Recycling Lithium Batteries, a viable industrial process

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December 2022

Abstract

Recycling lithium-ion batteries or finding a second life for any spent battery is a growing industry in renewables due to its environmental and economic benefits. Also, with the exponential growth in demand and supply of electric vehicles, renewable energy generation and storage are factors of the growing waste management of lithium batteries. The report presented aims to introduce the various recycling battery methods, with their benefits and economic advantages and disadvantages, as well as for second-life battery applications. In addition, different reports and case studies were studied to know the number of materials that can be recovered and the efficiency of the method applied through the recycling process.

Finally, three projects are analyzed, which are residential, commercial, and solar farm storage, the goal of the analysis is to calculate and compare the Net Present Value for the residential storage project, and the Equivalent Annual Cost of each project, to know which is the most viable industrial process within those parameters. The analysis demonstrated that the second-life battery project would be the one with the lowest Equivalent Annual Cost, making it the most viable industrial process out of the three. In addition, it presents the higher Net Present Value for the first 10 years of the project, but for the remainder of the 30-year project, the recycled battery shows the most Net Present Value.

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

1. Introduction

Lithium batteries have become the go-to technology when it comes to energy storage in the past few years due to their efficiency and capabilities to perform through a range of different applications. They are mostly found in laptops, electric vehicles, residential storage, and others. This thesis report provides a more in-depth explanation regarding lithium battery technologies, advantages, disadvantages, waste management, and environmental issues. Also, a brief explanation of the sources of lithium can be found together with the countries with the largest lithium reserves.

In addition, recycling methods are thoroughly explained for both steps during the pre-treatment of the lithium battery, and the actual treatment through recycling. Therefore, the report offers extended understanding during the pre-treatment phase of processes like sorting, dismantling, and discharging, pyrolysis deactivation, and mechanical separation. Also, through the treatment process, methods like thermal treatment, pyrometallurgy, hydrometallurgy, and electrochemical extraction are provided. 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 recycling or reused [1].

Furthermore, the possibilities and benefits of giving lithium batteries a second life is also explained since a lithium battery reaches its end-of-life when its capacity reaches 80%. However, it can still be used for energy storage in stationary applications, as analyzed in this report [1]. The European Union has been insisting on a battery passport for every battery in the market, and it will be a requirement for new manufacturers. The objective behind this is to understand what the battery has been through and how efficient and the status of the materials within them, to improve the recycling process, all of which will be provided through blockchain technology [2].

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

Lastly, three projects were analysed to determine and compare the most viable industrial process. These projects are residential, commercial, and industrial storage, comparing them between using recycling, second life, or new lithium batteries for their energy storage. Finally, a conclusion of the most viable industrial process is provided by calculating and comparing the Net Present Value of the residential storage project, and the Equivalent Annual Cost of all three projects.

2. Development

To know a viable industry process on recycling lithium batteries, three different battery selections are studied in this dissertation. The batteries are, a recycled battery, a second-life battery, and manufacturing a new lithium battery. Different case studies and theoretical papers were analysed to gather the most crucial information to compare the different scenarios.

a. Recycled Lithium Battery

Taking a reference in the prices per element can give a better understanding of the costs and savings performed through the recycling process [3]. The recycling value can be calculated by adding up different variables, adding up 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 has a useful life span of 10 years. For example, American Manganese, a company focusing on lithium recycling in the USA, states that nickel, manganese, and cobalt (NMC) batteries weigh approximately 7.3 kg/kWh, with materials ranging from €15/kg up to €95/kg. Depending on the type of battery recyclers are paid to recycle a specific battery, it is expected that NMC batteries have higher values, are purchased to be recycled, and can create more profit.

b. Second-life battery

Electric vehicles are expected to continue their growth in sales, and their batteries have a life expectancy of 8 to 10 years, which is when they reach 80% of their original capacity, hence no longer meeting the power range demand required by drivers. Therefore, second-life battery application needs to be taken into consideration to expand their life expectancy and usage, and at the same time, reduce waste. These end-of-life lithium batteries can have a second-life battery in applications life, residential and commercial energy storage, grid stabilization, portable energy storage, powertrains for low-speed vehicles, and others [4].

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 per kilowatt-hour, and they projected a price drop in 2030 to €43/kWh selling price. Also, it is estimated that the break-even point is achieved if a second-life battery is 60% cheaper than a new lithium battery. However, in certain applications, second-life batteries are more economically favourable if the system is dependent on 50% depth of discharge (DOD), which means the capacity left on the battery, and competitive with new lead-acid batteries [5].

c. New Lithium Battery

Back in 2010, the average price of a lithium-ion electric vehicle battery pack was €1,200 per kilowatt-hour, decreasing to €132 per kilowatt-hour in 2021, which is a price drop of 89% 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 takes place in China [6].

Table 1. EV battery cell component [6].

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

d. PV Solar Panels

Stand-alone systems have been increasing worldwide, specifically across the United States of America, Europe, and Asia. Due to the benefits of reducing your electricity bill, benefiting from generating and consuming your own energy, helping the fight again climate change, and tax break benefits.

A common household typically needs between 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.

e. Net Present Value (NPV)

Net present value (NPV) is the difference between cash value of inflows at the present and the cash value of outflows at present, as well as over a period of time, in months or years, most typically years. The main use of net present value is in capital budgeting and investment planning to analyse how profitable a project can be or the investment. Also, the NPV results from the present value of future payments [7].

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \qquad \text{Equation 1}$$

Where;

R_t: net cash inflow – outflows during a single period *t.*

i : discount rate

t : number of periods

Therefore, NPV can let you know the time value of money and used to compare similar investment alternatives, like recycling batteries, second-life batteries, and manufacturing new batteries. NPV depends on a discount rate that comes from the cost of the capital required for the project or investment. Also, if a NPV is negative, the project or investment must be discarded [7].

This thesis report considers both the electricity generated and the electricity stored during the project's lifetime. Then, the investment cost will need to be deducted to get the total NPV value. This investment cost is the sum of the solar panels' system plus the cost of the type of battery that is being analyzed, either recycled, second-life, or a new lithium battery. The net cash inflow-outflow (R_t) is calculated by multiplying the price of electricity in €/kWh times the capacity of the specific project analysed and deducting the investment costs in solar panels and battery, 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. The formula is the following:

$$WACC = \frac{E}{V} \times Re + \left(\left(\frac{D}{V} \times Rd\right) \times (1 - T)\right) \qquad \text{Equation 2}$$

Where;

E : market value of company's equity

D : market value of company's debt

V : value of capital

$\frac{E}{V}$: percentage of capital that is equity

$\frac{D}{V}$: percentage of capital that is debt

Re : cost of equity

Rd : cost of debt

T : tax rate

f. Equivalent Annual Cost (EAC)

The equivalent annual cost (EAC) is the annual cost of owning, maintaining, and operating the lithium-ion battery for its lifetime. This method allows companies to compare the cost-effectiveness of many assets with different lifespans. Other companies use equivalent annual cost by calculating the optimal life of an asset, in this case a battery, 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 determining the cost of keeping the existing one [8].

Also, the cost of capital is the required return needed to make a budgeting project, like building a new factory, or in this case, the most viable recycling method for a lithium battery. It also includes the cost of debt and equity. The lower the EAC value, the better the project is. The formula to calculate equivalent annual cost is the following [8]:

$$EAC = \frac{AP \times i}{1-(1+i)^{-n}} \qquad \textit{Equation 3}$$

where;

AP : asset price

i : discount rate

n : number of periods

Furthermore, as explained before in the NPV, the asset price (AP) is the total cost of the battery, divided by the annuity, which is shown further along the report, giving the result in €. Also, the discount rate would be the same as explained in the NPV above, which equals the WACC.

In addition, there is a relationship between net present value and equivalent annual cost, since the equivalent annual cost is equal to the net present value divided by the annuity factor, considering the cost of capital and the number of years. The annuity factor formula is the following [8]:

$$Annuity\ Factor = \frac{1-\frac{1}{(1+r)^t}}{r} \qquad \textit{Equation 4}$$

Where;

r : discount rate

t : number of periods

3. Results

This section compares the findings of residential storage, commercial storage, and solar farm storage applications. Also, the assumptions taken throughout the analysis process will be explained. For residential storage, a lithium battery with a capacity of 65 kWh was analysed. The project at the Johan Cruyff Arena in Amsterdam of 2.8 MWh was used as a reference for commercial storage. Lastly, for the solar farm storage, the project called Tomatoh Abira Solar Park 2, which consists of a 64.6 MW solar farm with 19 MWh battery energy storage capacity, was used as a reference. The comparison between each application was analysed through calculating the NPV for only the residential storage project taking into account the solar panel installation, and for the Equivalent Annual Cost a comparison between each project [9] [10].

a. Recycled Battery analysis

The cost distribution per weight would be the one shown in Table 3, knowing that a 1 kWh battery weighs 9 kg [11].

Table 2. Distribution of material costs of a battery in kilograms *[11]*.

Description	Cost distribution for a 9 kg battery
Cathode	4.6
Manufacturing	2.1
Anode	1.1
Separator	0.6
Electrolyte	0.4
Battery housing	0.3

The unit prices of the recovered materials from recycling batteries are shown in Table 3. The price of a new battery from recycled materials is shown in

Table 4 below by multiplying the unit price times the weight distribution of what makes the battery, as shown in Table 2. Given the unit prices of what makes the battery, to get the manufacturing unit cost results to 15.9 €/kg [12].

Table 3. Battery materials unit costs *[12]*.

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

Table 4. Unit cost of the material distribution for a new battery *[12]*.

Description	Unit cost (€/kg)
Cathode	10
Manufacturing	15.9
Anode	0.28
Separator	0.1
Electrolyte	0.15
Battery housing	1.3

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

b. Second Life Battery analysis

Given that the range of price for second-life lithium battery is 40-160 €/kWh, a 65 €/kWh price was chosen to calculate the price of second-life lithium battery for each application, because of the kind of battery that would be recovered to use as a second life to keep the same market difference as the new lithium-ion battery for this analysis. 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 came up to a total of € 4,225, € 182,000, and € 1,235,000, respectively, for the price of the second-life battery.

c. New Lithium Battery analysis

The same procedure as for second-life lithium battery was performed for the new lithium battery analysis given that the price of a new lithium battery is 132 €/kWh, as previously mentioned in Chapter 3, which correlates to the difference in price between a new lithium battery and a second life one displayed in the full thesis report, 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 the difference is close enough to the market. Also, the same calculation for the total price of a new lithium battery was carried out for the second-life battery. Therefore, the total cost for the residential storage, Johan Cruyff Arena, and solar farm projects came up to a total of 8,580 €, 369,600 €, and 2,508,000 €, respectively.

d. PV Solar Panels

A typical stand-alone system consists of 20 to 24 solar panels providing an estimated annual production of 12,800 kWh. Considering these parameters, the total system will cost 9,250 €, taking into account installation, inverters, cabling, and any other cost.

e. Net Present Value results

Firstly, the NPV of the solar panels was calculated for a 30-year system taking into account a yearly degradation of the solar panels of 0.6%. The cost of electricity is 0.24 €/kWh, which is assumed to increase 2% for the first 5 years and then stays 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 that amount that is used from the battery rather than buying it from the grid will also account as savings. These savings are calculated by the multiplication of the generation of electricity in kWh times the price of electricity in €/kWh in the solar panels' case, and for the battery would be the same process but multiplying the capacity of the battery times the cost of electricity, everything resulting in euros. Also, as previously mentioned, the discount rate is equal to WACC, which results in 5.8%.

The degradation of the batteries varies depending on the type of battery, 2% yearly for a recycled battery, 2.5% for a second-life battery, and 1.5% for a new lithium battery, affecting the total energy storage capacity. Then, after having calculated the entire savings from both the stand-alone photovoltaic system and the battery, the discount factor, the only step left would be to add both the cost of the PV system plus the cost of the type of battery to be subtracted from the NPV results for a complete NPV value.

Table *5* below shows the NPV calculation results for the residential storage project with a recycled battery, second life battery, and new lithium battery.

Table 5. Residential Storage NPV results

	PV with Recycled Battery	**PV with Second Life Battery**	**PV with New Lithium Battery**
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
25	91,317.3	90,904.2	87,926.3
30	109,903	109,289	106,612

After analysing the NPV results, it can be found that the recycled battery and second-life battery are the best options for this kind of project, since they provide the most value and have the highest NPV. Furthermore, between all projects, the second-life battery is the one that adds the most 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 10 years. For an application longer than that, recycled battery becomes the best option, and the margin of difference between the two becomes greater as the years go by.

f. Equivalent Annual Cost results

Lastly, to complete the analysis, the Equivalent Annual Cost 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 *6*.

Table 6. Annuity factor.

Life span (yrs.)	Annuity Factor
10	7.57
15	10.10
20	12.05
25	13.55
30	14.69

Hence, to calculate the EAC of each project for the different type of battery, it is needed to take the cost of the battery, which was previously shown for every type of battery and project size and divide it by the annuity factor for the different years during the life span. Table 7, Table 8, and Table 9 show the results below for the recycled battery, second-life battery, and new lithium battery, respectively.

Table 7. EAC result of Recycled Battery (€).

	EAC of Recycled Battery (€)		
Life span (yrs.)	Residential Storage	Johan Cruyff Arena	Solar Farm
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
25	349.18	15,038.94	102,050.20
30	321.86	13,862.25	94,065.51

Table 8. EAC result of Second Life Battery (€).

	EAC of Second life Battery (€)		
Life span (yrs.)	Residential Storage	Johan Cruyff Arena	Solar Farm
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
25	311.90	13,435.87	91,171.95
30	287.50	12,384.61	84,038.40

Table 9. EAC result of New Lithium Battery (€).

	EAC of New Lithium Battery (€)		
Life span (yrs.)	Residential Storage	Johan Cruyff Arena	Solar Farm
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
25	633.41	27,285.14	185,149.19
30	583.85	25,150.28	170,662.60

As seen above, across every project, and even at the latest lifetime, of 30 years, the second-life battery has the lowest EAC value, making this type of battery the most viable industrial application. However, understanding that not every battery has the same lifespan, and 30 years may be too long, a recycled battery could be a better option depending on the project's lifetime. Since a recycled battery would last longer than a second life for a 20-year project, whereas a second-life battery could only last 15, a recycled battery has a lower Equivalent Annual Cost in that scenario, making it a more viable application.

4. Conclusions

Improving the recycling methods, reuse, and manufacturing of batteries are essential to decrease lithium battery waste. The increase in investment and development of recycling technologies represents an excellent opportunity to reduce the carbon footprint from manufacturing new lithium batteries and offer a sustainable solution to dispose of batteries. In addition, given that only 10% of lithium batteries are recycled, improving recycling methods and finding solutions for reuse or refurbishing is a great opportunity for a more sustainable world and a business opportunity at the commercial and industrial level.

Three projects were analysed in this thesis report; these were residential, commercial, and solar farm storage. Within each project, three different applications were considered, recycle, second life, and new lithium battery. In addition, the analysis was completed by conducting a Net Present Value analysis of the residential storage project, considering the installation of solar panels. Also, an Equivalent Annual Cost was calculated for every type of battery and all three projects at different years of their 30 years lifespan.

The NPV results showed an increase in value when adding either a recycled battery or a second-life battery for the residential project. However, out of the two best options, for this kind of project with the same scenario of 24 solar panels generating an estimated 12,800 kWh/year, the second-life battery had the higher NPV for a 10-year lifetime project only. Still, for a project with a longer lifetime a recycled battery has a higher NPV making it a better option for residential storage with a lifetime longer than 10 years. The difference in value kept becoming higher and higher as the project requested a higher lifetime.

Furthermore, the EAC of residential, commercial, and solar farm storage was also analyzed and followed the same result as for the NPV. The recycled and second-life batteries showed the most prospect, although the second-life battery has the lowest EAC value, making it the most viable process for each project. However, expecting that with technology advances and understanding that not every battery has the same lifetime cycles, a recycled battery will have the edge over the second life battery, when the latter cannot provide a long lifetime, resulting in the recycled battery having the lower EAC value in that scenario where it can have a longer life cycle.

In conclusion, adding 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. However, the most viable industrial process among the projects studied in this dissertation is the second-life battery, because this application has the lowest Equivalent Annual Cost.

In the upcoming years, the battery passport is expected to be implemented more throughout the European Union and the World, providing a more efficient recycling process and better data gathering regarding the status of the battery. Also, technological advances are expected to increase over the years, improving recycling methods and reducing carbon footprint. The data and research show that recycling batteries will overtake second-life batteries, and new batteries, as the most optimal and viable industrial process, since consumers are already using most of the lithium supply. Hence, when people become aware and successful collection programs are implemented, along with technological advances, we could have a 100% recycled lithium battery and a full circular value chain.

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