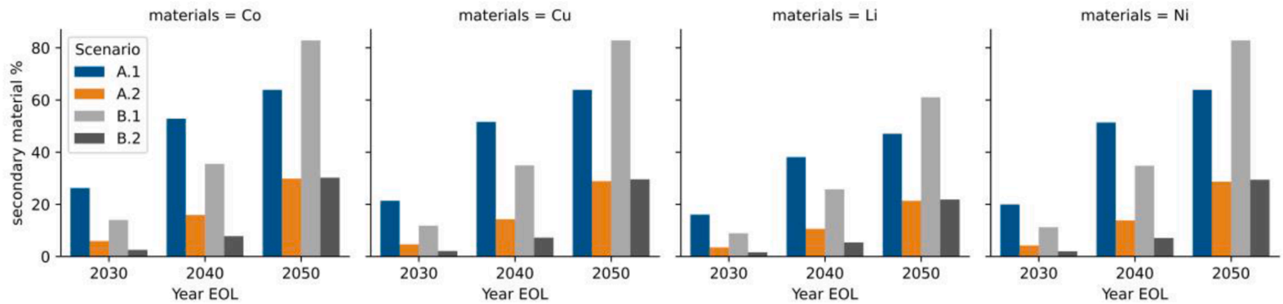

Fig. 3. Potential secondary materials to be recovered yearly from 2030 to 2050: cobalt (Co), copper (Cu), lithium (Li), and nickel (Ni).

treated when lifetimes are extended in sales scenarios A and B, respectively. Similarly, for the year 2050, these percentages would be 27% and 31%. Prolonging EV battery lifespans plays a major role in determining the EOL EV battery generation in a region. It helps understand the urgency to set up large-scale reuse and recycling infrastructure and strategies to ensure the close loop management of EV batteries.

In the EU, the draft of the new EU battery Regulation sets some implementing measures interesting to be discussed together with the results obtained in section 3. Some of these measures refer to recycling, the state of the battery, their architectural design, and their carbon footprint. The potential recycling of batteries has been extensively analysed in this study. As demonstrated in the results, there is a high potential to close the loop of cobalt, copper and nickel if recycling efficiency are met. From a life-cycle perspective, as we move from internal combustion to electric cars, the emissions generated during the extraction and refining of raw materials stages will gain further importance (Kawamoto et al., 2019). These emissions can be reduced through the secondary sourcing of materials. In fact, Hao et al. (2017) estimated that 10% of the life cycle EV greenhouse gas emissions could be reduced using secondary materials, of which the recycling of NMC batteries could account for 13–23% of the total reduction. As mentioned earlier, some of the materials within EV batteries are considered Critical Raw Materials by the EU mainly due to their high import reliance from third countries (Bobba et al., 2020; European Commission, 2020d). The draft of the new battery regulation (European Commission, 2020c) sets minimum mandatory levels of recycled cobalt, lithium, and nickel. However, the rapid demand for EV batteries as a result of policies promoting e-mobility in Spain will create short- and medium-term bottlenecks in their supplies, which will be exacerbated by the extension of battery lifespans. Therefore, the current EV sales targets combined with the recycling efficiency and secondary material use targets may result incompatible. Nevertheless, it is important to set recycling efficiency obligations and targets, particularly for lithium, for two reasons. First, lithium is a critical raw material only recoverable from li-ion batteries recycling (European Commission, 2020d). The other end uses of lithium are considered as in-use dissipation (i.e. lubricants and greases) and currently unrecyclable (i.e. glass and ceramics, continuous casting). Second, battery recycling is currently mainly motivated by the economic value of recovered cobalt, while lithium is left completely unrecovered (Lebedeva et al., 2016, European Commission, 2020d). An evolution to cathode chemistries mix with low or free of cobalt may provide even lower economic incentives for batteries recycling (Abdelbaky et al., 2021).

The draft of this new regulations sets the obligation to producers of providing extended producer responsibility on new batteries to ensure their collection and to proceed in the repurposing for a second use. The draft regulation, however, is not explicit about reuse targets. Indeed, the actual service lifespan and its reuse may undergo under an extended producer responsibility that will not necessarily follow any of the scenarios proposed in this paper. Regardless of the regulations over battery ownership, the life cycle of batteries will be eventually determined by the technical limitations to extend its first use and to give it a second use, and by the financial motivations to do so.

One measure included in the draft regulation related to reuse and recycling includes an obligation to batteries producers to facilitate the access to information on the state of the battery and the best practices for handling the battery to independent operators (third parties) trying to repurpose the battery (articles 14, 47 59) (European Commission, 2020c). The possibility of EV battery to be repurposed will be certainly influenced as well by its design architecture. This is the accessibility to the battery within the EV and the design features (i.e. connectors) of the parts and the components within the battery. In fact, the design of the EV battery is suspected to be highly influential not only for reuse but also to ensure repairing, repurposing and recycling (Kampker et al., 2021; Mossali et al., 2020). The sooner ecodesign strategies to facilitate battery disassembly are put in place, the sooner efficient reuse and recycling strategies would be achieved.

Another relevant measure is the obligation to provide a carbon footprint estimate for EV due to be commercialized in the EU. The calculation of the life cycle carbon footprint 'shall be based on the bill of material, the energy use, and the auxiliary materials used in a specific plant to produce a specific battery model'. Working towards more quantitative information about the bill of materials of battery components, especially cathode materials and the electronics, is needed as they represent the main contributor for the battery carbon footprint. Accounting for the carbon footprint of reused and remanufactured batteries is still incipient (Xiong et al., 2020). Data available are generally given as kg of CO2 equivalent per kg of battery compared to data for primary batteries calculated as kg CO2 equivalent per kWh (Hall and Lutsey, 2018) and without a clear description of the lifetime assumed.

Renewable energy generation for self-consumption is to play a major role in the shift of the current energetic paradigm to the Spanish Climate Change Law scenarios which aims at generating 74% of energy from renewable sources by 2030 (BOE, 2021a). EV batteries after the first life could represent a central element at facilitating the installation of photovoltaics in neighbour communities. Indeed, their use to support PV installations is the most promising second life application according to literature (Bobba et al., 2018a; Drabik and Rizos, 2018). Multiple benefits may arise from the synergies between retired EV batteries and photovoltaic energy, such as the smoothing of photovoltaic power generation (Ceja-Espinosa and Espinosa-Juarez, 2017), facilitating the access to electricity in remote location with limited access to electricity grid infrastructure and the reduction of the total cost of the EV batteries by giving them an EOL monetary value and promoting the leasing of batteries by car manufacturers.

4. Conclusions

As electric mobility continues to being promoted in Catalonia (and Spain), it is important to understand when EV batteries will reach their end-of-life to plan for a proper management. In this paper, we present a forecast on the EOL EV batteries to be treated yearly from 2020 to 2050. Four scenarios have been defined considering a combination of future EV sales and service lifetime of EV batteries. The results show that the amount of EOL EV batteries can increase up to 72-fold in 2040. Measures to ensure its optimal use either as a secondary energy storage equipment or for an optimal recovery of materials shall be put on place. Reusing these batteries in a second life can provide from 700 kWh to 35 MWh of storage capacity in 2050. The number of secondary materials will increase significantly as more EV batteries are put on the market. In 2050, secondary material from EV batteries could potentially supply up to 80% of cobalt, copper and nickel, and 60% of lithium.

Proper management strategies need to be implemented soon, as big influxes of retired EV batteries are to come in the following years. However, the increasing lifespan of EV batteries might soften the number of batteries to manage in the mid long term. Extending battery lifespans through second life uses – such as photovoltaic energy storage – can promote both the purchase of EVs and the generation of renewable energy for self-consume in households, while lowering the need for primary raw materials. After a second life, batteries can be recycled to recover valuable materials and reduce the dependency on the imports from third countries.

If the Spanish Climate Change Law targets are to be met, proper synergies between electric mobility and renewable energy systems are to be encouraged through policies and regulatory mechanisms that extend EV batteries lifetimes and recover the critical components within them. One interesting topic to explore further is a more detailed environment assessment, including the carbon footprint, of setting up close loop reuse of batteries and secondary material supply, and their effect in reducing material and energy dependency in the EU. Transitioning towards a more sustainable mobility system hence requires the involvement of policy-makers, raw materials producers, battery manufacturers, car producers and the general public to have a long-term vision that aligns with the objectives of the proposed new batteries regulation (European Commission, 2020c), the 2020 circular economy action plan (European Commission, 2020b) and the communication on EU critical raw materials. In Catalonia, the number of EOL EV battery treatment centres are really limited. Setting up these centres close to existing automotive factories would help optimise even further closing the loop.

CRediT author statement

Mateo Sanclemente Crespo: Methodology, formal analysis, writing- review and editing, and visualization **Marta Van Ginkel Gonzalez**: Methodology, investigation and Writing- Original draft preparation. **Laura Talens Peiró**: Conceptualization, Supervision, Writing- Reviewing and Editing and funding acquisition.

Declaration of Competing 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.

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Supplementary materials

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