Perspective

Estimate of Economic Impact of EVs Li-ion Batteries Recovery

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ABSTRACT: Nowadays, increasing attention is directed towards the sustainable use of raw materials. For a circular economy, recovery from spent devices represents a fundamental practice. With the transition to electric mobility, an increasing number of devices powered by lithium batteries are produced. Indeed, this is the fastest growing sector producing spent batteries, which are an important secondary source of critical raw materials, such as lithium, cobalt, graphite, and nickel. Therefore, this work aims to quantify the economic impact of recovering raw materials from lithium batteries used in the electric vehicles sector. Based on the chemical composition of the various lithium batteries and their market diffusion, the intrinsic economic value of this waste has been estimated to be around 6500 €/ton. Starting from the literature data on the global energy demand from lithium batteries and deriving the trend of their specific energy over time, the mass of material introduced into the market annually is estimated to reach 60 Mton/year by 2040. The annual amount of end-of-life lithium batteries was calculated by applying the Weibull distribution to describe the probability of failure, yielding 10 Mton/year by 2040. Finally, based on these results, the economic impact of the recovery market was assessed for two different scenarios.

Keywords: Li-ion battery; Recovery; Lithium; Graphite; Cobalt; CRMs; Economic impact; End-of-life

1. Market Analysis

Lithium batteries have become a key element in the electrification of transportation, energy storage, and the transition to a low-carbon economy. Their growing popularity is due to their unique characteristics, such as high energy density, long life, and low spontaneous discharge rate [1,2]. Their use is extended to numerous sectors and can be found everywhere: from small electronic devices such as smartphones and tablets to the electric mobility and energy storage sector. Over the last few years, the demand for electronic devices and electric vehicles has grown exponentially [3], fueled by awareness of climate change and the need to reduce greenhouse gas emissions. Electric vehicles offer benefits not only on an environmental level but also on a technological and economic level. The lower recharging costs, when compared with traditional fuels, imply a lower operating cost than internal combustion vehicles. In addition, electric vehicles require less maintenance as they have fewer moving parts that wear less. Technologically, a lot is being invested in reducing charging times to increase the autonomy of the accumulators [4,5] and the number of public and domestic charging stations. Much of the safety of the battery relies on the Battery Management System (BMS); the component that is responsible for balancing the charge between cells in the battery pack; evaluating the State of Charge (SoC); and monitoring temperature. It is vitally important to improve the accuracy of thermal models to design the battery in a way that limits precisely the temperature, preventing and intervening in a timely manner in case of malfunction, avoiding the propagation of thermal leakage between cells [6–10].

There are many types of electric motorized vehicles [11]: Battery Electric Vehicles (BEV), powered exclusively by an electric motor and a battery; Plug-in Electric Vehicles (PHEV), for a gradual transition to electric mobility, are equipped with both an electric motor and an internal combustion engine; Hybrid Electric Vehicles (HEV), cannot be charged from an external socket but the battery recharges while driving; Fuel Cell Electric Vehicles (FCEV), use fuel cells to produce electricity on board, by combining hydrogen with oxygen from the air and generating water as a by-product. All these electric vehicles, based on different technologies, use lithium-ion batteries in common.

This kind of battery has proven to be the ideal choice for electric energy storage in vehicles, offering a more extended range than other battery technologies [12,13]. In addition to electric vehicles, lithium batteries are revolutionizing the sustainable energy sector. These accumulators are essential for storing the excess energy produced during high-generation periods and using it when production is reduced. This energy storage capacity helps create a more flexible and sustainable energy system.

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In 2022, the global energy demand for lithium-ion battery cells was approximately 700 GWh. The country with the highest demand was China, with around 370 GWh, followed by the EU and the USA, with around 150 and 120 GWh, respectively [14]. The total demand is growing exponentially, as shown in Figure 1. It is estimated that the global energy demand from lithium batteries will reach a value of around 50 TWh in 2040, of which the electric mobility sector requires 30 TWh. This growth involves placing large quantities of batteries on the market with a consequent increase in the demand for critical raw materials (CRMs), as defined in [15].

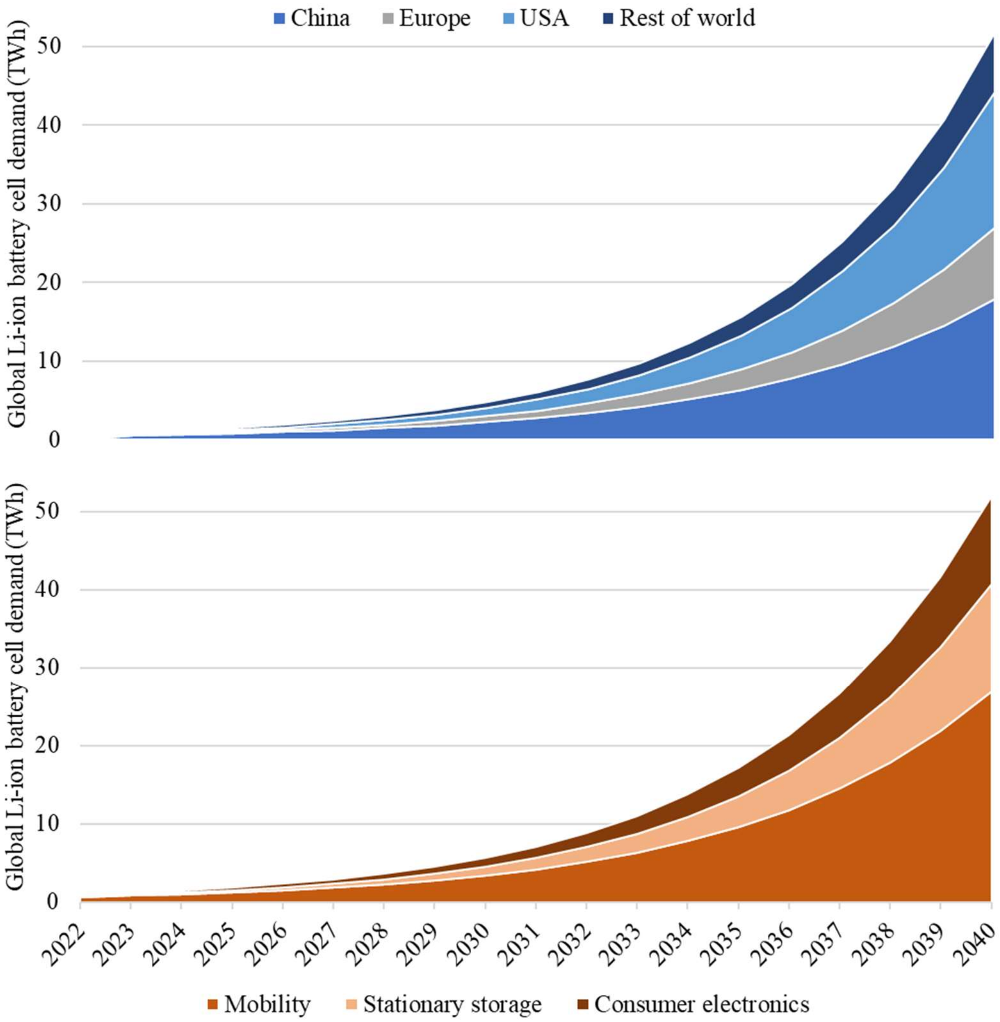

Figure 1. Global Li-ion battery demand by geographical region (up) and by application (down).

Despite the many benefits of lithium batteries, some challenges need to be addressed to ensure even greater market uptake. One of the main concerns is procuring raw materials needed to produce lithium batteries, such as lithium itself, cobalt, nickel, and graphite. These materials are mined in different parts of the world, often in developing countries, raising concerns about environmental sustainability, human rights, and price stability [16]. Figure 2 shows the percentages of raw materials extracted by country in 2021 [17,18]. It must be considered that these values may change according to changes in production and mineral exploration. The primary mineral deposits of the raw materials contained in the Li-ion Batteries (LIBs) are concentrated in a few countries, such as Congo, China, Australia, and Russia.

Furthermore, the waste management of lithium batteries is an important issue to address, as they contain harmful chemicals that can have a negative impact on the environment if not disposed of properly, such as heavy metals, flammable electrolytes, and polymeric materials. The quantities of waste generated by these devices are starting to be considerable. Estimating these quantities is essential to understand the potential and capabilities of a hypothetical recovery plant within the lithium battery waste treatment market. With this study, we want to understand the practical attractiveness of this market from an economic point of view.

A careful bibliographic analysis has shown how recent studies have led to a marked improvement in the performance of LIBs, especially in terms of specific energy [1]. This constant increase is due to the optimization of the LIBs cell chemistry [1], the introduction of new anodic and cathodic materials which have contributed to the increase in energy density [2], the optimization of the cell design with the reduction of the thickness of the electrodes, the optimization of the structure of the separators and the use of chemical additives [19]. Figure 3 shows the bibliographic data of the energy density over the years (orange dots) [1], and our estimate up to 2040 (blue line), obtained by applying a sigmoidal fit to literature data. Notably, a maximum specific energy density of about 700 Wh/kg has been chosen as a boundary condition [20].

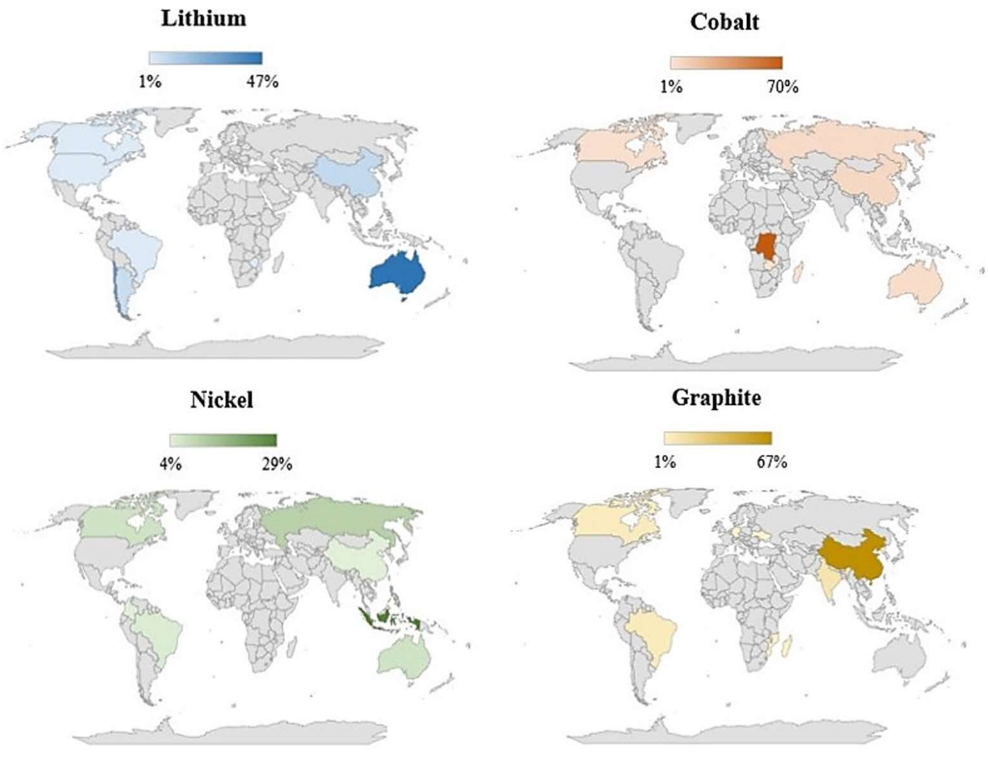

Figure 2. Geographical distribution of lithium, cobalt, nickel, and graphite production in 2021.

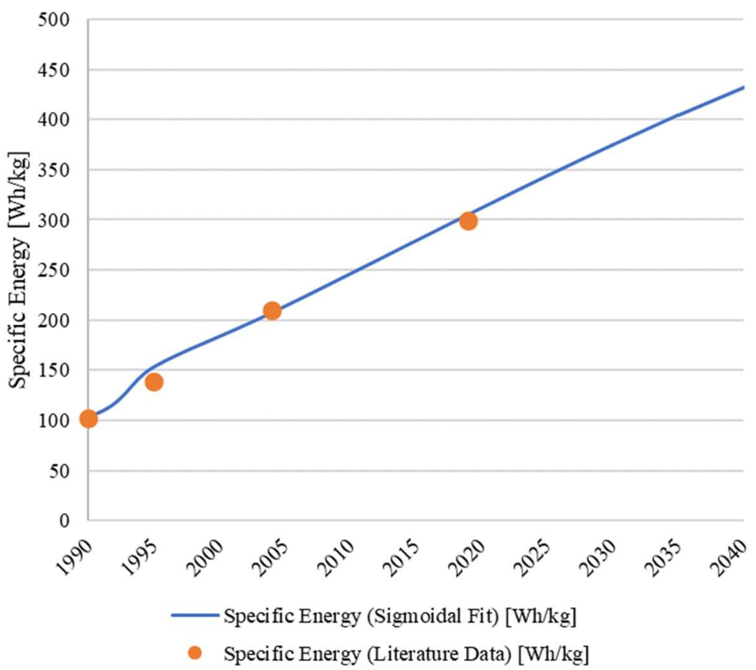

Figure 3. Specific Energy [Wh/kg] trend of EV Lithium-Ion Batteries (Blue line) from literature data (Orange line).

Considering this specific energy trend and the analysis of the data reported in Figure 1, which estimate the trend over time of the energy required by the various countries in the lithium battery sector, it was possible to convert the TWh/year of energy into tons/year of LIBs as shown in Figure 4.

Starting from the quantity of LIBs introduced into the market each year in terms of quantity of material, it is possible to trace the mass of waste generated each year by LIBs at the end of their life (EoL-LIBs) through the Weibull probability distribution (Eq. 1).

$$F(t) = 1 - e^{-\left[{(t-t_0)}/{\tau}\right]^{\alpha}} \tag{1}$$

where t is the time expressed in years, t_0 is the year of placing the generic mass of LIBs on the market, τ is the average lifetime of a LIBs and α is the shape factor of the distribution. For the case under consideration, the following parameters of the Weibull function were taken from the literature: α equals to 5.70 and an average lifetime of 12 years has been assumed [3,21]. These parameters approximate those of a representative LIB in the EV sector. By multiplying the Weibull function by the mass of material placed on the market each year, we obtain the trend of the waste generated by that material. In this sense, it was possible to trace the amount of waste generated each year by EoL-LIBs as shown in Figure 4.

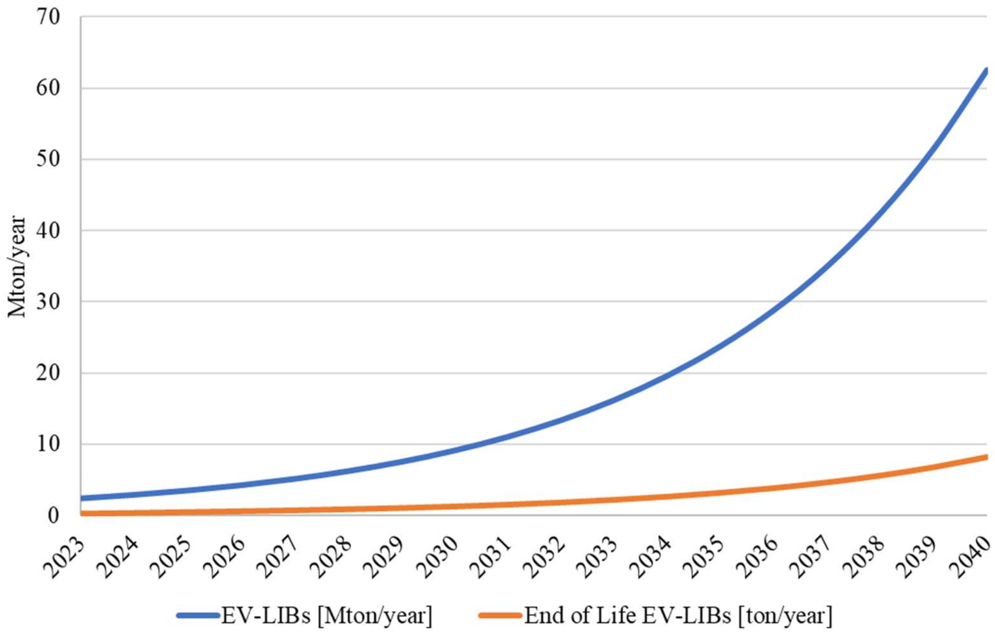

Figure 4. Estimation of EVs LIBs and EoL-LIBs.

Starting from these estimates about the volume of EoL-LIBs and from the regulatory state of the different countries, the authors intend to provide an overview of the economic aspects related to the recycling of LIBs, giving their opinion about the challenges, the opportunities, and prospects in this sector. More precisely, thanks to literature data, we want to answer exhaustively questions such as: How is the production of the critical raw materials in the LIBs distributed? What are the volumes of waste from LIBs to be treated annually? What is the intrinsic economic value (IEV) of recyclable materials? What is the value of possible recycling of these materials?

2. Intrinsic Economic Value

Based on literature data, a simple chemical breakdown approach is proposed to give an estimate of the proportion of chemical elements that compose an average EV LIB. Generally, a LIB is made up of completely different sections, such as the cathode, the anode, and the electrolyte. The relative weight fractions of such sections in an average LIB are given in Table 1, from two different literature sources. For the breakdown analysis reference [22] has been used, being the most recent. Notably, reference [23] provides enough data to calculate average values and associated standard deviations.

Table 1. Mean weight fractions of each LIB's element [22,23].

Part	Weight Fraction [wt%] [23]	Weight Fraction [wt%] [22]
Cathode	32.3 ± 1.4	~31
Anode	20.0 ± 1.8	~22
Anode Current Collector	8.2 ± 0.4	~8
Cathode Current Collector	15.6 ± 0.9	~17
Electrolyte Solution	16.7 ± 2.9	~15
Binders/Separators	7.2 ± 0.2	~7

Since each section can be composed of different chemical elements, these should be analyzed separately to estimate their chemical composition.

Cathode: There are many different cathodes for EV LIBs, usually classified by their chemical composition. Some of the main cathode types for EV LIBs are Li-Iron Phosphate (LFP), Li-Manganese Oxide (LMO), Li-Cobalt Oxide (LCO), Li-Nickel Cobalt-Aluminium (NCA) and Li-Nickel Manganese Cobalt Oxide (NMC) [24,25].

Most cathodes contain lithium and cobalt, which are interesting from a recovery point of view [15]. Table 2 presents the market shares of the most relevant cathode types of EV LIBs, according to ref [24].

Table 2. Market Share of LIBs Cathodes as of 2022 [24].

Cathode Type [Chemical Formula]	Market Share in 2022 [%]
LFP [$LiFePO_4$]	~35
NMC 811 [$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$]	~17.5
NMC 622 [$LiNi_{0.6}$ $Mn_{0.2}$ $Co_{0.2}O_2$]	~17.5
NMC 532 [$LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$]	~15
NMC 333 [$LiNi_{0.3}Mn_{0.3}Co_{0.3}O_2$]	~5
NCA [$LiNi_{0.85}Co_{0.15}Al_{0.05}O_2$]	~10

To obtain the elemental composition of a representative cathode by a weighted average, the market shares have been used as the relative weights of each cathode type, as reported in Table 2.

Anode: a single or two-element part. In LIBs, the most common materials are graphite, silicon, lithium, metallic alloys (e.g. containing aluminium, tin, magnesium, silver) and transition metal oxides [24,26]. Table 3 presents the market share of the most used anode types over the total of EV LIBs. Notably, other types of anodes are in the study as new-generation materials [26]. However, since they still comprise a small percentage of the overall anodes or are still in academic/industrial development, we excluded them from the following statistics.

Table 3. Market Share and chemical composition of LIBs Anodes as of 2022 [24].

Anode Type	Market Share (%)
Li metal	~1
Si [75 wt%]–Gr [25 wt%]	~30
Graphite	~69

Current Collectors: In LIBs, there are two solid metallic components. Usually, the cathode current collector is made of copper [27], and the anode current collector of aluminium [27]. Table 1 attests that these comprise around 17% and 8% of the total device mass, respectively [24,25].

Electrolyte Solution, Separator, and Binders: Other chemicals that make up a LIBs are the electrolyte solution, the anode–cathode separator, and the polymeric binders, which are used both in the anode and the cathode [28] to enhance mechanical and electrical properties. The most widely used electrolyte is $LiPF_6$ [19], dissolved in organic solvents with a typical concentration of 1 mol/L [29]. Other electrolyte solutions are sometimes used. However, for this work, only the widespread $LiPF_6$ will be considered. Again, since this work focuses on the economic advantage of materials recovery from spent EV LIBs, the separators and the polymeric binders will be considered entirely made of carbon.

Based on the data previously presented, Figure 5 presents an estimate of the weight percentage of chemical elements in an average EV LIBs. More precisely, representative cathodes and anode types have been obtained by a weighted average, based on their market shares as of 2022 [24] (see Tables 1 and 2). Both current collectors do not require an average composition, being pure metals [27]. Regarding the electrolyte solution, it must be remembered that the $LiPF_6$ salt accounts for approximately 15% of the total solution weight [19], with the rest being organic solvents, for simplicity assumed to be ethylene carbonate. Finally, separators and binders were only represented by carbon. To obtain the final composition of an average EV LIBs, each part (cathode, anode etc.) has been multiplied by its weight fraction in the overall battery, according to Table 1.

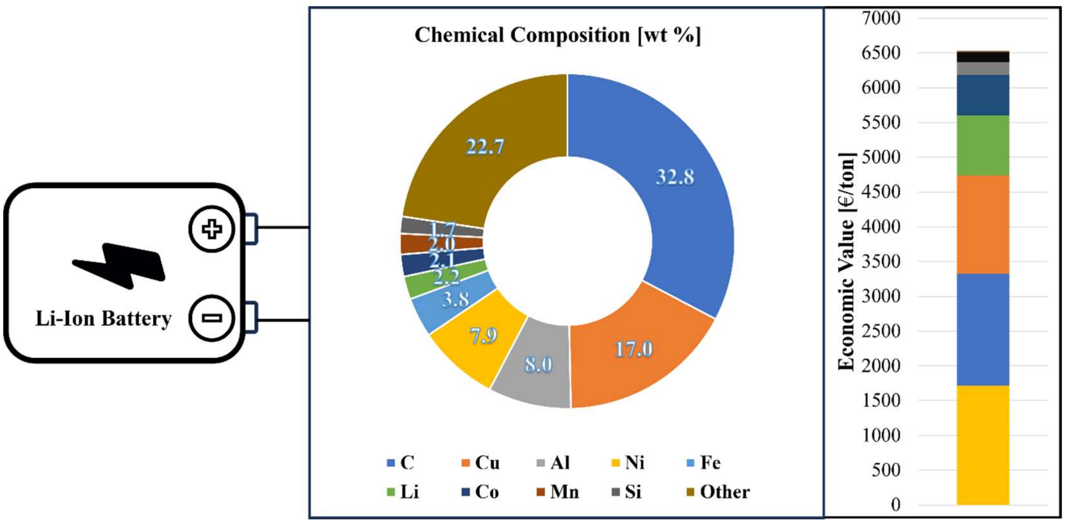

Figure 5. Chemical composition of a representative LIB and its Intrinsic Economic Value.

Table 4. Updated market quotations for each element and relative references.

Element	Market Quotations	Ref.
C	7.34	[30]
Cu	8.29	[31]
Al	2.23	[31]
Ni	21.76	[31]
Fe	0.23	[31]
Li	38.87	[32]
Co	27.34	[31]
Mn	0.01	[31]
Si	9.00	[31]

To define and calculate the Intrinsic Economic Value of waste LIBs, the amount of each chemical element present in a ton of waste has been multiplied by its most recent market quotation (see Table 4). The IEV is different to the real economic value (REV) of a device and represents the economic value associated with the materials that compose the device. IEV and REV differ in most cases for the added value (considered in REV) given by the manufacturing process and the performance that the device can offer [31]. Figure 5 shows the average composition of a representative sample of EoL-LIBs and the related IEV as a contribution of the different raw materials.

Notably, based on the data in Figure 5 and Table 4, four of the elements, specifically lithium, cobalt, graphite, and nickel, represent about 73% of the above-defined total IEV, even representing the 50% of the total weight fraction. Interestingly, carbon-based materials, namely graphite, plastic separators, polymeric binders and electrolyte solution account for around 25% of the total IEV, while representing the 33% of the weight fraction. While the value of recovering graphite from LIBs has been discussed in literature [30], and methods have been proposed to recover the electrolyte solution [33] and the polymeric binders [34], a deeper discussion on the economic impact of recovering the carbon-based fraction is needed. However, thanks to IEV, it is possible to estimate the economic margin of a possible recovery process for one or more chemical elements reported in Figure 5.

3. Economic Impact of Recovery

Starting from the results obtained in the previous chapters, it was possible to identify the economic value associated with the recovery of CRMs from EoL-LIBs. The intrinsic economic value was estimated by combining the average composition of the EVs EoL-LIBs and the related raw material prices. The economic impact deriving from the recovery of raw materials was estimated through this quantity and the estimate of the quantity of EoL-LIBs.

The estimate of the economic impact was carried out for two different scenarios: an ideal scenario and a realistic scenario. In the ideal scenario, it has been assumed that the EoL-LIBs are collected with an efficiency of 100%, and the recovery yields of the different raw materials are total. In the realistic scenario, the collection efficiency was established considering European legislation [35].

In the EU, Directive 2006/66/EC establishes rules for the collection and recycling of batteries and accumulators to reduce the environmental impact deriving from their disposal. This directive requires Member States to establish systems for the separate collection of used batteries and promote recycling. On 14 June 2023, the new legislation on battery recovery was approved, setting a target for the collection of portable batteries at 45% by 2023, reaching 63% in 2027, while for the batteries of light transport vehicles to 51% by 2028 and 61% in 2031 [36]. The decision to use European policy as a reference for the collection is because the latter is undoubtedly the most recent and is placed between very different behaviours according to the countries.

In China, the Ministry of Ecology and Environment has long adopted regulations such as GB/T 18287-2013 containing the technical standards for lithium-ion batteries used in electronic devices. Battery management and environmental policies in China may vary between provinces and cities, as local authorities may implement specific regulations and national laws.

In the USA, the Environmental Protection Agency (EPA) is the federal agency responsible for promoting the regulation of batteries and accumulators. The “Batteries Act” establishes requirements for the handling, collection, recycling, and disposal of batteries to prevent pollution and promote the conservation of resources. This law provides for the promotion of battery recycling programs, the minimization of hazardous materials in batteries, and the proper management of used batteries. However, in the US, the recovery rate is still relatively low [3].

In the realistic scenario, the recovery yields are considered total according to different literature data [35]. In fact, many recovery processes have been developed that combine consolidated and cutting-edge technologies in recent years. Hydrometallurgical, pyrometallurgical, and bio-hydrometallurgical processes currently allow critical and base metals to recover with extraction yields higher than 99% [37,38]. Also, for the organic fraction, some processes allow recovery with high yields [39,40]. Furthermore, where a total recovery of the organic fraction is not possible, it is always possible to envisage energy valorization steps. Technologies such as pyrolysis or gasification are increasingly associated with types of electrical and electronic waste [41,42].

The estimation of the economic impact of the recovery of raw materials is not influenced by the type of process but only by the yields that it can achieve. This study is essential for creating business plans that allow understanding the operating economic margin of any process, depending on the capacity of the plant or the market share that can be reached. For example, assuming that a company in 2030 manages to supply about 1% of all EoL-LIBs collected, it will have about 50 M€ of annual revenue from which Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) have to be subtracted for profit determination.

The analysis shows how the regulations aim to increase the percentages of batteries collected and raw materials recovered, decreasing the gap between the ideal scenario and the real one. Figure 6 shows the trend over time of the economic impact of the recovery. The trend is obtained by multiplying three factors: the IEV, the estimated mass of EV EoL-LIBs, and the collection rate.

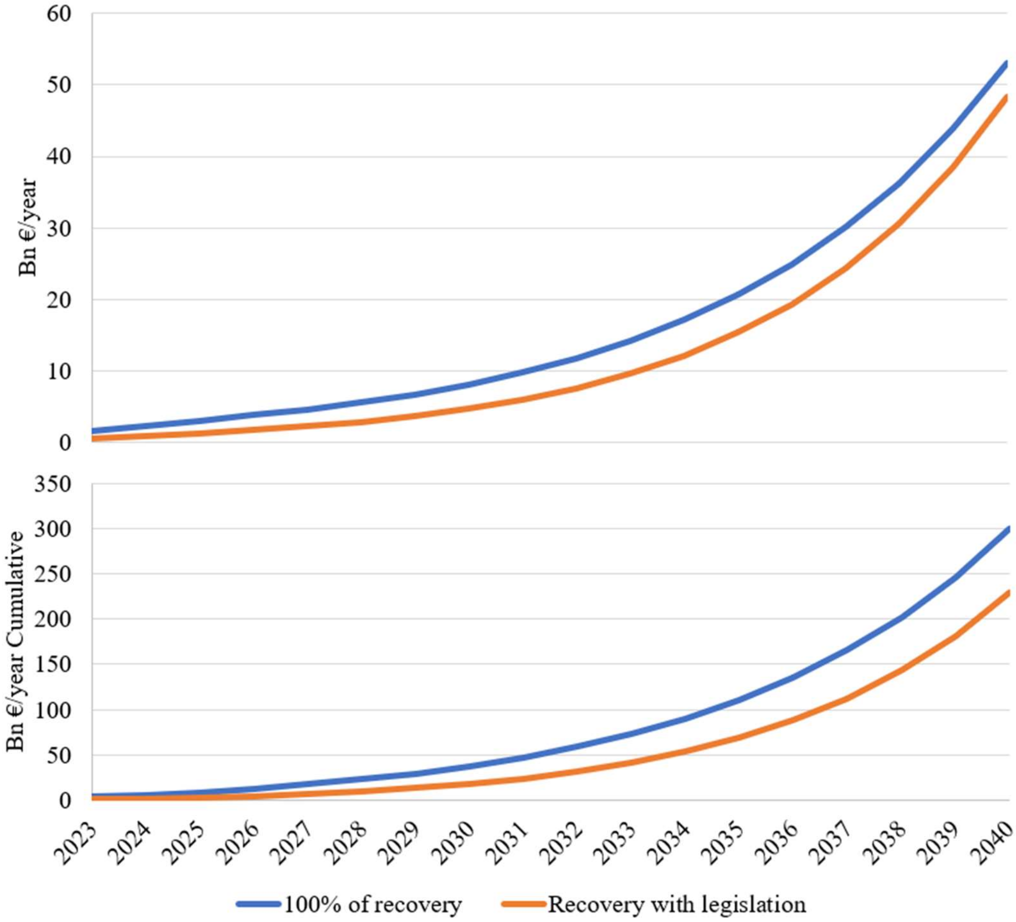

Figure 6. Annual economic impact (Up) and cumulative economic impact (Down) of material recovery from EV EoL-LIBs.

It is possible to see how the trend of the economic impact is exponential, with the two curves tending to approach each other over time due to increasingly stringent regulations on treating this waste. It is estimated that the economic impact of this market will reach a value of around 10 billion EUR in the ideal scenario and around 5 billion EUR in the most realistic case in 2030. These values will rise significantly, reaching an ideal and real economic impact of approximately 54 and 48 billion EUR, respectively, in 2040. Among the countries pushing the most for the recovery of raw materials from EoL-LIBs, we find China and South Korea. Figure 7 shows how China and South Korea will come to generate a market for recovered raw materials of 2.5 billion EUR and 1 billion EUR, respectively, in 2030. they will reach respectively 45 billion EUR and 10 billion EUR in 2040. The European market is smaller in terms of the quantities of EoL-LIBs generated and in terms of recovery. The market is estimated to be around 5 billion EUR in 2040. Two other relevant countries for recovery are the USA and Japan but with much lower percentages than those mentioned above.

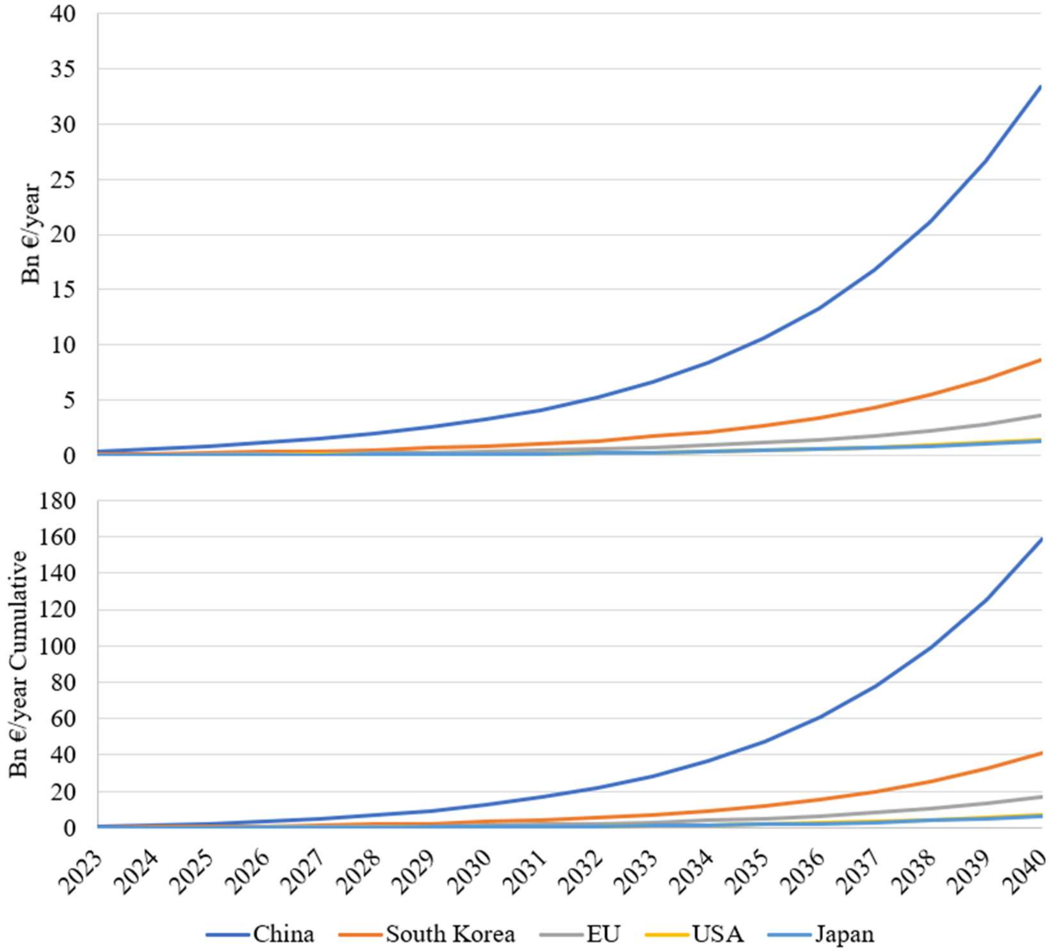

Figure 7. Annual economic impact (Up) and Cumulative economic impact (Down) of material recovery from EV batteries per country.

4. Conclusions

The recovery of raw materials from secondary sources is a significant challenge for many countries. The mineral availability of these raw materials is concentrated in a few geographical areas, making it necessary to increase the percentage of recovery from EoL devices. Hence, this work estimates the economic impact of recovering the materials contained in the EV EoL-LIBs.

The trend of the global demand for energy required by LIBs was analyzed using data in the literature. The quantity of material required by the market was estimated by combining the latter study with the one on the evolution of their specific energy over time.

The Weibull function was used to estimate the waste generated over time. This function allowed us to describe the LIBs failure probability as a function of time and the quantity of material returning from the market each year. The resulting trend is exponential, with values reaching 1 Mton/year in 2030 and 8 Mton/year in 2040.

Combining the percentage of diffusion on the market of various LIBs and their composition, a weighted average composition of the generated waste was estimated. By multiplying the fraction of each raw material of the waste by the respective market quotation, an intrinsic economic value of approximately 6500 EUR/ton was determined.

Finally, by multiplying the amount of waste by the IEV, the economic impact of recovery was estimated for an ideal and a real scenario. In the first scenario, the annual economic impact reaches a value of 10 billion EUR in 2030 and 54 billion EUR in 2040. In the second scenario, the annual economic impact in 2030 and 2040 is 5 and 48 billion EUR, respectively. Regarding the geographical subdivision of the recovery, the dominant geographical areas are China and South Korea, followed by the EU.

The recovery of raw materials from LIBs is essential for the following reasons: in terms of environmental impact, it avoids the accumulation in landfills and the loss of resources; at a strategic level, it allows to increase the independence of those countries that do not have significant mineral sources; economically it represents an extremely attractive and rapidly growing market. Moreover, this growth is further driven by both technological developments and regulations to increase recovery. In this context, laws and projects aimed at creating collaborations and consortia between different stakeholders should be of great help in order to favour the sharing of knowledge, resource optimization, and market development. All this would make it possible to increase the sustainability of the energy transition and to get closer and closer to the very important concept of circular economy in this sector.

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Author Contributions

Conceptualization, P.R.; Methodology, P.R.; Validation, P.R., N.S. and V.R.; Investigation, N.S.; Data Curation, V.R.; Writing—Original Draft Preparation, P.R., N.S. and V.R.; Writing—Review & Editing, P.R., N.S. and V.R.; Visualization, V.R.; Supervision, N.S. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

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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.

Nomenclature

F	Probability density of failure
t	Time
t_0	Year of placing the generic mass
wt%	Weight fraction
Greek letters	
α	Shape factor of the distribution
τ	Average lifetime
Abbreviations	
BEV	Battery electric vehicles
BMS	Battery management system
CAPEX	Capital Expenditure
CRMs	Critical raw materials
EoL	End-of-Life
EPA	Environmental Protection Agency
EVs	Electric vehicles
FCEV	Fuel Cell electric vehicles
HEV	Hybrid electric vehicles
IEV	Intrinsic Economic Value
LIBs	Lithium-ion batteries
OPEX	Operational Expenditure
PHEV	Plug-in electric vehicles
REV	Real Economic Value
SOC	State of Charge

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