



CIRCULAR IMPACTS

Prospects for electric
vehicle batteries in a
circular economy



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Abstract

The objective of this paper is to provide information and estimates about the impacts of managing the large number of lithium-ion batteries for electric vehicles that enter the market and will reach the end of their life in the coming years. The analysis compares two different hypothetical scenarios involving different levels of ambition regarding battery collection rates for recycling in Europe and the recycling efficiency rate for different materials.

Four key materials are selected based on their economic, societal and environmental importance and data is collected through a literature review and information from interviews and consultations with experts. The study found that increased collection and recycling efficiency rates of EV batteries in the EU can mitigate dependence on imported materials and help retain the value of recovered materials within the EU economy. Further benefits of increased collection and recycling efficiency rates include job creation in the recycling sector and mitigating CO₂ emissions. It is recommended that the EU continues and strengthens its support for R&I for lithium-ion battery recycling processes to improve their cost effectiveness and efficiency. The paper also suggests that more research is needed to provide evidence about the costs of recycling batteries, the level of investment needed to set up recycling facilities in Europe and the net impact on employment.

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Executive Summary

Electric vehicles (EVs) are a key technology to decarbonise the road transport sector and their use is expected to increase. At present, lithium-ion batteries are the most common type of battery used in these vehicles; consequently, the projected diffusion of EVs is expected to increase demand for lithium-ion batteries. The question of what will happen to the huge number of lithium-ion batteries that reach the end of their life is important for the EU, which has set as a priority the development of a full value chain for batteries in Europe. How the valuable materials within each battery can be recovered and recycled will thus become more important, as will information on the impacts of developing a lithium-ion battery recycling industry within the EU.

With this in mind, this study analyses the impacts of managing lithium-ion batteries from EVs that reach their end of life in the coming years. It first reviews the trends and technological developments in the EV lithium-ion battery market as well as the lithium-ion battery value chain. It then identifies the key materials within EV batteries that are important from Europe's economic, social and environmental perspective.

This is followed by an investigation into the impacts of managing end-of-life batteries from EVs based on a comparison of two different hypothetical scenarios. Scenario 2 is more ambitious, with higher collection and recycling efficiency rates, showing the scale of benefits that can be achieved with different levels of ambition. Assumptions are based on information and data gathered through a literature review and interviews/consultations with experts from different segments of the lithium-ion battery value chain. The data and information collected was validated through an expert workshop and further interviews with specialists in the field.

This study focuses on the volume and value of materials that could be recovered (trade effects), as well as the employment and environmental impacts. For reasons of data availability, the costs of collecting, dismantling and recycling batteries, together with investment costs and employment effects on other sectors, have not been included in this study. Further research is recommended to evaluate these factors.

The study forms part of a wider project, CIRCULAR IMPACTS, which looks at the economic, employment and societal impacts of shifting towards a circular economy.

The paper concludes that increasing the collection and recycling efficiency rates of EV batteries in the EU can mitigate dependence on imported materials and help to retain the value of recovered materials in the EU economy.

- It is estimated that by 2030, €408 million in current prices could be recovered from the four key materials included in the study, i.e. cobalt, nickel, aluminium and lithium from EV batteries under scenario 1, and €555 million under the more ambitious scenario 2.
- In 2040, these figures could increase to around €1.9 billion under scenario 1 and €2.6 billion under scenario 2.
- Regarding cobalt, a critical raw material, 2,922 tonnes of material worth of €213 million could be recovered by 2030 under scenario 1. Under scenario 2, 4,058 tonnes with a value of €295 million could be recovered during the same year; this amount is 41% of all cobalt imports into the EU in 2012. In 2040, 18,763 tonnes of material worth around €1.37 billion could be recovered under scenario 2.

- The value of nickel that could be recovered in 2030 under scenario 2 (€157 million) is around 9% of the value of net EU imports in the year 2015.
- Further potential benefits include job creation in the lithium-ion recycling sector for the collection, dismantling and recycling of EV batteries.
- The study also concludes that recycling certain materials in lithium-ion batteries, as opposed to extracting the raw material, may mitigate CO₂ emissions. The net savings of over 1 million tonnes of CO₂-eq in 2040 (Scenario 2) are equivalent to the CO₂ emissions of producing 261,000 tonnes of aluminium, which is comparable to the annual production of two primary aluminium smelters.

1 :: Introduction

The traditional internal combustion engine (ICE) has been the dominant power source for cars for decades, but more recently there has been momentum for alternative powertrain¹ technologies (ACEA, 2017). A number of countries, including France (Schneider, 2017) and the UK (UK government, 2017), have put forward plans to ban sales of petrol- and diesel-powered cars in coming years, while several governments around the world have set targets² for the deployment of electric vehicles (EVs) (IEA, 2017). Such policy developments, coupled with technological advancements and commitments from various automobile manufacturers,³ send positive signals about the proliferation of alternative powertrain technologies. Estimates about the future deployment of electric vehicles vary but the majority project a significant increase in EV sales over the next 10 to 20 years.

Electric vehicles powered by an electric motor using electricity stored in an on-board battery⁴ are among the key technologies⁵ for decarbonising road transport. At present, lithium-ion batteries are the most common type of battery used in such vehicles (EEA, 2016). The manufacture of these batteries requires several different raw materials, some of which have a high economic importance and face supply risks (Lebedeva et al., 2016). The anticipated increase in EV sales will also increase demand for lithium-ion batteries and the materials needed for their manufacture (IEA, 2017). To this end, questions of what will happen to the large number of lithium-ion batteries that reach the end of their life and how the valuable materials within can be recovered and recycled will become increasingly important. These questions are highly relevant for Europe, which lacks a strong domestic battery-cell manufacturing⁶ base (Lebedeva et al., 2016).

In view of this issue, in October 2017 the Vice-President for Energy Union, Maroš Šefčovič, announced the launch of a process to develop an ‘EU Battery Alliance’ to support the “establishment of a full value chain of batteries in Europe, with large-scale battery cells production, and the circular economy” (European Commission, 2017a). In May 2018, the Commission published a Strategic Action Plan on Batteries as part of the third Mobility Package, which includes specific measures “in order to make Europe a global leader in sustainable battery production and use, in the context of the circular economy” (European Commission, 2018a, p.2).

The objective of this paper is to provide information and estimates about the impacts of managing the large number of lithium-ion batteries for electric vehicles that enter the market and will reach the end of their life in the coming years. The analysis is based on a comparison of two different hypothetical scenarios regarding the collection and recycling efficiency rates of lithium-ion batteries in Europe. Information and data have

¹ According to ACEA (2017, p.4), “alternative powertrains include propulsion systems that are not based exclusively on the internal combustion engine”.

² Such policy commitments are often driven by concerns about urban air quality and/or the need to achieve the goals of the Paris Agreement (Schneider, 2017).

³ For a list of major automobile manufacturers that have made announcements regarding targets and investment plans for EVs, see, Schneider (2017).

⁴ This category of EVs includes both battery electric vehicles (BEVs) powered solely by an electric motor, using electricity stored in an on-board battery and plug-in hybrid electric vehicles (PHEVs) that have an on-board battery as well as an internal combustion engine (EEA, 2016).

⁵ Other technologies include hydrogen fuel cells and compressed natural gas (ACEA, 2017).

⁶ According to Lebedeva et al. (2016), cell manufacturing is one of the six segments of the automotive lithium-ion battery. For more details see sections of this paper on technological development and the battery value chain.

been collected by the research team through a literature review and interviews with experts from different segments of the lithium-ion battery value chain, specifically from battery recyclers, the automotive industry, research organisations and trade associations. The list of interviewed experts is presented in Annex 2.

This paper has been prepared in the context of the CIRCULAR IMPACTS project,⁷ which aims to collect evidence on the macro-economic impacts of the circular economy transition based on specific case studies. The methodology used in this paper was guided by the stepwise methodology developed by Smits & Woltjer (2017) to assess the impacts of circular-economy case studies. The steps included in this methodology⁸ were adapted to the specificities of this case study on end-of-life EV batteries.

Section 2 of this paper deals with trends related to technological developments and the battery value chain. It also identifies the key materials covered by this study. Section 3 builds the two scenarios and presents the variables and assumptions used to perform the scenario analysis. A presentation of the assessed trade, employment and environmental impacts then follows. Section 5 identifies a number of key policies associated with lithium-ion batteries, and the last section presents the summary and conclusions of this study.

2 :: Trends, technological developments and the battery value chain

2.1 Sales and price trends

Battery-powered electric vehicles are among the key technologies used to decarbonise the road-transport sector. The projected diffusion of this technology is expected to trigger an increase in demand for lithium-ion batteries. In 2016, 750,000 EVs were sold worldwide (IEA, 2017) and Shankleman et al. (2017) predict that annual global EV sales will grow from 1 million in 2017 to 24.4 million by 2030. While most will be sold in China and the US, it is expected that one-fifth of such cars will be sold in Europe (Bloomberg New Energy Finance, 2017). These figures equate to a global growth in the EV battery market from 21GWh in 2016 to 1,300 GWh by 2030 (ibid), calling for a necessary scale-up of the supply chain to meet growing demand.

The use of lithium-ion batteries is not just limited to the car industry, they are also used in electricity-storage systems and portable electronic devices, with demand expected to increase. The lithium-ion battery market is thought to have a compound annual growth rate of 14%, with the transport sector accounting for 60% of the market by 2025 (Roskill, 2017). The continuously increasing appeal of this technology has caused a steep drop in price over the past five years (Shankleman, 2017), which is likely to continue. In 2015, the price of EV batteries ranged from \$320-460/kWh and many predict that by 2030 the price will fall significantly, even to as little as €60-75/kWh (Berckmans et al., 2017;

⁷ For more info, see <http://circular-impacts.eu/>.

⁸ The methodology envisages the following steps: Step 1: Defining the baseline; Step 2: Defining the new business case; Step 3: Changes in the key sector; Step 4: Expected effects on other parts of the economy; Step 5: The impact on society; Step 6: Are alternatives available?; Step 7: Policy options; and Step 8: Overall conclusions (Smits & Woltjer, 2017).

European Commission, 2016; Curry, 2017). The price of batteries will influence the incentive to recycle or reuse the cells, for example, in stationary storage applications.

2.2 Technological developments

There have been significant improvements to lithium-ion batteries in the last decade, notably technological developments in energy density (energy capacity per weight and size), price, environmental impact and endurance. Several changes relate to the composition of elements within the cathodes of these batteries. Because of the vast improvements and numerous features used in an array of applications, there are many lithium-ion battery types on the market (Battery University, 2018).

The most traditional lithium-ion battery is one that uses a lithium cobalt oxide cathode (LCO), found in common devices such as mobile phones, laptops and digital cameras. Despite LCO being the usual battery for most devices, the car industry has been developing other types of lithium-ion batteries that use less cobalt and have features specific to automotive user requirements.⁹ Tesla uses lithium-ion batteries with a cathode combination of lithium, nickel, cobalt, aluminium oxide, known as the NCA¹⁰ type battery, while the most popular EV in Europe on the road today, the Nissan Leaf, uses a cathode combination of the LMO¹¹ and NMC¹² types of battery (Battery University, 2018).

As the price of cobalt increases, it is predicted that there will be a continued shift towards NMC and NCA types of lithium-ion batteries that are more economical, while still achieving a good performance (Battery University, 2018). By 2025, Shunmugasundaram et al. (2017) predict that less than 20% of cells will use the more traditional LCO technology while more than 40% will use NMC cathodes. Even the detailed chemistries of materials used in the NMC-type batteries are shifting from a ratio of 1:1:1 wherein nickel, manganese and cobalt are all present in the same quantities, to a ratio of the more advanced NMC811 battery chemistry that contains more nickel and less cobalt (Fickling, 2017).

Due to this shift towards reduced valuable material in battery chemistries, the industry is concerned that there could be reduced incentives for effective recycling (CEC, 2015). For this reason, other methods might be required to encourage a shift to more circular-economy approaches for end-of-life lithium-ion batteries.

2.3 Battery value chain

The lithium-ion battery value chain can be divided into six key segments, starting with the mining and processing of the raw materials right up until the recycling of the end product, with cell component, cell manufacturing, battery pack manufacturing and electric vehicle manufacturing between (see Figure 1). The extraction of minerals and raw materials used in lithium-ion batteries along with the processing of these materials generally takes place outside the EU. China is the leader in cell-component manufacturing and cell-manufacturing; in 2014, it had a 41% share of the global automotive cell

⁹ Such batteries use nickel-based cathodes, which are cheaper than cobalt.

¹⁰ This stands for lithium nickel cobalt aluminium oxide.

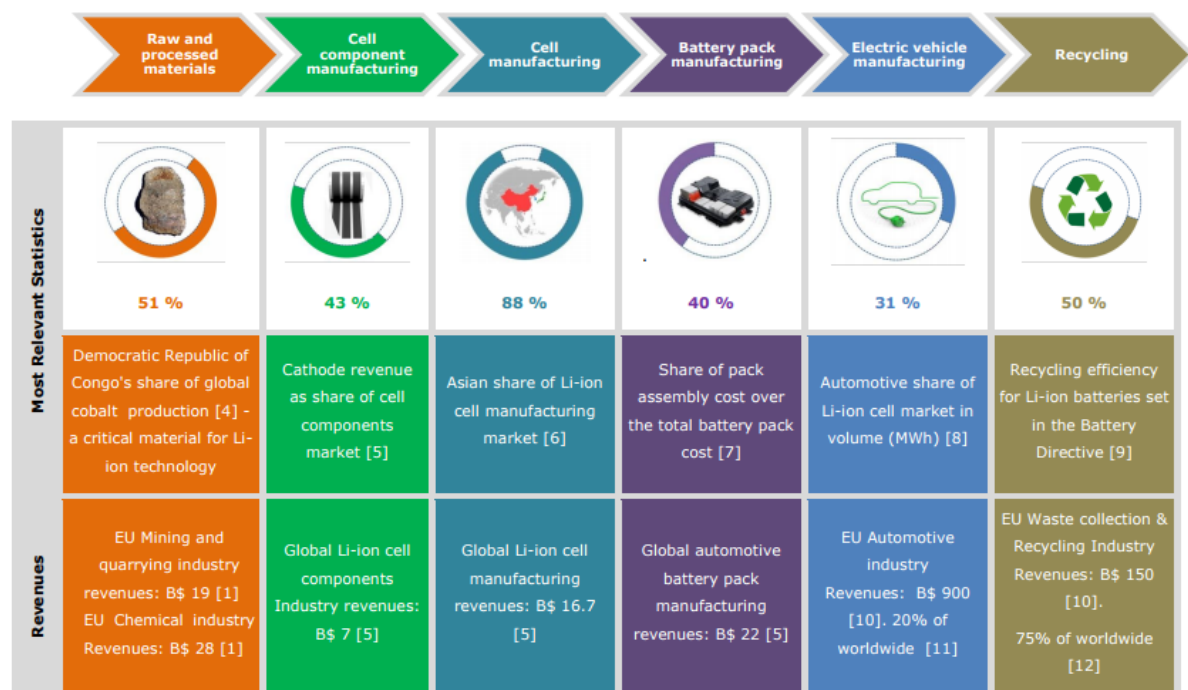
¹¹ Lithium manganese oxide.

¹² Lithium nickel manganese cobalt oxide.

manufacturing capacity, while the EU had a 5% share. The next stage of the process is battery-pack manufacturing, which accounts for approximately 40% of the cost of an EV battery. Regarding EV manufacturing, similar to the US and Japan, the EU has a global market share of 22% of the top 20 plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) producers, while China is the leader with a 33% market share. As for the recycling of EV batteries, although the EU is in a strong position (mainly due to the legislative requirements in the field) it is not yet prepared to manage a large number of end-of-life batteries (Lebedeva et al., 2016).

One part of the value chain that seems to be missing from Figure 1 is the option for second-life applications. This would typically appear between EV manufacturing and recycling, and should be considered when interpreting the value chain.

Figure 1: Automotive lithium-ion battery value chain



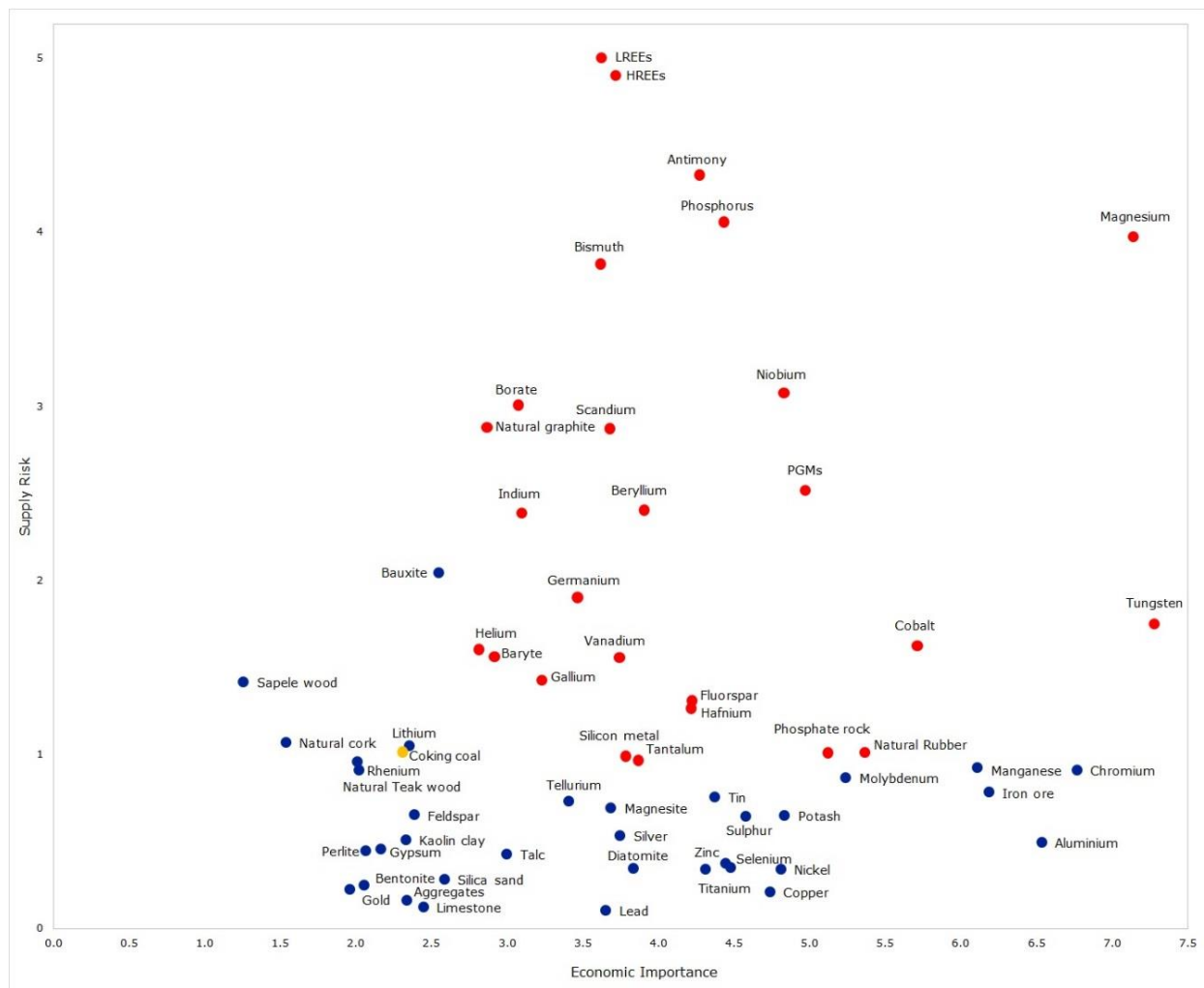
Source: Lebedeva et al. (2016).

With regards to the first and last stages of the battery value chain, lithium-ion batteries contain materials that are either considered as critical or are among the candidates classified as critical raw materials (CRMs), determined in an assessment by the European Commission (European Commission, 2017b).

CRMs can be defined as raw materials that are both of high economic importance for the EU and vulnerable to supply disruptions (European Commission, 2017b). Materials with a high economic importance are those that are important to EU industry sectors and that create added value to the EU economy, as well as jobs, while materials that are vulnerable to supply disruption are those that have a high risk of supply to adequately meet EU industry demand. The European Commission has recently revised its methodology for assessing whether a raw material is critical or not such that it is now based on a backward-looking approach. In the 2017 critical raw material assessment carried out by the European Commission, out of 61 candidate materials, 27 are currently considered to be critical. With a high economic importance and moderate supply risk, cobalt is considered

one of the 27 CRMs, while lithium, nickel and aluminium are all within the candidate materials (see Figure 2).

Figure 2: Critical Raw Materials



Note: Critical raw materials are indicated by the red and yellow dots.

Source: European Commission (2018b).

2.4 Key raw materials in EV batteries

A transition to EVs will have an impact on the demand for several raw materials, although it is difficult to make specific predictions given the rapid pace of innovation in EV batteries, which will continue to change material-demand patterns (Roskill, 2017). Within this case study, we look in detail at four key materials used in most EV batteries, cobalt, nickel, aluminium oxides and lithium.¹³ The importance of these materials and the reasons for including them in the analysis are presented in detail in the following sub-sections. In short, cobalt and nickel have been selected due to their economic importance, which provides a significant incentive for recycling (Romare & Dahllöf, 2017). Cobalt has been identified by the European Commission as a critical raw material that is

¹³ Raw materials are also used in other EV body and components (see section 2.4.3 on aluminium).

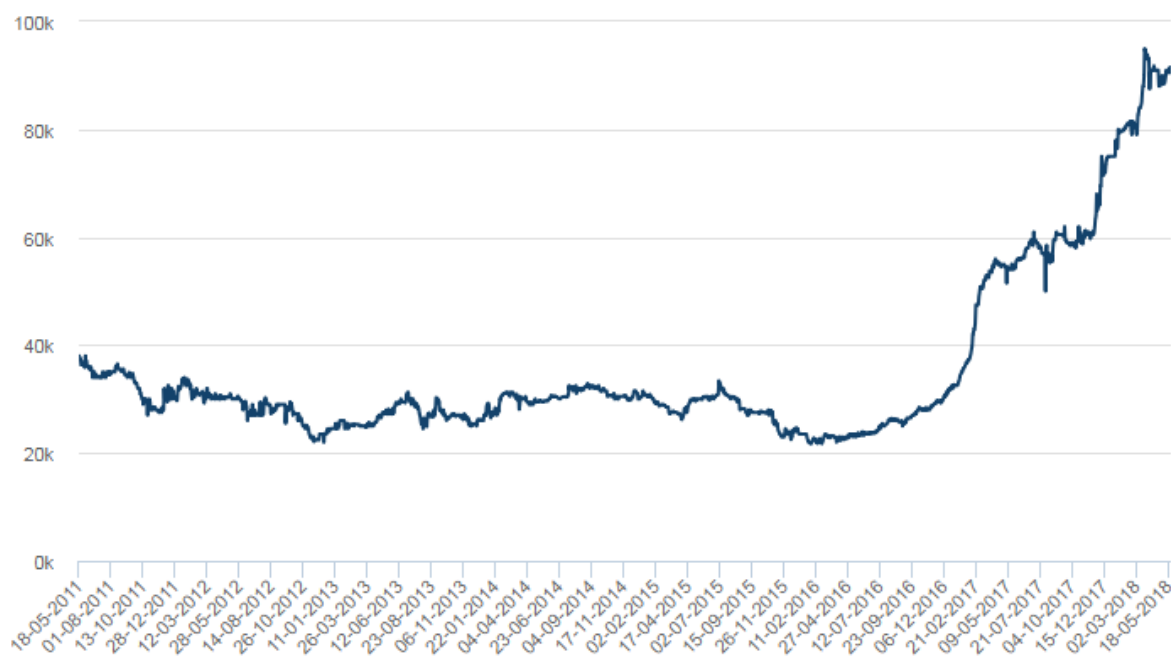
both of high economic importance for the EU and vulnerable to supply disruptions, while nickel is a highly sought-after metal for many products including lithium-ion batteries. Aluminium has been selected on the basis that it is used in high quantities in the casing of the battery pack and recycling of this material can provide significant CO₂ reduction benefits. Lithium has been selected because it is projected to experience increased demand in line with the expected growth in demand for EVs.

2.4.1 Cobalt

Most cathodes of lithium-ion batteries contain cobalt. Cobalt is often produced as a by-product of copper and nickel production in numerous deposits across the globe. Most prominent is the deposit in the Democratic Republic of Congo (DRC), where 51% of global cobalt production is mined through the copper-mining industry. By 2050, Lebedeva et al. (2016) predict that demand for cobalt will take up all known sources today. Due to this high concentration of cobalt from the DRC, coupled with the increase in demand for this material in lithium-ion batteries, supply-risk concerns are likely to continue.

With the boom in electric-vehicle sales, cobalt demand has been increasing at a rate of 3% - 4% annually since 2010 (Statista, 2018a), which has ultimately had an effect on its price. In two years since March 2016 the price of cobalt has quadrupled to a recent price of 91,000 US\$/tonne (LME, 2018a).¹⁴ The graph in Figure 3 shows the recent global price developments of this metal, which has been subject to acute price developments since the end of 2016. This trajectory is expected to continue until alternative materials are found that can replace cobalt while maintaining or improving the characteristics of the battery by reducing the cost and increasing energy density.

Figure 3: Historical price developments of cobalt (US\$/tonne)



Source: LME (2018a).

¹⁴ Market prices for cobalt were retrieved on 23 May 2018.

The increasing demand and subsequent rising prices are motivating battery developers to reduce the amount of cobalt needed to manufacture EV batteries. This is particularly the case for the NMC type lithium-ion batteries, which have previously been in the ratio 1:1:1 (nickel, manganese, cobalt), but battery developers have been altering the composition of cathode materials to use much less cobalt in exchange for more nickel (Chung & Lee, 2017).

2.4.2 Nickel

Nickel is a key component of lithium-ion batteries and is the metal used in the highest quantity in lithium-ion cathodes. It makes up around 80% of an NCA cathode used in Tesla vehicles and around 33% in NMC1:1:1 cathodes, but in the future it is estimated to move to around 80% of the cathode in the shift towards NMC8:1:1 batteries (UBS, 2017). This shift will almost certainly have an impact on the nickel market.

Currently, 2 million tonnes of nickel are sold worldwide annually. Key producing countries are the Philippines, Russia, Canada and Australia. If electric vehicles reach 10% of the global car fleet, demand for nickel within the batteries would increase to around 400,000 tonnes (Desjardins, 2017). As increasing numbers of EVs hit the roads, demand for nickel will increase significantly. Unlike the other metals observed in this study, since 2010, the overall price of nickel has been in decline. In 2011 it peaked at almost \$29,000 per tonne and in 2018 it declined by half to \$14,500 per tonne (LME, 2018b).¹⁵ Since 2016, however, there has been a gradual increase in the price of nickel. As more vehicles that are electric continue to hit the market, the price of nickel will likely continue to increase.

2.4.3 Aluminium

Aluminium is an internationally commodity traded in different forms (primary aluminium, downstream and secondary aluminium). The EU produces approximately 7% of all primary aluminium but remains a net importer with the main trade partners being Norway, Russia, Switzerland and the United Arab Emirates (Marcu et. al., 2016). Aluminium is used in several components of electric vehicles. It makes up the body of these vehicles, the battery and casing, and the brake component (Djukanovic, 2017). In the majority of EV battery packs, aluminium is used in the casing that carries the battery cells. The amount of aluminium, compared to other materials in the battery pack, is substantial (UBS, 2017). As such, the growth in the EV market will likely mean an increase in demand for aluminium (Djukanovic, 2017).

The price of aluminium has fluctuated significantly since the start of the century. In 2011 it peaked at \$2,720 per tonne and dropped in 2016 to \$1,442 per tonne. Since then, the price of aluminium has been gradually rising, reaching \$2,226 per tonne in May 2018 (LME, 2018c).¹⁶ Given the transition to electric vehicles, demand for this metal will rise and could have an impact on price.

Primary aluminium production has much higher emissions than secondary (recycled) production. Since aluminium is used in large quantities in the battery casing, recycling EV batteries has clear climate benefits. Although other materials, such as cobalt and nickel are more important for battery recycling from an economic point of view, recycling aluminium has significant CO₂-reduction potential (ICCT, 2018). Remelting existing

¹⁵ Market prices for nickel were retrieved on 23 May 2018.

¹⁶ Market prices for aluminium were retrieved on 23 May 2018.

aluminium requires just 5% of the energy of new aluminium production, thus yielding significant energy savings and CO₂ reductions (Material Economics, 2018).

2.4.4 Lithium

Lithium is an essential element for EV traction batteries and in view of the anticipated increase in demand for EVs, it is expected that demand for lithium, or more specifically the lithium carbonate that is used in lithium-ion batteries, will start to increase significantly. In 2015, around 40% of lithium carbonate equivalent (LCE) production was used for lithium-ion batteries and Roskill (2017) predict that demand will triple by 2025. Lebedeva et al. (2016) calculate that by 2025 demand for lithium carbonate equivalent will increase to 200,000 tons for EV batteries alone, which equates to the total global supply today. With the abundance of this material, although recycling lithium is technically feasible, it is considered by many to be not yet economically viable. Due to the high recycling costs and the low and volatile price of lithium, recovery and recycling of lithium from lithium-ion batteries is almost non-existent (GLOBAL 2000, 2013; Swain, 2017).

The price for this material has increased significantly over the past two decades. In 2002 the price for one tonne of lithium was \$1,600 and since then has increased tenfold to \$16,500 per tonne in 2018 (Metalary, 2018). Similarly, the price for lithium carbonate has increased from \$5,180 per tonne in 2010 to \$7,400 in 2016 (Statista, 2018b). Should increased demand for lithium result in significant price increases in the future, recovery could become more economically viable in years to come, i.e. the value of lithium recovered could compensate for the costs of recycling (Lebedeva et al., 2016).

The majority of the world's lithium refining facilities are in China, enhancing China's dominant power in the lithium-ion battery value chain (Steen et. al., 2017). Most known reserves of lithium, however, are found in South America,¹⁷ accounting for 69% of global reserves (Lebedeva et al., 2016). In this region, lithium is extracted through a process whereby waters rich in lithium salts are pumped from aquifers to the surface and evaporated in lakes. This form of lithium production requires high volumes of water and most mining is currently concentrated in areas where water is scarce. Improved lithium recycling may reduce the need for lithium mining (Shankleman et al., 2017) and the associated water-scarcity risks that lead to social and environmental problems.

3 :: Scenario development

The main objective of this study is to provide information and estimates on the impacts of collection and recycling of EV batteries within the EU. To this end, quantitative analyses were carried out to provide insight into the possible effects of increasing collection/take-back rates of EV batteries within the EU and the recycling efficiencies of certain materials within those batteries. This was investigated using two *ex ante* scenarios, scenario 1 and scenario 2, with the latter being the more ambitious one. This section presents the scenario variables and the assumptions used to perform the scenario analysis.

¹⁷ Specifically, in Argentina, Chile, Bolivia and Brazil.

3.1 Methodology

To draw practical conclusions and implementable policy recommendations for a shift towards a circular economy, this case study employs a process of examining possible future events that could take place. Studies that use scenario analysis can be classified into three main groups: predictive, explorative and anticipative (Nielsen & Karlson, 2007). This study applies a predictive scenario analysis model by observing what might happen given changes in certain variables. Although it applies a predictive model, the exercise does not provide forecasts for future years but rather shows the impact of shifting to a more circular economy, through changes in specific variables.

The aim of the variables selected is to reflect different options for processing batteries that have reached their end of life. The first variable observed is collection/take-back rates, which can be defined as the amount of batteries that are collected (either following their first life within an EV or second life in another application) with the intent of being recycled in the EU. Those not collected are assumed to be sold to third countries in second-hand vehicles, or leave to recycling facilities operating outside of the EU. The recycling efficiency rate is our second set of variables; in this case study, material-specific recycling efficiency rates were observed. The recycling efficiency rate of a material can be defined as the percentage of that material within a battery that is extracted during the recycling process.

In addition to the scenario variables, a number of assumptions have been used by the research team in the scenario analysis. The scenario assumptions and variables are defined in the following two sub-sections 3.2 and 3.3.

This forward-looking analysis uses scenario variables and assumptions that have been developed for the year 2030. There is a high degree of uncertainty beyond 2030,¹⁸ but given that a significantly higher volume of EV batteries that would be at their end of life in years later than 2030, the years 2035 and 2040 have also been analysed applying the same assumptions as those developed for 2030. Despite the uncertainties involved, the exercise provides a useful indication of the magnitude of the potential impacts when changing collection/take-back rates and recycling-efficiency rates within the EU.

The scenario analysis was conducted between September 2017 and June 2018. To perform this exercise, data¹⁹ and qualitative information were initially collected through a literature review of secondary sources. Interviews were also conducted with experts in the field in order to fill any gaps and collect data that could not be identified through desk-based research. To validate the collected data and information, the team organised a workshop on 7 December 2017²⁰ that brought together experts from various segments of the battery value chain as well as from academia and NGOs. Following the event, further interviews were conducted with experts in the field, while the draft results of the analysis were circulated to all workshop participants for comments. The list of experts interviewed during the course of the study is presented in Annex 2.

¹⁸ As mentioned in section 2.2, there are many uncertainties related to future battery-technology developments as well as the materials used in future batteries.

¹⁹ Such data refer to, for example, the number of batteries at their end-of-life in future years, the amount of materials (cobalt, nickel, lithium, manganese, aluminium) in those batteries, the price of materials, the average length of second-life, the number of people employed in EV battery recycling, collection/take back rates etc.

²⁰ For more details see: <https://www.ceps.eu/events/circular-economy-perspectives-future-end-life-ev-batteries>.

3.2 Assumptions for scenario analysis

To perform the scenario analysis, several assumptions are used by the research team, based on forecasts from a number of sources or on current 2018 values in the absence of credible forecasts.

3.2.1 Quantity of EV batteries at their end of life

To compute the quantity of EV batteries at their end of life in the years 2030, 2035 and 2040 two elements are combined: EV sales in the years leading up to these years and the average lifetime of EV batteries. In their Electric Vehicle Outlook, Bloomberg New Energy Finance (2017) expect a more aggressive adoption of EVs than in previous forecasts. To estimate the amount of end-of-life EV batteries in the years studied, these forecasts²¹ are combined with the expected average lifetime of EV batteries, accounting for second-life assumptions.

In the available literature it is generally suggested that EV batteries provide useful life in vehicles until they degrade to around 80% of their original capacity²² (Casals et al., 2017) (see section 3.2.4 below). Tesla and Nissan warrant their batteries against malfunction for eight years. Based on this and on information received from experts, as well as a report on the capacity loss of Nissan Leaf batteries (Myall et. al., 2018), it is assumed that an average EV battery has a lifespan of eight years within a vehicle. By using figures from the National Renewable Energy Laboratory (Neubauer et. al., 2015), the study also assumes that batteries used for second-life applications will have a further 10 years added to their lifetime before fully reaching their end-of-life.

Figures on the quantity and capacity of batteries expected to be at their end-of-life in 2030, 2035 and 2040 are shown in Table 1.

Table 1: Quantity and capacity of batteries at their end of life.

	2030	2035	2040
Quantity	1,163,500	2,596,100	5,380,000
Capacity (MWh)	46,540	103,844	215,200

Sources: Authors' own calculation based on figures from Bloomberg New Energy Finance (2017); Casals et al. (2017); Myall et. al. (2018); Neubauer et. al. (2015); Curry (2017).

3.2.2 Volume and price of raw materials in end-of-life EV batteries

The volume of material that it is possible to extract from available spent EV batteries in future years is uncertain. In this report, estimations were made by using data for EV sales across the EU (Statista, 2018c), taking into consideration the type of lithium-ion batteries (NCA or NMC) within those EVs in order to calculate the share of batteries at their end of life that utilise certain cathode battery chemistries. Combining this data with the amount

²¹ The forecasts include car sales in the EU-28 as well as in Iceland, Norway and Switzerland. In 2016, the number of car registrations in the EU-28 plus Iceland, Norway and Switzerland came to almost 17 million, of which registrations in Iceland, Norway and Switzerland made up approximately 3% (Eurostat, 2018).

²² It should be noted, however, that Saxena et al. (2015) argue that batteries can continue to meet driver needs even after they reach 80% of their original capacity since they could be used for shorter range trips, for example.

of material (cobalt, lithium, nickel, aluminium) in the various battery chemistries on the market now, we can start to calculate the volume of materials that could be extracted from end-of-life batteries in the case-study years for each scenario, by applying the scenario variables. Fickling (2017) provides figures on the amount of material per unit capacity for particular metals, including cobalt, nickel and lithium, in certain battery chemistries. The amount of aluminium used in EV batteries, particularly for the battery casing, was estimated in a study performed by UBS (2017). The projected volume of material in end-of-life EV batteries can be approximated, as shown in Table 2.

Table 2: Volume of materials in end-of-life EV batteries in the EU

Material	Average weight (g/kWh)	Estimated weight in end-of-life EV batteries (tonnes)		
		2030	2035	2040
Cobalt	116	5,410	12,072	25,017
Nickel	400	18,604	41,512	86,026
Aluminium	1,163	54,126	120,771	250,278
Lithium	73	3,397	7,581	15,710

Sources: Authors' own calculation based on figures from Table 1 and Fickling (2017); UBS (2017).

Naturally, there is great uncertainty regarding the price of the key materials found in EV batteries in future years due to unpredictable changes in demand patterns for those materials as a result of technological developments. Current prices have been used to calculate the value of raw materials in the scenario analysis since reliable forecasts are unavailable (see Table 3). The results are shown in section 4.

Table 3: Price of materials used in the analysis

Material	Price (\$/ton)	Source ²³
Cobalt	91,000	LME (2018a)
Nickel	14,500	LME (2018b)
Aluminium	2,226	LME (2018c)
Lithium	16,500	Metalary (2018)

3.2.3 Employment

It is assumed that at each stage of the recycling process, i.e. collecting, dismantling and processing, jobs will be created to varying degrees. The collection of EV batteries is considered to be labour intensive, while the recycling process is generally more capital intensive. Since the recycling industry of lithium-ion batteries is not yet developed on a large scale, employment figures from a reliable source are not available in the literature.

²³ Market prices for cobalt, nickel and aluminium were retrieved on 23 May 2018.

For this study employment values have been calculated from data gathered through interviews with recyclers of lithium-ion batteries. By putting together the information collected, it is assumed that per thousand tonnes of lithium-ion battery waste, 15 jobs are created for the collection, dismantling and recycling of these batteries. Of those 15 jobs, about 80% would be for the collection and dismantling of lithium-ion batteries while the remaining 20% of jobs would be for the recycling of batteries. It should be noted that these figures do not take into account technological developments. It is therefore likely, especially beyond 2030, that the number of jobs per thousand tonnes of lithium-ion batteries will depend on the technologies used.

What is also available is employment figures on the collection and recycling of e-waste to cross-check our values calculated from data provided by recyclers for their lithium-ion battery recycling facilities. The WEEE Forum (2017) has provided a summary of figures from different sources on employment rates. One source, OCAD3E, calculates that for each additional thousand tonnes of e-waste recycling, seven to eight new jobs are created. This is in line with the assumption guiding this study, since recycling lithium-ion batteries is expected to be more labour intensive than recycling e-waste, due to the more complicated procedure.

3.2.4 Second-life rates

Instead of recycling batteries that have been removed from vehicles, the battery can be remanufactured and the cells can be provided with a second-life in a storage application. Electric vehicles generally require high-performance batteries, hence, a battery is removed from a vehicle once the capacity declines past a certain point. It is estimated that this generally happens when batteries reach 70% to 80% of their original capacity. Although no longer practical for use in vehicles at this point, the batteries are still able to cope with charge and discharge for other applications such as electricity storage (Berkeley Lab, n.d). Second-life EV batteries available for storage applications could still provide a useful life in a future electricity system due to further increases in intermittent renewables connected to the European electricity grid. Flexible capacity in our future power system will be crucial to complement the renewable electricity technologies. Electricity storage should be able to consume and generate electricity at times when it is needed and battery technologies can provide a solution. This technology is considered to be highly flexible, providing instantaneous power when needed (Hassel et. al., 2017).

Reusing EV batteries in second-life applications extends their lifetime. Various sources show very different views and predictions regarding the share of batteries that will sustain a second-life, emphasising that the market is currently very uncertain. Some anticipate that very few batteries will endure a second-life considering the reduction of lithium-ion battery prices in the future market, while others expect most batteries to undergo a second-life before being recycled. Although uncertain, Bloomberg New Energy Finance (Curry, 2017) forecasts that in the year 2025, 27% of those batteries will have a second-life in stationary storage units, while the remaining 73% would be available to be recycled. However, this will depend on a number of factors, including the cost to remanufacture EV batteries for storage applications, the value of materials that could be extracted from lithium-ion batteries and recycling costs. For this study, a slightly more ambitious second-life rate of 30% is used in the scenario analysis.

3.2.5 CO₂ emissions

Emissions from the production of lithium-ion batteries are a concern. Energy for the extraction, processing, manufacturing and delivery of lithium-ion batteries is known by the research community as embodied energy. At the same time, recycling lithium-ion batteries and their embedded materials could help avoid emissions associated with the extraction and transportation of raw materials.

Romare & Dahllöf (2017) present results from the LithoRec project (Buchert, et al., 2011) demonstrating that CO₂ emissions can be mitigated by recycling lithium-ion batteries. To give an indication of the net energy demand and CO₂ emissions at each stage of the recycling chain, based on a hydrometallurgy process and calculated at pilot scale, they conclude that recycling lithium-ion batteries can provide a net saving of 1 kg CO₂ per kg battery. Around 2.5 kg CO₂ per kg battery is emitted in the battery recycling process (dismantling, cell and cathode separation, hydro-processing) while 3.5 kg CO₂ per kg battery is saved from reducing the need to extract virgin material.

3.3 Building the scenarios

In order to develop the two scenarios this study applies two types of variables that have been determined through a review of secondary resources. Collection/take back rates have been taken from the European Commission's SET-Plan Action No.7 (European Commission, 2016), while recycling efficiency rates have been taken from the JRC report on the lithium-ion battery value chain by Lebedeva et al. (2016). These are described in the following sub-sections.

3.3.1 Collection/take back rates

The collection/take back rate can be interpreted as the share of lithium-ion batteries that are collected for recycling in the EU at their end of life. It is assumed that the remaining batteries not collected would leave the EU to be used in second-hand cars or sold as scrap to third countries.

Collection rates for the scenarios are taken from the SET-Plan strategy document (European Commission, 2016). Manufacturing target rates are set within this document, including EV battery collection/take back rates. Specifically, the target rate is set at 70% for the year 2020 and at 85% for the year 2030. Taking these figures into account, a collection rate at the target rate for 2030 (85%) is used in the more ambitious scenario 2 and a collection rate that is 20 percentage points below the 2030 target rate (65%) is used in scenario 1.

3.3.2 Recycling efficiency rates

Recycling efficiency can be defined as the weight percentage of materials recovered from collected spent lithium-ion batteries. In a circular economy, materials that are recovered through recycling processes can be sold back on the market as secondary raw materials. This prevents more materials from being extracted from mines and value is retained within the EU market. Recycling lithium-ion batteries and extracting the raw materials is more complicated than recycling lead acid batteries due to the more complex combination of materials. The process of recycling these batteries means that it is more expensive than most other groups of batteries that currently have high recycling

efficiency rates. Added to this complexity are the various types of lithium-ion battery chemistries.

Although there are many ways to recycle lithium-ion batteries, two key processes exist within the EU: pyrometallurgical and hydrometallurgical. The pyrometallurgical process uses high temperatures to recover cobalt, nickel, copper and iron while manganese and lithium are generally lost, however, this process is generally combined with the hydrometallurgical process. The hydrometallurgical process includes mechanical pre-treatment and metal recovery and is a method that can also recover lithium (Friedrich & Peters, 2017). The most common is a combination of the two processes, but in a purely hydrometallurgical process, chemicals are used to separate all metals so that more can be recovered.

The JRC (Lebedeva et al., 2016) has calculated recycling efficiency rates for various elements in selected processes for NMC-type lithium-ion batteries. The first procedure, which is a combination of pyrometallurgical & hydrometallurgical processes, achieves a recycling efficiency rate of 57% for lithium, 94% for cobalt and 95% for nickel and these rates are used in scenario 1. The second procedure, which uses a purely hydrometallurgical process, can achieve a recycling efficiency rate of 94% for lithium, almost 100%²⁴ for cobalt and 97% for nickel; these rates are used in the more ambitious scenario 2. Aluminium was not included in the JRC report. Most of the aluminium is found in the battery casing and some in NCA-type battery cathodes. It is likely that most of this aluminium will be recycled, with small residues lost in the slag during the recycling process (Lebedeva et al., 2016), hence a recycling efficiency rate of 98% is used for aluminium for both scenarios; this figure was also confirmed through consultations with experts. These procedures are considered technically feasible but their economic feasibility has not been evaluated.

3.3.3 Defining the two scenarios

Considering the points made above, two scenarios are defined in Table 4. The intention of this exercise is not to provide recommendations as to which specific technology should be used for the recycling of batteries but rather to provide estimates about the impacts of increasing collection and recycling efficiency rates.

²⁴ To account for small losses of material during the recycling process, 99% instead of 100% is used in our scenario.

Table 4: Scenario variables

Battery Recycling	Scenario 1	Scenario 2
Collection/take back rate for recycling within the EU	65%	85%
Cobalt recycling efficiency rate	94%	99%
Nickel recycling efficiency rate	95%	97%
Aluminium recycling efficiency rate	98%	98%
Lithium recycling efficiency rate	57%	94%

Sources: Authors' own elaboration based on Lebedeva et al. (2016); European Commission (2016); interviews with experts.

3.4 Limitations

Although the methodology provides a transparent analysis of the benefits of shifting to a more circular economy by highlighting the effects of increasing collection/take back and recycling efficiency rates of EV batteries, there are a number of limitations that should be recognised. The first is the availability of data. There is a limited amount of information on the recycling of EV batteries and this is because currently very few batteries have reached their end-of-life. It was not possible to gather information on the costs of collection, dismantling and recycling EV batteries through the desk-based research or through the interviews conducted (see section 3.1). Investment costs were only provided by one recycler; hence, to provide meaningful results and conform to confidentiality commitments, these figures on investment costs were not appropriated within this study. Data on the employment effects on other sectors was also not available therefore only estimates of the number of jobs created in the recycling sector could be calculated.

Uncertainty about raw material prices and technological advancements is also a key limitation of the study, especially when providing results for future years. Raw material prices, particularly for cobalt, are experiencing significant volatility. With technological advancements in the recycling sector, the technical and/or economic feasibility of recycling EV batteries and recovering particular materials within those batteries may change. It may also change the feasibility of battery cells enduring a second-life within a storage application. On the other hand, business models may evolve and develop a market for reusing battery cells from EVs that make it more economical than direct recycling.

4 :: Impacts

4.1 Trade

The global dimension of the battery sector should be considered when observing the impacts of recovering materials found within these batteries. The expansion in world trade over the past half century and rapid growth in the lithium-ion battery market has meant that the battery value chain has evolved worldwide. By adopting the scenario assumptions, certain potential trade effects of recovering particular materials within lithium-ion batteries are discussed within this section.

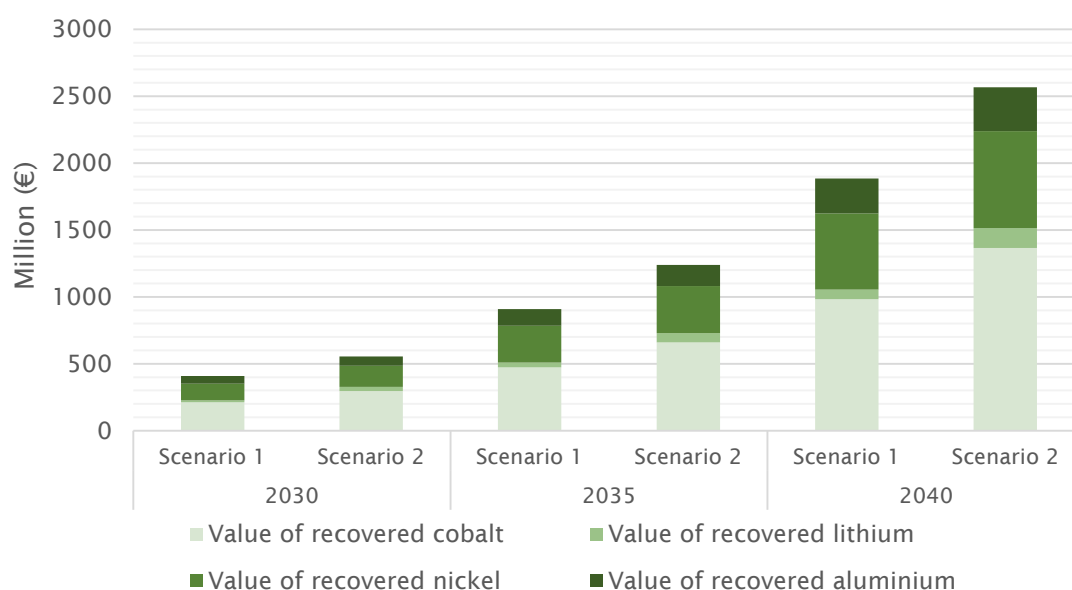
Table 5 shows the results of the scenario analysis based on the collection/take back and recycling efficiency rates, previously described in section 3. Specifically, the table presents the estimates for the amount and value of materials that would be recovered in the years 2030, 2035 and 2040. To calculate these figures, the scenario assumptions in Table 4 have been applied to the volumes and prices in tables 2 and 3. As shown in Table 5, the largest amount of material recovered from batteries would be from the aluminium casing, while the largest value would be through cobalt, due to the high market price. Figure 4 shows the total value of materials that could be recovered in the years assessed.

Table 5: Amount and value of materials recovered

	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
	2030		2035		2040	
Amount of recovered material (tonnes)						
Cobalt	2,922	4,058	6,519	9,054	13,509	18,763
Nickel	10,604	13,535	23,662	30,200	49,035	62,584
Aluminium	31,826	39,783	71,013	88,766	147,163	183,954
Lithium	1,162	2,421	2,593	5,401	5,373	11,193
Value of recovered material (million €)						
Cobalt	213	295	475	659	983	1,366
Nickel	123	157	274	350	569	726
Aluminium	57	71	126	158	262	328
Lithium	15	32	34	71	71	148
Total	408	555	909	1,238	1,885	2,568

Source: Authors' own calculation.

Figure 4: The value of materials recovered in each scenario for the years 2030, 2035 and 2040



Source: Authors' own calculation.

With increased recycling and more materials recovered, the effect would be reduced imports required for those materials and ultimately savings for the EU. Box 1 summarises imports and exports for each of the materials included in this analysis.

Box 1: Trade effects of recycling materials within lithium-ion batteries

Cobalt

In 2012 the EU-28 imported over 10,000 tonnes of primary material cobalt while it exported only 111 tonnes (BIO by Deloitte, 2015). This equates to a value of €227 million of cobalt imported and just €2.5 million exported. The annual global production of cobalt concentrate is around 130,000 kt and the DRC accounts for 67% of global production (ibid). With such concentrations of cobalt exported from a country currently experiencing economic and political instability (the DRC), the supply risk associated with this material is high. Along with the price increases, this has led to the continued shift towards lithium-ion batteries that contain less cobalt. Despite the shift towards batteries with lower percentages of cobalt, it is expected that imports of unwrought cobalt into the EU will increase in the 2020s and 2030s if Europe develops a lithium-ion cell manufacturing capacity.

Scenario 2 estimates that the EU could recover 4,058 tonnes of cobalt in the year 2030. This is over 41% of all cobalt imports into the EU in 2012. Although these values are not comparable as it is uncertain if cobalt imports will increase over the next few decades, this analysis provides an indication of the magnitude of cobalt that could be recovered in 2030. Results from the scenario analysis also show that in the year 2035 €659 million worth of cobalt could be recovered from end-of-life EV batteries under scenario 2; in current prices this figure could reach around €1.37 billion in 2040. This is approximately a 40% increase from scenario 1.

Nickel

The EU is a net importer of unwrought nickel, importing over 212,000 tonnes in 2015, equivalent to approximately €2,244 million. The EU exported €578 million in the same year, with a net import value of €1,666.²⁵ Approximately 30% of EU imports come from Russia, 20% from Norway and the rest from several countries including Madagascar, Australia, China and Canada. Growth in the lithium-ion battery market is expected to increase global demand for nickel. Similar to cobalt, if Europe develops lithium-ion cell manufacturing capacity, demand for nickel in the EU will likely increase.

Nickel is a highly sought-after metal for many applications and products beyond lithium-ion batteries. Taking the more ambitious scenario 2, the value of nickel that could be recovered in 2030 is approximately 9% of the value of net EU imports in the year 2015, for 2035 it comes to 21% and 44% for 2040. In scenario 1, approximately 20% less nickel is recovered from the end-of-life EV batteries when compared to the more ambitious scenario 2 for all three years. As the battery market develops and demand for nickel increases, it is likely that both the price and the volume of imports into the EU will be impacted. Recovering nickel from lithium-ion batteries can reduce dependence on nickel imports and create value for the EU and the recycling industry.

Aluminium

In 2015, the EU imported 5 million tonnes of unwrought aluminium and exported just over 200 thousand tonnes at a net import value of €8,686 million.²⁶ As the EV market develops, demand for aluminium from this market is expected to increase because the usage of aluminium in electric vehicles is significantly higher than in vehicles with internal combustion engines. EVs are already manufactured in the EU so it is expected that imports of aluminium into the EU for that purpose will start to increase.

Aluminium is used in many applications and products. As a result, the amount of material traded is significant when compared to cobalt and lithium. Although aluminium is found in higher quantities than other materials in EV batteries, particularly for the battery cell casing, recycling end-of-life EV batteries in 2030 will generate between €57 (scenario 1) and €71 million (scenario 2), which is under 1% of the net import value in 2015. In 2040, the aluminium that can be recovered from end-of-life EV batteries could reach up to €262 (scenario 1) and €328 (scenario 2), rising to around 4% of the net import value in 2015.

Lithium

Recycled lithium will likely come in the form of lithium carbonate. The EU imported a net value of €41 million lithium carbonate in 2015 with 86% of its imports coming from Chile.²⁷

Results from the scenarios shows that the EU could recover up to €32 million of lithium from the end-of-life EV batteries in 2030. By 2040, this increases to €71 million (scenario 1) and €148 million (scenario 2), with scenario 1 recovering less than half the value of lithium than scenario 2.

²⁵ Data has been obtained from the Comtrade (<https://comtrade.un.org/data/>) database using the code HS 7502. Comtrade provides values in \$, hence the exchange rate of 1 US dollar equals 0.84 euro was used.

²⁶ Code HS 7601 has been used for obtaining the data from Comtrade.

²⁷ Code HS 283691 has been used for obtaining the data from Comtrade.

4.2 Investment and employment

The increased collection and recycling rates in the two scenarios analysed in this paper would entail key changes in the recycling sector. The collection of battery cells is a labour-intensive process, meaning that increased collection rates would likely result in job creation in the recycling sector. With more batteries collected, many more will be recycled and facilities for the dismantling and recycling of these batteries will require huge infrastructural development. This would create further jobs to construct and manage these facilities and increase investment within the EU. The output would be increased volumes of secondary raw materials circulating in the EU, with less need for raw materials to be extracted from mines, mostly located outside the EU, which would ultimately create added value for the EU economy.

4.2.1 Recycling

As the EV industry grows, battery recycling will become crucial. It is a key sector where value can be created through jobs and materials (Lebedeva et al., 2016). Europe has the advantage being among the market leaders, particularly for the recycling of lithium-ion batteries (ibid). Although there is huge opportunity for EU industry, and some companies²⁸ are already recycling these batteries, the lithium-ion battery recycling industry is not yet adequately developed to meet the expected volumes in years to come. The majority of EV batteries that have entered the market in recent years have not yet reached their end-of-life cycle. To meet the growing demand for lithium-ion batteries, Umicore (2017) has advised that a specific approach, guided by collection and recycling rates, should be developed for lithium-ion batteries.

The recycling process of lithium-ion batteries is very complex, as previously discussed; EV batteries come in a variety of structures and cathode compositions, which means that the costs to recycle these batteries are generally high. Currently in the EU, the value of the retrieved raw material is often not sufficient to pay for the labour needed to extract the material, hence there might be no business case at the moment for recycling these batteries. This will change, however, as the EV industry grows.

4.2.2 Investment opportunities

In the year 2030, approximately 1.2 million EV batteries are expected to be at their end-of-life. After this year, the number of EV batteries reaching their end-of-life is projected to increase significantly to 2.6 million and 5.4 million respectively in the years 2035 and 2040 (refer to Table 1). The exact number will depend on the rate of batteries that have a second life in a storage application. The EV-battery recycling industry is currently relatively underdeveloped due to, inter alia, the low number of batteries reaching their end-of-life. If the EU is to exploit this opportunity, then recycling infrastructure will need to be advanced to manage the forecasted volume of spent EV batteries in future years. A simple, clear, predictable and stable regulatory framework, at both the EU and member state level, would encourage investments for long-term projects (European Commission, 2014) such as recycling infrastructure.

Establishing a lithium-ion battery-recycling sector could lead to wider investment opportunities for manufacturing facilities. Although the EU is leading the lead-acid

²⁸ For example, Umicore, Accurec, Recupyl and SNAM.

industry, manufacturing capacity currently exists at a small-scale in the EU for traction battery cells. Data from Comtrade shows that in 2015 the EU imported just over \$2,500 million worth of lithium-ion accumulators,²⁹ while it only exported a tenth of that amount. China, for example, has a leading position in developing and manufacturing lithium-ion cells. Opportunities exist to extrapolate EU competencies in disruptive battery technology research and development. Synergies could also be formed with existing EU battery manufacturing to scale up the manufacturing processes of traction batteries. Another way to stimulate the manufacturing of cells in the EU is through foreign investment via foreign-owned manufacturing plants establishing themselves in the EU (European Commission, 2016).

4.2.3 Employment

Table 6 and Figure 5 below provide estimates about the number of jobs that would be required to recycle the EV batteries under the two different scenarios. To calculate these figures the research team used the assumptions outlined in section 3.2.3 that are based on interviews with lithium-ion battery recyclers, cross-checked with calculations from research by OCAD3E, summarised by the WEEE Forum (2017). The figures below provide an indication of the number of jobs that would be required for the recycling of the batteries that will reach their end of life in the coming years.

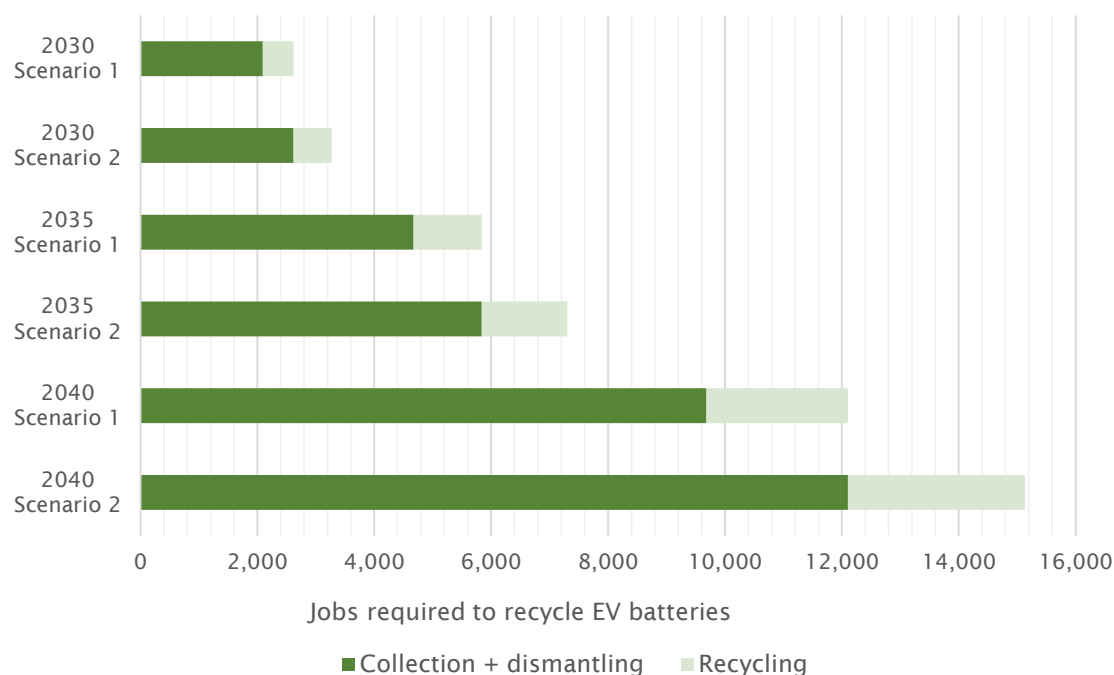
Table 6: Employment for each scenario in 2030, 2035 and 2040 (jobs required to recycle EV batteries)

	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
	2030		2035		2040	
Collection + dismantling	2,094	2,618	4,673	5,841	9,684	12,105
Recycling	524	654	1,168	1,460	2,421	3,026
Total	2,618	3,272	5,841	7,302	12,105	15,131

Source: Authors' own calculation.

²⁹ Code HS 850760 has been used for obtaining the data.

Figure 5: Jobs required to recycle EV batteries for each scenario in the years 2030, 2035 and 2040



Source: Authors' own calculation.

It should be noted that these figures concern only the collection, dismantling and recycling of the batteries, not the construction and development of recycling facilities. Additionally, the improved recycling of batteries may have some employment effects in other sectors and other regions outside the EU. For example, it might reduce the need for extracting raw materials from mines located outside the EU and may therefore affect the associated sectors in these countries. Such impacts were not considered in this analysis due to limited data.

4.3 Environment

Increasing the recovery of materials within EV batteries will result in a reduced need for primary raw materials and the transportation of those materials from other parts of the world. The production of raw materials that make up batteries account for approximately half of the greenhouse gas emissions from battery production (ICCT, 2018). Recycling materials generally mitigates carbon emissions when compared to extracting those materials from virgin sources. Based on a hydrometallurgical recycling process, a report by IVL (Romare & Dahllöf, 2017) that looks at the life-cycle energy consumption and greenhouse gas emissions of lithium ion-batteries concludes that per 1kg of battery recycled a net 1kg of CO₂-eq is mitigated (see section 3.2.5). They break the process down into different stages including the dismantling, cell separation, cathode separation and hydro-processing. At each stage the g CO₂-eq emitted from the recycling process is shown, as is the amount in credit, i.e. the g CO₂-eq that are avoided by recycling EV batteries. Using their analysis, results for each scenario are shown in 7. Based on the

scenario analysis, scenario 2 shows that 218,156 tonnes of CO₂-eq could be mitigated in 2030, while this figure increases to over 1 million by 2040 (see Table 7 and Figure 6).

Table 7: Net savings of CO₂-eq emissions (tonnes)

Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
2030		2035		2040	
174,525	218,156	389,415	486,769	807,000	1,008,750

Sources: Authors' own calculation based on Table 1 and Romare & Dahllöf (2017).

Figure 6: Net savings of CO₂-eq emissions (tonnes)



Source: Authors' own calculation based on Table 1 and Romare & Dahllöf (2017).

The figures in Table 7 show the net savings of CO₂-eq emissions through recycling lithium-ion batteries. The net savings of CO₂-eq in 2030 (Scenario 2) are equivalent to the amount emitted in the production of around 56,000 tonnes of primary aluminium in the EU, using the electricity generation mix of 2014. In 2040, the net CO₂-eq savings will be equivalent to that emitted in the production of approximately 261,000 tonnes of aluminium in the EU (2014 electricity generation mix), which is comparable to the annual production of two primary aluminium smelters.³⁰ These values are based on the assumption that the smelting of aluminium uses 13-15 MWh of electricity per tonne of metal produced (Material Economics, 2018) and that the CO₂ emissions intensity of electricity generation in the EU in 2014 was 276 gCO₂/kWh (EEA, 2017a).

It should be borne in mind that additional environmental benefits would arise from reducing the need for extracting raw materials, which are not easily quantifiable. For instance, the process of extracting lithium can cause water pollution, air contamination and release of chemicals (GLOBAL 2000, 2013). Moreover, given that landfilling lithium-ion EV batteries is prohibited (see section 5.1), batteries at their end-of-life must either

³⁰ There are 16 primary aluminium smelters in Europe today.

be recycled within the EU or would leave the EU where they may well be recycled if recycling facilities are in place. These aspects should be taken into account when drawing conclusions about the overall environmental benefits of recycling batteries in the EU.

5 :: Policies

Recycling could allow the EU to have its own supply of resources without having to rely on imports from third countries (Mancha, 2016). As we have seen from the scenario analysis, there are benefits for the EU if a large share of lithium-ion batteries is collected and recycled within the EU. How the EU plans to deal with end-of-life batteries is important for the long-term ambitions and targets already suggested by the European Commission as part of the SET-Plan (European Commission, 2016). Suggestions include the goal for EV battery recycling to become economically viable by 2030, with a target of collection and recycling efficiency rates of 85% and 50% respectively.

Currently however, there is no regulation dealing explicitly with lithium-ion batteries in the EU. Given that the market is expected to expand rapidly in the coming decades, it is important that regulations and policies are developed. That said, lithium-ion batteries are regulated non-explicitly in some EU legislative directives, with the scope to be regulated further. The key policies and initiatives associated with lithium-ion batteries are described in the following sub-sections.

5.1 The Batteries Directive

The primary objective of the Batteries Directive (2006/66/EC) is to minimise the negative environmental impacts of waste batteries, contributing to the protection, preservation and improvement of the quality of the environment. It prohibits placing batteries and accumulators with a certain mercury or cadmium content on the market and establishes rules for the collection, recycling, treatment and disposal of waste batteries and accumulators. Specifically, the directive sets collection and recycling efficiency rates for certain types of batteries.

In the Battery Directive, lithium-ion batteries are not specifically mentioned, but EV traction batteries fall under different categories for different regulatory requirements. For example, EV batteries are categorised as “industrial batteries” for collection rates and “other waste batteries” for recycling efficiency rates. For industrial batteries, collection rates are not quantified; instead it is stated that “The disposal of industrial and automotive batteries and accumulators in landfill sites or by incineration should be prohibited.” With regards to recycling efficiency rates provided under Annex III of the directive, it stipulates that other batteries should achieve a minimum recycling efficiency of 50%. This rate is mass-based, i.e. 50% of the weight of the battery must be recycled and does not guarantee the recovery of particular elements such as CRMs. As a result, materials that are easy to extract from spent lithium-ion batteries and/or have a high market price, such as cobalt, nickel, aluminium and copper, are generally recovered first, while lithium and other elements are often discarded (GLOBAL 2000, 2013).

The Batteries Directive is currently undergoing review. Requirements for EV and portable lithium-ion battery collection and recycling efficiency rates should be developed. The directive should also include an element of flexibility to include new and emerging technologies that are not yet on the market.

5.2 Extended Producer Responsibility schemes

Extended Producer Responsibility (EPR) is an approach aimed to make producers responsible for the environmental impact of their products right up until the end-of-life stage of a product's lifecycle (OECD, 2016). In this way responsibility for managing end-of-life products is shifted to the producer, seeking to relieve the burden on municipalities and taxpayers (ibid). Among other EU directives, the Batteries Directive 2006/66/EC introduces EPR as a policy approach for end-of-life batteries (Bourguignon, 2018). Since the Batteries Directive became effective from 2006, EPR policies associated with end-of-life batteries exist in all 28 member states.

These schemes are included in the requirements within the current Batteries Directive. Under Article 16, it states that member states shall ensure that producers, or third parties acting on their behalf finance any net costs arising from the collection, treatment and recycling of all waste industrial and automotive batteries. This means that the original equipment manufacturer (OEM) is responsible for ensuring that 50% of the weight of the end-of-life battery is recycled. The OEM can enter into an EPR scheme either with several other OEMs or in an individual scheme. The most popular are collective schemes that function with a Producer Responsibility Organisation (PRO), which is a third party that controls the management of waste using fees paid by producers (EEA, 2017b). Within the EU, there are mostly collective schemes for batteries where fees are modulated by the average weight of the battery.

5.3 Rules for second-life

Rules for second-life have not yet been developed. This is a relatively new concept for EV battery manufacturers since not many batteries have reached their end-of-first-life yet. Some car manufacturers are starting to invest in facilities that take cells from batteries that have been removed from vehicles and reassemble them for use in energy storage, lower energy applications or in replacement EV batteries.³¹ This market will develop according to the cost of batteries in future years, the cost of recycling and the price of key materials within EV batteries; i.e. if there is a clear business case to reuse rather than recycle those cells. Policy should support the feasibility of second-life applications by reducing any regulatory barriers and providing a legal framework for second-life applications (European Commission, 2017c), particularly associated with EPR schemes.

In light of this, in March 2018 the European Commission announced that it is tackling barriers to innovation by focusing on batteries for electric vehicles in its second 'Innovation Deal' (European Commission, 2018c). Innovation Deals are voluntary agreements that bring together regulatory bodies to overcome regulatory barriers to innovation. The key objective of this second Innovation Deal is to assess whether existing EU law hampers the recycling or re-use of batteries for electric vehicles, specifically looking into regulatory barriers associated with second-life application and ways to overcome them. Results from this Innovation Deal should be transposed into EU legislation where specific regulatory barriers occur, especially barriers relating to which

³¹ One example is the 4R Energy Corporation in Japan which reassembles high-performing modules removed from batteries, see <https://goo.gl/UaiGVG>.

entity is responsible for the battery during a second-life, which should also be considered in the review of the Batteries Directive.

5.4 Ecodesign

Ecodesign is a method to encourage manufacturers to design products that minimise their impact on the environment throughout their entire life-cycle so that they are more environmentally friendly (Elibama Project, 2014). In the EU, the Ecodesign Directive (2009/125/EC) establishes a framework for setting mandatory ecodesign requirements for energy-related products sold on the EU market (Egenhofer et al., 2017). Currently EV batteries are not regulated under the directive. Lithium-ion batteries are regulated within specific regulations for products that use this type of battery. For example, the EU Regulation No 617/2013 that sets ecodesign requirements for computers and computer services states that information on the minimum number of loading cycles that a battery can withstand within a computer should be provided by manufacturers. Similarly, as a potential future requirement for EV batteries, manufacturers of EVs and EV batteries could also be required to provide technical documentation and make information about EV batteries publicly available.

The European Commission (2018a) has announced their strategic action plan on batteries. Within this communication, they announce endeavours to support a sustainable battery value chain and state that there are various instruments that could be considered to drive robust environmental and safety requirements for batteries. They suggest that full advantage should be taken of the Eco-design Directive framework, where opportunities exist to design an innovative regulation. These regulations include requirements on energy efficiency, but in the future could also include circularity requirements for EV batteries, for example on durability, repairability and recyclability. The environmental benefits of setting requirements for lithium-ion batteries and more specifically EV batteries should be the subject of further research.

6 :: Summary and conclusions

As sales of EVs grow, it is anticipated that in coming years a large number of batteries will enter the market and at some point reach their end of life, raising questions about what should happen to these batteries – whether they will be recycled or have a second life in the EU. Such batteries contain materials that often combine a high economic importance with a supply risk (e.g. cobalt).

The development of a viable lithium-ion battery value chain in Europe, in line with the objectives of the European Commission, necessitates a stable and fair access to battery component materials. Achieving high levels of battery recycling can support the supply of materials for the battery value chain (Steen et al., 2017). This paper offers insights into the scale of benefits that could be accrued through developing a recycling sector with a capacity to manage a large share of end-of-life batteries and their materials. The four materials covered by the study are cobalt, nickel, aluminium and lithium. While there will be many effects and benefits from developing and expanding this sector in Europe, for reasons of data availability this study focuses on the volume and value of materials that could be recovered (trade effects) as well as employment and environmental impacts. Impacts are calculated on the basis of an analysis of two hypothetical scenarios

characterised by different levels of ambition regarding the battery collection rates for recycling in Europe and the recycling efficiency rate for each material. Data has been collected through secondary sources and validated through a workshop and interviews/consultations with experts in the field.

Our analysis shows (see Table 5, Figure 4) that realising high rates of recycling of EV batteries in Europe can mitigate dependence on imported materials and help to retain the value of recovered materials in the EU economy. In short, it is estimated that in 2030 materials³² with a value of €408 million in current prices could be recovered under scenario 1 and €555 under the more ambitious scenario 2. Moving beyond 2030 there are many uncertainties regarding battery technologies but, as an indication of the magnitude of potential benefits, it is estimated that in 2035 materials worth €909 million could be recovered and retained in the EU economy under scenario 1 and around €1.2 billion under the more ambitious scenario 2. In 2040 the value of recovered materials at current prices increases and could be around €1.9 billion under scenario 1 and €2.6 billion under scenario 2. As discussed below, there is also potential for employment creation in the recycling sector as well as for CO₂ emissions savings.

Looking in more detail at the trade effects, cobalt is a key component of EV batteries of which the EU imported over 10,000 tonnes of primary raw material in 2012 with a value of €227 million; with most imports coming from the DRC. In scenario 1 we estimate that a battery collection rate for recycling in Europe of 65% combined with a recycling efficiency rate of 94% could lead to the recovery of 2,922 tonnes of cobalt in 2030. The value of this material at current prices would be €213 million. In the more ambitious scenario 2 a collection rate of 85% combined with very high levels of recycling efficiency (99%) could lead to the recovery of 4,058 tonnes of cobalt in 2030, which is equivalent to just over 41% of all cobalt imports into the EU in 2012. At current prices the value of that recovered cobalt would be €295 billion. Moving beyond 2030, with more batteries reaching their end of life, the value of recovered cobalt could reach €659 million in 2035 and around €1.37 billion in 2040 under the more ambitious scenario 2 (again at current prices).³³ The latter figure is approximately a 40% increase on the value of material under the less ambitious scenario 1 (€983 million).

Nickel is a highly sought-after metal for use in lithium-ion batteries and other products of which the EU imports significant quantities; in 2015 the EU imported over 212,000 tonnes, equivalent to approximately €2,244 million. Under scenario 1, which assumes a battery collection rate of 65% combined with a nickel recycling efficiency rate of 95%, around 10,604 tonnes of material would be recovered in 2030 and 49,035 tonnes in 2040. The respective values in current prices would be €123 million in 2030 and €569 in 2040. Under scenario 2 a battery collection rate of 85% combined with a recycling efficiency rate of 97% could lead to the recovery of 13,535 tonnes in 2030 and 62,584 tonnes in 2040. The value of this material would be €157 million in 2030 and €726 million in 2040; the former value is around 9% of the value of net EU imports in the year 2015 (€1,666 million).

Aluminium and lithium are two other materials for which demand is expected to increase as the EV market develops. With regard to aluminium, under scenario 1 which assumes a battery collection rate of 65% combined with aluminium recycling efficiency rate of 98%, around 31,826 tonnes of material would be recovered in 2030 and 147,163 tonnes in

³² This refers to cobalt, nickel, aluminium and lithium.

³³ €659 million would be the value in current prices of 9,054 tonnes of cobalt, while 1.37 billion would be the value of 18,763 tonnes.

2040. The value of this material in current prices would be €57 million in 2030 and €262 million in 2040. Under the more ambitious scenario 2, which assumes a battery collection rate of 85% combined with the same aluminium recycling efficiency rate, 39,783 tonnes would be recovered in 2030 and 183,954 in 2040. Their respective values would be €71 and €328 million. For lithium, whose recycling is considered by many not yet economically viable, scenario 1 assumes a recycling efficiency rate of 57% in 2030, while scenario 2 assumes a rate of 94%. Based on these variables, it is estimated that the EU could recover, under scenario 1, 1,162 tonnes of material in 2030 and 5,373 tonnes in 2040. Their value in current prices would be €15 million in 2030 and €71 million in 2040. Under scenario 2, 2,421 tonnes would be recovered in 2030 and 11,193 in 2040. The value of the former would be €32 million and of the latter €148 million. Scenario 2 provides over 50% more recovered lithium than scenario 1.

Further benefits take the form of the creation of jobs in the recycling sector (see Table 6 and Figure 5). Specifically, under scenario 1, 2,618 jobs would be required to recycle EV batteries in 2030, while in the more ambitious scenario 2 this figure could reach 3,272. In 2035, the number of end-of-life batteries would be higher and would require 5,841 employees for recycling within the EU under scenario 1 and 7,302 under scenario 2. The respective figures for 2040 would be 12,105 (scenario 1) and 15,131 (scenario 2) jobs. Notably, these figures concern only the collection, dismantling and recycling of the batteries, while the construction and development of recycling facilities would require additional labour. Although the calculation of these figures does not take into account the effects on other sectors and involves some uncertainties, they provide an indication of the employment benefits through increased collection, dismantling and recycling of a large number of these batteries in Europe.

With regards to environmental benefits, this study provides estimates about the CO₂ emissions that can be mitigated through recycling end-of-life batteries (see Table 7 and Figure 6). Based on figures from the literature on the life cycle benefits that can be achieved through the hydrometallurgical recycling process, it is estimated that in 2030, 174,525 tonnes of CO₂-eq savings could be achieved under scenario 1 and 218,156 under the more ambitious scenario 2. In 2035 the respective figures would be 389,415 tonnes of CO₂-eq under scenario 1 and 486,769 under scenario 2. In 2040, it would be 807,000 under scenario 1 and 1,008,750 under scenario 2, the latter being equivalent to the CO₂ emissions of producing 261,000 tonnes of aluminium, which is comparable to the annual production of two primary aluminium smelters (based on the CO₂ emissions intensity of electricity generation in the EU in the year 2014).³⁴ However, as noted before, results beyond 2030 are subject to high uncertainty due to technology evolution. Additional environmental benefits, which are not easy to quantify, would occur from the reduced need for extracting raw materials. Notably, even if these batteries leave the EU it is likely that they would be recycled at some stage if recycling facilities are in place.

Based on the above findings and the analysis conducted for this study, it is recommended that the EU continues and strengthens its support for R&I for lithium-ion battery recycling processes. Although lithium-ion battery recycling processes already exist within the EU, there is significant room to improve their efficiency, especially considering that recovery and recycling of some materials (e.g. lithium) is not yet economically viable. The latter is confirmed by several literature sources but also by interviews with experts conducted as

³⁴ There are 16 primary aluminium smelters in Europe today.

part of this study. R&I support is thus needed to improve both the cost effectiveness and the efficiency of the lithium-ion battery recycling processes.

Additionally, the availability of data has been a key limitation of the study, which has meant that only a certain number of benefits are presented. The costs of collecting, dismantling and recycling batteries should also be evaluated in a longer study, which would allow a comparison of costs and benefits. Investment costs should also be studied, which should be done by collecting information from recyclers. Regarding the impact on employment, research into the effects on other sectors is needed to calculate the net impact of recycling EV batteries in Europe, as well as the impacts on countries outside the EU. This study adds to current research into the impact of recycling end-of-life EV batteries in Europe, but does not claim to be exhaustive. It could serve as a basis for further research to gain a fuller understanding of the impacts of supporting the development of an EV battery recycling sector in the EU.

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Annexes

Annex 1. Summary of literature sources

Table A 1. Literature sources used for the various assumptions/variables

Assumption		Source
EV sales in the EU the years leading up to 2030, 2035 and 2040	0.145 million in 2015, 1 million in 2020, 2.5 million in 2025 and 5 million in 2030	Bloomberg New Energy Finance (2017)
Lifetime of EV batteries	8 years	Based on this and on information received from experts, as well as a report on the capacity loss of Nissan Leaf batteries (Myall et. al., 2018)
Length of second-life	10 years	National Renewable Energy Laboratory (Neubauer et. al., 2015)
Percentage of batteries used for second-life	30%	Bloomberg New Energy Finance (Curry, 2017) and interviews/consultations with experts.
Average weight of cobalt in an EV battery	116 g/kWh	Fickling (2017)
Average weight of nickel in an EV battery	400 g/kWh	Fickling (2017)
Average weight of aluminium in an EV battery	1,163 g/kWh	UBS (2017)
Average weight of lithium in an EV battery		Fickling (2017)
Price of cobalt in 2030	91,000 \$/ton	LME (2018a). Market prices for cobalt, nickel and aluminium were retrieved on 23 May 2018.
Price of nickel in 2030	14,500 \$/ton	LME (2018b).
Price of aluminium in 2030	2,226 \$/ton	LME (2018c).
Price of lithium in 2030	16,500 €/ton	Metalary (2018)
Employment	15 jobs created per thousand tonnes	Based on employment rates provided by lithium-ion battery recyclers. Of those 15 jobs, about 80% would be for the collection and dismantling of lithium-ion batteries while the remaining 20% of jobs would be for the recycling of batteries.
CO ₂ emissions	Net saving of 1 kg CO ₂ per kg battery	Romare & Dahllöf (2017) present results from the LithoRec project (Buchert, et al., 2011).

Variable		Source
Collection/take back rates	Scenario 1: 65% Scenario 2: 85%	European Commission (2016), "SET-Plan ACTION n°7 -Declaration of Intent - Become competitive in the global battery sector to drive e-mobility forward".
Recycling efficiency rates	<u>Scenario 1</u> Cobalt: 94% Nickel: 95% Aluminium: 98% Lithium: 57% <u>Scenario 2</u> Cobalt: 99% Nickel: 97% Aluminium: 98% Lithium: 94%	Lebedeva et al., 2016 "Lithium ion battery value chain and related opportunities for Europe".

Annex 2. List of experts* consulted

Astrid Arnberger, Project Manager Research & Development, Saubermacher Dienstleistungs AG.

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Claude Chanson, General Manager, The Advanced Rechargeable & Lithium Batteries Association (Recharge).

Mattia Dalle-Vedove, EU Affairs manager for energy and transport, Hitachi.

Jennifer Diggins, Director Government and Regulatory Affairs - The Americas, Albemarle.

Pierre Gaudillat, Scientific Officer, Joint Research Centre – European Commission.

Carol Handwerker, Reinhardt Schuhmann Jr Professor of Materials Engineering and Environmental and Ecological Engineering, Purdue University.

Oliver Hately, Senior Policy Advisor, Critical Raw Materials Alliance.

Ian Higgins, Managing Director, Less Common Metals Ltd.

Ajay Kochhar, President and CEO, Li-Cycle Corp.

Pascal Leroy, Secretary General, WEEE Forum.

Stephan Laske, Head of Research & Development, Saubermacher Dienstleistungs AG.

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René Schroeder, Executive Director, Eurobat.

Kamila Slupek, Sustainability Manager, Eurometaux.

Martin Tauber, President, Critical Raw Materials Alliance.

Willy Tomboy, The Advanced Rechargeable & Lithium Batteries Association (Recharge).

Jan Tytgat, Director Government Affairs, Umicore.

Alain Vassart, Secretary General of EBRA, European Battery Recycling Association (EBRA).

*Three additional experts were interviewed but have remained anonymous.

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