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Research article

Economic analysis of lithium-ion battery recycling

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Abstract: Battery needs are increasing due to the exponential growth in demand for electric vehicles and renewable energy generation. These factors lead to the growing waste management of lithium-ion batteries (LIBs). Thus, recycling or finding a second life for LIBs is a growing industry due to its environmental and economic benefits. This work compares the benefits, economic advantages and disadvantages of battery recycling, including second-life battery applications. Different reports and case studies are analyzed to define the materials that may be recovered and the efficiency of the recycling process. To understand the economics of using recycled, second use, or new LIBs, this work evaluates three distinct projects, namely residential, commercial, and solar farm storage. The investigation aims to calculate and compare the net present value (NPV) for the residential storage project and the equivalent annual cost (EAC) for each project to determine the most viable industrial process within those parameters. The data analysis demonstrated that the second-life battery project has the lowest EAC, making it the most viable industrial process. However, although the second-life battery project presents the highest NPV for the project's first 10 years, the recycled battery project shows the highest NPV for the remainder of a typical 20-year project.

Keywords: lithium-ion batteries; second life; recycling batteries; battery reuse; battery refurbishing

1. Introduction

In the past few years, lithium-ion batteries (LIBs) have become the go-to technology for energy storage due to their efficiency and capabilities to perform through various applications. They are mostly found in laptops, electric vehicles, and residential storage. This work provides a more in-depth explanation of LIB technologies, including various advantages, disadvantages, types of waste management, and environmental issues. Additionally, a brief description of the lithium sources is provided alongside the countries with the largest lithium reserves.

In addition, recycling methods are discussed for both steps during the pre-treatment of LIBs, and the actual treatment through recycling. Therefore, this work offers an extended understanding during the pre-treatment phase of processes such as sorting, dismantling and discharging, pyrolysis deactivation, and mechanical separation. Moreover, the treatment process may involve different methods such as thermal treatment, pyrometallurgy, hydrometallurgy, and electrochemical extraction. These recycling methods are expected to improve as technologies advance and become a requirement for every battery that reaches the end of its life cycle, since only 10% of batteries are currently being treated for either recycling or reuse [1].

Furthermore, the possibilities and benefits of giving LIBs a second life are herein discussed, since a LIB reaches its end-of-life when its capacity reaches 80%. However, it can still be used for energy storage in stationary applications [2]. The European Union has been insisting on a battery passport for every battery in the market, which will become a requirement for new manufacturers. This program aims to improve the recycling process by understanding what the battery has been through and the status of its components, all of which will be provided through blockchain technology [3].

Past reports, projects, and case studies were thoroughly studied to gather the most efficient work regarding recycling, second-life, and new LIBs. These studies provide in-depth knowledge and information about the amount of material recovered during the recycling process and its efficiency and method deployed. Additionally, they provide the economic aspects of each approach to understand how viable it is and how profitable it can be.

Lastly, three projects were analyzed to determine and compare the most viable industrial process. These projects are residential, commercial, and industrial storage. Their energy storage capabilities were compared using recycling, second-life, or new LIBs. Finally, a conclusion of the most viable industrial process was provided by calculating and comparing the net present value (NPV) of the residential storage project and the equivalent annual cost of all three projects.

2. Description of LIB technology

Compared to other batteries, lithium-ion batteries (LIBs) are in a category of their own due to their high energy density and low cost per cycle. They are classified into cells, modules, and packs. In addition, they are formed by four key components: the cathode, anode, electrolyte, and separator [4].

The cathode is the positive electrode that is reduced during cell discharge, receiving electrons from the external circuit. Additionally, it determines the voltage and capacity of LIBs and the source of their ions, as well as ensuring a stronger molecular bond capable of sustaining extreme charging conditions. The anode is the negative electrode and allows for the intercalation of Li ions when the battery is charged, being then oxidized during cell discharge. Furthermore, the electrolyte is composed of salts, solvents, and additives. It works as a channel for lithium ions to move between the anode and the cathode. Finally, the separator is a physical barrier separating the cathode and the anode. It works as an insulating material but allows for ion transfer (Figure 1).

Figure 1. Simplified scheme of the inside of a lithium-ion battery (LIB) [5].

The applications of LIBs are endless. These batteries can be found in multiple devices and applications, such as phones, computers, homes, electric vehicles, etc. LIBs can take different shapes depending on the application, including cylindrical, prismatic, or pouch cell configurations.

LIBs have a vast number of applications, providing numerous advantages, which include the following [6]:

- High energy density: this is the main advantage of LIBs, together with their safety and high life cycle. Mobile phones, portable computers, electric vehicles, and others systems that need to operate for an extended period between charges while consuming high power require high-density batteries, meaning they can have a high capacity while not being bulky.
- Self-discharge: a low self-discharge means a LIB can retain the charge longer than any other battery when left unused. Typically, it discharges around 5% in the first four hours, and then approximately 1% or 2% monthly.
- Low maintenance: LIBs rarely require maintenance. The only necessary maintenance is ensuring that every cell in the battery bank is charged equally. However, it is usually automatically performed through a management system.
- Cell voltage: a higher voltage in each cell can satisfy systems with one single cell by simplifying power management in applications such as smartphones.
- No requirement for priming: the cells found in a LIB bank are ready to go, meaning they do not require priming when receiving the first charge.
- Longevity: life cycles on LIBs are higher than any other battery, and they can be charged many times without causing any adverse effect on their capacity and efficiency.

Similar to every application or technology with significant advantages, LIBs also have disadvantages that must be considered when choosing between them. These include the following [6]:

- Cost: LIBs usually cost around 40% more to manufacture than nickel-cadmium (Ni-Cd) cells; hence, when mass production is considered, any additional charges are a major issue.
- Transportation issues: airlines limit the number of LIBs that can be taken aboard the plane, meaning that its transportation is limited to ships.
- Protection: LIBs need protection from being overcharged, which could increase the risk of over-discharge and the battery exploding, as they need to maintain the current within safe limits.

Implementing a battery management system (BMS) allows for the battery to be left on charge and, once fully charged, stop the supply immediately.

- Developing: even though lithium iron phosphate ($LiFePO_4$) batteries have been around for many years, some consider it an immature technology. Technology is not stagnant, and better solutions may become available soon.
- Aging: even if the battery is unused, it is still affected by aging, causing a reduction in capacity.

3. Waste management of LIBs

LIBs have an approximate life expectancy of three years for small electronic devices such as laptops, cell phones, tablets, and cameras. Moreover, LIBs last five to ten years for large electronic devices such as electric vehicles and energy storage systems, having a shorter lifespan than other batteries. It is estimated that 80% and 20% of LIBs are used for small and large electronic devices, respectively. Additionally, in 2012, approximately 10,000 tons of LIBs were disposed of. This value has been increasing and was estimated to reach about 250,000 tons in 2020. It is expected to reach nearly 500,000 tons by 2025 due to increased use and demand for electric vehicles and energy storage systems [7].

Only up to 5% of LIBs are collected in Australia, the European Union, and the United States of America due to the lack of awareness of consumers and the constant reselling of electronic devices or batteries instead of recycling them. In addition, even the most developed and advanced countries in sustainability with recycling trends lack efficiency, safety, and transportation of disposed LIBs. Therefore, impactful improvements must be made to tackle this issue [7].

Significant environmental problems arise from using LIBs, as well as natural resource pressure and pollution from the exploration, extraction, and processing of metals that comprise the battery. The demand of heavy metals such as cobalt and nickel are expected to increase in the future for energy storage. Additionally, the disposal of LIBs is a major concern, which is why recycling processes, and the second life of these batteries are being studied and discussed in the renewable energy industry since approximately 90% of LIBs end up in landfills, making the materials impossible to recover for recycling purposes [8]. Lithium can be extracted in three different ways: (i) from hard rock, which is very common in Australia; (ii) from sedimentary rock, which is under development in the United States of America; and (iii) from the evaporation of brines, which is found beneath the salt flats on South America's Atacama Plateau.

In 2016, major concerns were raised in the lithium mine of Ganzizhou Rongda in Tibet. Protestors rallied together in Tagong, a nearby town, when the fish from the Liqi River, where these fishermen fish to provide food for their families and communities, were found dead from an outrageous toxic chemical leak from the lithium mine. Unfortunately, due to the high number of mining activities, this was not the only incident in this town in recent years; seven years prior, a similar accident occurred where fish and other livestock were found dead within the river [9]. Unfortunately, these catastrophic events do not solely occur in Tibet; they occur worldwide in many lithium mines where the proper procedures, equipment, and trained workforce are not considered when operating them [9].

There are high levels of unawareness amongst people on the importance of recycling batteries, as evidenced by the number of individuals who throw their batteries away. As mentioned, about 90% of batteries end up in landfills, and around 10% of the remaining batteries are recycled. Environmental specialists suggest recycling used batteries since one can recover the expensive materials in their composition. This can be reflected in the price fluctuation of nickel and cobalt, whose costly cathodes are used regularly. Therefore, considering that LIBs comprise high concentrations of lithium, nickel, manganese, and cobalt, if these materials are recycled, they can have the same benefits as natural ore [1].

Moreover, it is understood that recycling will decrease the electronic waste that is present in landfills nowadays. Countries such as the Democratic Republic of the Congo are responsible for approximately 50% of the cobalt used in batteries worldwide. Australia, Chile, Argentina, and Tibet are leading countries responsible for lithium mining. Situations such as environmental damage, social conflicts, and human rights abuse may be reduced by recycling batteries, consequently decreasing the dependency on these materials. Therefore, there will be an improvement in the security and safety of the mines, which will show benefits in the social and environmental impact that have been affected by the mines [1].

On the business side of recycling batteries, major companies with a high reputation and knowledge are developing and commercializing recycling processes to recover the waste materials in batteries to obtain the most value possible (Figure 2).

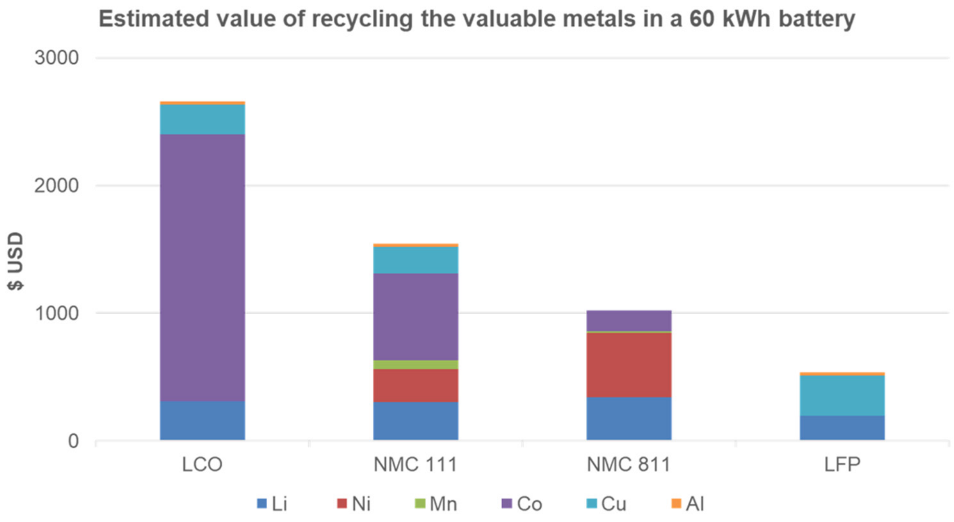

Figure 2. Estimated material value in a 60 kWh battery [10].

Currently, there are three main points to which LIBs are being sent at their end-of-life stage: previously mentioned landfills controlled by municipalities, waste-to-energy facilities, and recycling-focused facilities. The objective is to eliminate the first two destinations and solely utilize recycling facilities for every end-of-life (EOL) LIB. Different recycling processes for LIBs are now taking place and are under development. These recycling processes for LIBs have different unit operations. First, the battery must face deactivation, which is performed in the following three ways [11]:

- Discharge: reduces stored energy, preventing the activation of further reactions, hence reducing the hazardous level.
- Thermal treatment: all organic compounds of the battery cell are decomposed along with the volatilization of the electrolyte.
- Freezing electrolyte: the electrolyte is exposed to freezing conditions to prevent any electrochemical reaction and short circuits.

These unit operations can be divided into three treatment methods: mechanical, pyrometallurgical, and hydrometallurgical treatment [11].

In the mechanical treatment, battery cells or modules are first crushed to open them. The valuable materials are extracted, followed by classification and separation processes for the aluminum foil, copper foil, separator, and active electrode materials. Additionally, modules and battery cell castings are recovered alongside the connecting components.

In the pyrometallurgical treatment, many components from the battery cell are melted. Through this process, lithium and aluminum remain in the slag, while metals such as nickel, cobalt, and copper are recycled from the battery cell cast. However, an additional procedure is needed to recover the lithium, which is when hydrometallurgical treatment takes place.

The hydrometallurgical treatment consists of using aqueous chemistry to recover metals. It is used to recover lithium from the slag after the pyrometallurgical treatment and the separated electrode active material from the mechanical treatment. Moreover, this treatment includes the discharge of the main metals, extraction, and separation to recover the products from the separate streams by crystallization and precipitation.

In addition, safety regulations play a significant role in the life cycle of LIBs, especially during the collection, storage, and dismantling of each end-of-life LIB. However, in certain circumstances, mistreatment of the batteries may cause leakage of LIB components and thermal runaway, as it can catch on fire and result in an explosion.

4. Recycling/reusing LIBs

In this study, three different battery selections are analyzed to determine the most viable industry process for recycling LIBs. The three approaches are a recycled battery, a second-life battery, and the manufacturing of a new LIB. Different case studies and research papers were analyzed to gather the most crucial information to compare the different scenarios.

Referring to the prices per element can provide a better understanding of the costs and savings performed through the recycling process [12]. The recycling value can be calculated by adding different variables to a total of 26 €/kWh, with a recycling fee of 10 €/kWh. A recycling plant must operate for 320 days per year, 20 hours a day, and have a useful life span of 10 years. For example, American Manganese, which is a company in the USA that focuses on lithium recycling, states that nickel, manganese, and cobalt (NMC) batteries weigh approximately 7.3 kg/kWh, with materials ranging from 15 €/kg up to 95 €/kg. Thus, industrial recycling units are paid based on the type of battery being recycled. NMC batteries are expected to attain higher values, leading to higher demand for recycling, and generating an increased profit.

Electric vehicles are expected to continue their growth in sales, and their batteries have a life expectancy of eight to ten years, which is when they reach 80% of their original capacity, thereby no longer meeting the power range demand required by drivers. Therefore, second-life battery applications need to be considered to expand their life expectancy and usage, and reduce waste at the same time. These end-of-life LIBs can have a second life in applications such as residential and commercial energy storage, grid stabilization, portable energy storage, and powertrains for low-speed vehicles, among others [13].

In addition, a report by the Global Battery Alliance in 2018 mentioned that the selling price of the second-life battery ranges from 60 € to 300 €/kWh. They projected a price drop in 2030 to 43 €/kWh selling price. Moreover, it is estimated that the break-even point is achieved if a second-life battery is 60% cheaper than a new LIB. However, second-life batteries are more economically favorable in specific applications if the system depends on a 50% depth of discharge (DOD), signifying the capacity left on the battery, and is competitive with new lead-acid batteries [14].

In 2010, the average price of a lithium-ion electric vehicle battery pack was 1,200 €/kWh, decreasing to 132 €/kWh in 2021, which is an 89% price drop within eleven years. In addition, the cost of manufacturing a new lithium-ion EV battery cell component breakdown is shown in Table 1. The largest electric vehicle battery manufacturers have headquarters in Asia, and 80% of all cell manufacturing occurs in China [15].

Table 1. Typical cost breakdown of EV battery cell components [15].

EV battery cell component	Cost (%)
Cathode	51
Manufacturing and depreciation	23
Anode	12
Separator	7
Electrolyte	4
Housing and other materials	3

Renewable energy generation needs to be considered when analyzing batteries, since the excess of renewable energy will be stored in the batteries. For this purpose, photovoltaic solar panels need to be considered. Stand-alone systems have increased worldwide, specifically across the United States, Europe, and Asia. This is due to the benefits of reducing your electricity bill, due to generating and consuming your own energy, helping to fight climate change, and tax break benefits. A common household typically needs 20 to 24 solar panels to cover over 100% of the electricity consumption. This gives the homeowner an estimated annual production of approximately 12,800 kWh.

5. Economic analysis

Before proceeding with the economic analysis, it is essential to define the most relevant parameter used in such analysis. The NPV is the difference between the cash value inflows and outflows at present, as well as over a period of time (Eq 1), in months or, most typically, in years. NPV is mainly used in capital budgeting and investment planning to analyze how profitable a project or investment can be. Additionally, the NPV results from the present value of future payments [16], where R_t is the net cash inflow–outflows (including the investment) during a single period t, i is the discount rate, and t is the number of periods:

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

Therefore, the NPV can inform one about the time value of money and can be used to compare similar investment alternatives, such as recycling batteries, second-life batteries, and manufacturing new batteries. NPV depends on a discount rate from the cost of the capital required for the project or investment. Moreover, if an NPV is negative, the project or investment must be discarded [16]. This work considers the electricity generated and stored during the project's lifetime. Then, the investment cost will need to be deducted to obtain the total NPV value. This investment cost is the sum of the solar panels' system plus the cost of the type of battery being analyzed, either recycled, second-life, or a new LIB. The net cash inflow-outflow, R_t, is calculated by multiplying the price of electricity in €/kWh by the capacity of the specific project analyzed and deducting the investment costs for the solar panels and batteries, resulting in the total savings in €.

The discount rate, which is equal to the weighted average cost of capital (WACC), is a combination of the cost of capital from all possible sources, including debt, preferred shares, and common shares (Eq 2):

$$\mathrm{WACC} = \frac{\mathrm{E}}{\mathrm{V}} \times \mathrm{R_e} + (\frac{\mathrm{D}}{\mathrm{V}} \times \mathrm{R_d} \times (1 - \mathrm{T})) \tag{2}$$

where E is the market value of the company's equity, D is the market value of the company's debt, V is the capital value, E/V is the percentage of capital that is in equity, D/V is the percentage of capital that is in debt, R_e is the cost of equity, R_d is the cost of debt, and T is the tax rate.

5.1. Equivalent Annual Cost (EAC)

The EAC is the annual cost of owning, maintaining, and operating the LIB for its lifetime. This method allows companies to compare the cost-effectiveness of many assets with different lifespans. Other companies use EAC by calculating the optimal life of an asset, such as a battery in this case, to determine the best option between buying or renting, how the maintenance cost will impact the battery, the necessary cost savings by purchasing a new battery, and choosing the cost of keeping the existing one [17].

Additionally, the cost of capital is the required return needed to make a budgeting project, such as building a new factory, or in this case, the most viable recycling method for a LIB. It also includes the cost of debt and equity. The lower the EAC value, the better the project is. The formula to calculate the EAC is given by Eq 3 [17]:

$$\mathrm{EAC} = \frac{\mathrm{NPV} \times \mathrm{i}}{1-(1+\mathrm{i})^{-\mathrm{n}}} \tag{3}$$

where NPV is the net present value, i is the discount rate (which equals the WACC), and n is the number of periods.

5.2. Annuity factor

There is a relationship between the NPV and EAC, since, considering the cost of capital and the number of years, the EAC is equal to the NPV divided by the annuity factor. Thus, the annuity factor is given by Eq 4 [17]:

$$\text{Annuity Factor} = \frac{1-\frac{1}{(1+\mathrm{i})^{\mathrm{n}}}}{\mathrm{i}} \tag{4}$$

In addition, this section compares the findings of residential storage, commercial storage, and solar farm storage applications. Moreover, the assumptions taken throughout the analysis process will be explained. A LIB with a capacity of 65 kWh was analyzed for the residential storage. The project at the Johan Cruyff Arena in Amsterdam of 2.8 MWh was used as a reference for the commercial storage.

Lastly, the project Tomatoh Abira Solar Park 2, which consisted of a 64.6 MW solar farm with a 19 MWh battery energy storage capacity, was used as a reference for the solar farm storage. The comparison between each application was analyzed by calculating the NPV for the residential storage project considering a solar panel installation. On the other hand, the EAC analysis was performed to compare each project, not just the residential one [18,19].

5.3. Recycled battery analysis

The unit prices of the recovered materials from recycling batteries are shown in Table 2. The cost distribution per weight of a 1 kWh battery weighing 9 kg is shown in Table 3. In addition, the price of a new battery from recycled materials is obtained by multiplying the percentage from Table 1 by the weight distribution of the battery composition. Thus, Table 3 also shows the unit cost per kg, which would be the product between the cost distribution for a 9 kg battery in Table 3 and the unit cost of the battery materials from Table 2. Given the unit prices of what makes the battery, the result of the manufacturing unit cost is 15.9 €/kg [20,21].

Table 2. Battery materials unit costs [21].

Material	Unit cost (€/kg)
Aluminum	1.3
Plastics	0.1
LMO	10
Electrolyte	0.15
Graphite	0.28

Table 3. Cost distribution and unit cost of the material for a new battery [20,21].

	Cost distribution for a 9 kg battery	Unit cost (€/kg)
Cathode	4.6	10
Manufacturing	2.1	15.9
Anode	1.1	0.28
Separator	0.6	0.1
Electrolyte	0.4	0.15
Battery housing	0.3	1.3

Therefore, given that 1 kWh is 9 kg, to calculate the price of the recycled battery for each of the applications studied for this analysis, after collecting the weight of the battery for each application, the total price was 4,730 €, 203,715 €, and 1,382,355 € for the residential storage, Johan Cruyff Arena, and Solar Farm applications, respectively.

5.4. Second-life battery analysis

Given that the range of price for a second-life LIB is 40–160 €/kWh, a 65 €/kWh price was chosen to calculate the price of a second-life LIB for each application because of the kind of battery that would be recovered to use as a second life.

Hence, the total price of the second-life battery will be the multiplication of the battery price (€/kWh) by the capacity (kWh). Therefore, the total price for the residential storage, Johan Cruyff Arena, and solar farm projects was 4,225 €, 182,000 €, and 1,235,000 €, respectively, for the price of the second-life battery.

5.5. New LIB analysis

The same procedure as the second-life LIB was performed for the new LIB analysis, where the price of a new LIB is 132 €/kWh, which correlates to the difference in price between a new LIB and a second-life one, which shows a 47% difference in price. There is a 51% difference in price between 65 €/kWh and 132 €/kWh, as chosen for the analysis, and this difference is close enough to the market. Moreover, the same calculation for the total price of a new LIB was carried out for the second-life battery. Therefore, the total cost for the residential storage, Johan Cruyff Arena, and solar farm projects were 8,580 €, 369,600 €, and 2,508,000 €, respectively.

5.6. PV solar panels

A typical stand-alone system comprises 20 to 24 solar panels, providing an estimated annual production of 12,800 kWh. Considering these parameters, the system would cost 9,250 €, considering installation, inverters, cabling, and other costs.

Furthermore, the aforementioned information and equations were sufficient to perform an economic analysis by calculating both the NPV and EAC for the three different kinds of batteries, and for the three different projects in the case of the EAC analysis.

First, the NPV of the solar panels was calculated for a 20-year system considering a yearly degradation of the solar panels of 0.6%. The cost of electricity is 0.24 €/kWh, which is assumed to increase by 2% for the first five years and then remain stagnant for the remainder of the project's lifetime. The cash flows will be the savings created by both the generation from the photovoltaic system in the house and the energy stored in the battery that will be consumed at night; hence, the energy used from the battery (rather than buying it from the grid) will account as savings. In the solar panels' case, these savings are calculated by multiplying the generation of electricity in kWh by the price of electricity in €/kWh; for the battery, it would be the same process but multiplying the capacity of the battery by the cost of electricity, resulting in a value in euros. Moreover, as previously mentioned, the discount rate equals the WACC, which results in 5.8%.

Table 4. Residential storage NPV results.

	Recycled battery	Second-life battery	New LIB
Total system cost (€)	13,980	13,475	17,830
Years	NPV (€)	NPV (€)	NPV (€)
10	30,317.1	30,504.8	26,625.8
15	51,524.3	51,511.7	47,933.1
20	71,857.7	71,644.8	68,366.6

The batteries' yearly degradation depends on the type of battery: 2% for a recycled battery, 2.5% for a second-life battery, and 1.5% for a new LIB, affecting the total energy storage capacity. Then, after having calculated the discount factor and the entire savings from both the stand-alone photovoltaic system and the battery, the only step left would be to add both the cost of the PV system and the cost of the type of battery to be subtracted from the NPV. Table 4 shows the NPV calculation results for the residential storage project with a recycled, second-life, and new LIB.

After analyzing the NPV results, the recycled battery and the second-life battery are the best options for this kind of project since they provide the greatest value and have the highest NPV. Furthermore, among all projects, the second-life battery is the project that adds the greatest value for residential storage use, with a stand-alone PV system with 24 solar panels producing an estimated 12,800 kWh yearly, only for the first ten years. For an application longer than ten years, the recycled battery becomes the best option, and the margin of difference between the two becomes more significant as the years go by.

Lastly, to complete the analysis, the EAC results must be compared to determine the most viable industrial process for each application, given that they have different demands. The first step would be to calculate the annuity factor for the different years of the application, and the result is shown in Table 5.

Table 5. Annuity factor.

Life span (yrs.)	Annuity factor
10	7.57
15	10.10
20	12.05

Hence, to calculate the EAC of each project for the different types of LIB batteries, it is necessary to consider the battery cost, which was previously shown for each type and project size, and divide it by the annuity factor for the different years during the life span. Table 6 shows the results for the recycled battery, second-life battery, and new LIB.

Table 6. EAC results (in €) for a recycled battery, a second-life battery, and a new LIB applied to three scenarios over three different life spans (in years).

	Life span (years)	Residential storage	Johan Cruyff arena	Solar farm
Recycled battery	10	624.51	26,896.93	182,515.31
	15	468.10	20,160.57	136,804.20
	20	392.53	16,905.58	114,716.73
Second-life battery	10	557.84	24,029.85	163,059.71
	15	418.13	18,011.56	122,221.28
	20	350.62	15,103.53	102,488.26
New LIB	10	1,132.84	48,799.08	331,136.65
	15	849.12	36,577.31	248,203.21
	20	712.02	30,671.79	208,130.00

As seen above, across every project, and even at the longest lifetime of 20 years, the second-life battery has the lowest EAC value, suggesting this type of battery as the most viable industrial application. However, considering that not every battery has the same lifespan, and 20 years may be too long, a recycled battery could be a better option. A recycled battery would last longer than a second-life battery for a 20-year project. In fact, a second-life battery could only last for 15 years, making the recycled battery a more viable application due to its lower EAC.

6. Conclusions

In this study, three projects were analyzed: residential, commercial, and solar farm storage. Within each project, three different applications were considered: recycling, second life, and new LIBs. The work conducted an NPV analysis of the residential storage project, considering the installation of solar panels. Additionally, an EAC was calculated for every type of battery and all three projects at different years of their 20-year lifespan.

The NPV showed an increased value when adding a recycled or a second-life battery for the residential project. However, out of the two best options for a scenario of 24 solar panels generating an estimated 12,800 kWh/year, the second-life battery only had the highest NPV for a 10-year lifetime project. Still, a recycled battery had a higher NPV for projects with longer lifetimes, making it a better option for residential storage over a 10-year lifetime. The difference kept increasing as the project requested higher lifetimes.

Furthermore, the EAC of residential, commercial, and solar farm storage was also analyzed and followed the same result as the NPV. In this type of analysis, the recycled and second-life batteries were the most promising, with the second-life battery having the lowest EAC value, making it the most viable process for each project. However, with technological advances and considering that not every battery has the same lifetime cycles, a recycled battery will have the edge over a second-life battery when the latter cannot provide a longer lifetime, resulting in the recycled battery having a lower EAC.

In conclusion, adding either a recycled or second-life battery to a house for energy storage with an existing solar system installed is a good investment since the NPV result is positive. Considering the technology improvements, that a recycled battery will potentially have a lower EAC than a second-life battery, and that a recycled battery already has a greater NPV for more than 10-year lifespan projects, it can be concluded that battery recycling is a more viable industrial process.

In the upcoming years, the battery passport is expected to be further implemented throughout the European Union (and the rest of the World), thereby providing a more efficient recycling process and improved data gathering regarding the battery status. Additionally, technological advances are expected to increase over the years, thereby improving recycling methods and reducing carbon footprint. The data show that recycling batteries will overtake second-life batteries. New batteries are the most optimal and viable industrial process since consumers already use most lithium supplies. Hence, along with technological advances, when people become aware and successful collection programs are implemented, one can expect a 100% recycled LIB and a fully circular value chain.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Diogo M.F. Santos is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article. All authors declare no conflict of interest.

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