MSc Program
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A bet on electrification. Challenges, insights and opportunities in the end of life management of li-ion electric vehicle batteries

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **B.A. FELIX TIMMER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A BET ON ELECTRIFICATION. CHALLENGES, INSIGHTS AND OPPORTUNITIES IN THE END OF LIFE MANAGEMENT OF LI-ION ELECTRIC VEHICLE BATTERIES", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 20.04.2022

Signature

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"If future generations are to remember us more with gratitude than sorrow, we must achieve more than just the miracles of technology. We must also leave them a glimpse of the world as it was created, not just as it looked when we got through with it."

- Lyndon B. Johnson, Former President of the United States of America

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Abstract

Electrification is set to change mobility as we know it. Governments have pursued legislative changes to enhance the prospect of climate neutrality. This change, is primarily facilitated through the employment of electric vehicles, which run on li-ion batteries. These circumstances will result in unprecedented volumes of retired li-ion batteries. Consequently, the recycling industry will have to adapt.

This investigation initially focuses on providing a macro outlook on how li-ion batteries work, if they have a future and what this incremental change in mobility means in regard to total CO2 emissions. The investigation especially focuses on the end of life management of li-ion batteries. A field worth investigating since, on average li-ion batteries have a lifetime expectancy of 7 – 10 years, before losing some of their capacity output, deeming them redundant for electric vehicles as the already limited kilometer reach will be reduced.

Furthermore, this investigation will explore the notion of repurposing li-ion batteries and the challenges and obstacles revolving around establishing a second life for the battery. Economic aspects of both recycling and repurposing will be explored to shed light on the viability of such processes. Specifically the investigation will analyze direct recycling methods and hydrometallurgical recycling methods.

This investigation relies on proving or disproving three hypotheses, with the aim of providing a sound understanding of end of life management in regard to li-ion batteries. Ultimately aiming at formulating the ground work in regard to the crucial and important aspect of establishing a circular economy within the EV battery market, through optimization in end of life management.

Theoretical Framework

Before indulging into details and concise empirical evidence, it is important to understand the theory behind this thesis, its core claims and hypothesis.

I argue that in order to appropriate the claims of climate neutral mobility through electrification it is necessary to expand immensely in the end of life management of EV batteries and their subsequent component reuse, I further argue that due to micro and macro externalities there will be a profitable business opportunity in the recycling market. This is due to the fact that we are shaping the mobility industry toward the direction of general electrification with the aim of decreasing the per capita CO2 output within Europe at a rapid rate, especially through directives and regulations from the head of the European Union. (Rendal, 2020)

Regarding the projected increased volumes of EV battery production I argue that the status quo of ion lithium recycling is not close to the capacity we will need it to be in the coming years, it is therefore important to expand on the topic of end of life management. This is further supported by the fact that there is no homogenous recycling process that offers both efficient and economical viability in dismantling and reusing e waste. This has pushed many modern nations to ethically questionable decisions, which this investigation will also provide an understanding too. Furthermore, Political decisions are forcing the Automotive market to respond with more climate neutral and efficient mobility solutions. It is significant to look at the political directives and regulations from a regional (European) yet also domestic approach in order to provide a sound understanding of the topic.

End of life management is a crucial step to consider when implementing electrification directives, primarily due to two reasons; 1. We only have a limited amount of resources on the planet to appropriate an electrification of mobility, especially considering Ion-Lithium and Cobalt. 2. We have a moral obligation and a judicial obligation to ensure a circular economy, since the status quo at the moment displays grievous mismanagement of products (that reach their end of life time cycle. In order to sum up the theoretical framework I would like to refer to the quote by Matthew Gandy in his book “recycling and the politics of urban waste he states that:

“Recycling is more than just a response to the environmental crisis and has assumed a symbolic role in beginning to change the nature of western societies and the culture of consumerism. Indeed many environmentalists assume that there will be an inevitable shift from our "throwaway" society to a post-industrial "recycling" society of the future.” (Gandy, 1994)

This quote goes beyond the scope of this thesis yet invokes overlapping aptitudes since it tackles the focus of end of life management which is to change the fundamental consumerist attitude the world has come to accept. Rather than push for the continuation of the “throwaway society” we have to set core principals to facilitate a circular economy approach and ensure proper recycling in all industries. I argue that although many industries have been optimized to fit a circular economy principle. Ion lithium recycling has yet to do some catching up.

This thesis will be broken down into two primary sections. Initially I will conduct an investigation into the current status quo of ion lithium recycling, I will analyze the industry and will indulge on the primitive argument of repurpose vs reuse, and ultimately concoct a conclusion to why reuse is necessary. Furthermore I will provide an insight into what recycling methods are most suitable in regard to ion-lithium recycling as there seems to be no homogenous method. After having established an understanding into how to recycle and the current status quo of the industry, the thesis will follow to its second section which is the iteration of a business case in regard to the opportunity connected to the young and niche industry of ion-lithium recycling in the context of EV batteries in Europe.

Having established that Ion lithium EV recycling is a relevant topic to explore, with its connected issues related to end of life management and the establishing of a circular economy, I will now present my underlying Hypothesis.

Hypothesis 1:

Repurposing of Electric vehicle batteries will only work if the industry creates a viable tracking framework revolving around metrics such as; quality, energy density, chemical compositon.

Hypothesis 2:

The reuse (Recycling) of EV batteries and their subsequent components will be inevitable. Hydrometallurgical recycling in combination with Direct recycling will be key to facilitate a economically viable framework

Hypothesis 3:

There will be an opportunity to establish a sound and reliable business case in regard to EV end of life management within the European union.

Methodology / Research Design

To test these hypothesis, the paper will start by elaborating on the status quo of lithium ion EV batteries. Initially it will be important to understand how EV li-ion batteries are made, what components they encapsulate and what different kinds of batteries there is, and wether this is a challenge to the end of life management in regard to li-ion batteries. It is also worth investigating the yearly production of li-ion batteries and their projected production cycles in the future, as this will allow an understanding of the gravity and importance of implementing a professional and efficient end of life management. Henceforth, the literature review will also focus on iterating an understanding of two recycling processes; hydro and direct, each one will be evaluated in order to ensure the reader with an understanding of the advantages and disadvantages of each. This section is critical to the sustenance of this investigation, since the basis of the hypothesis argument that, ultimately in the life cycle of a EV li-ion battery it will be necessary to reuse the materials in order to facilitate an ethical and efficient circular economy. I argue that the current status quo (capacity) of recycling li-ion is far away from where it needs to be. Furthermore, I argue that the ethics of electrification in general are questionable if we ascertain the notion that the industry will remain at its current state. The paper will then analyze the status quo of the current end of life management of EV batteries in order to shed light on the fallacies of electrification.

Methodology for Hypothesis 1:

Repurposing of Electric vehicle batteries will only work if the industry creates a viable tracking framework revolving around metrics such as; quality, energy density, Cost.

To achieve sound understanding of the arguments underlying the repurposing of EV batteries it is of grave importance to understand key metrics within the li-ion EV market as the repurposing of li-ion requires knowledge of the condition, kind, and capacity output of the battery. As repurposing a EV battery can be cost extensive and time contingent. It is important to investigate how batteries can be repurposed, and what limitations are set when repurposing batteries, furthermore it is important to question whether the repurposing of batteries is economically viable.

The methodology for this hypothesis will revolve around providing a sound understanding of why key metrics are important to track during the lifetime of a EV battery due to the problematic singularities that are confined in the making and usage of a EV battery.

Methodology for Hypothesis 2:

The reuse (Recycling) of EV batteries and their subsequent components will be inevitable. Hydrometallurgical recycling in combination with Direct recycling will be key to facilitate a economically viable framework.

To achieve an understanding of hypothesis 2 it is important to investigate what happens during the process of repurposing batteries, how long the batteries can be used after being repurposed and whether it is economically viable to do so.

In order to achieve this understanding, I will analyze the core of repurposing, where do batteries go and how are they repurposed. The lifetime of a battery just like everything else In this world will one day come to an end, as even when the battery is repurposed for storing electricity or providing a different service than its original make, at some point batteries will lose their energy density and thus, be forced to recycle. This part of the investigation is rather difficult as the EV battery market is rather young. Henceforth, there is hardly any information available on the repurposing of batteries. The investigation will therefore concoct projections on EV batteries after repurposing based on the statistics and data that is currently available.

In order to comprehend whether the hydrometallurgical and direct recycling process is most profitable, an analysis based off the work by Laura Lader will be made, which allow this investigation to critically state if these recycling processes are in fact the most economically viable.

Methodology for Hypothesis 3:

There will be an opportunity to establish a sound and reliable business case in regard to EV end of life management within the European Union.

This hypothesis is dedicated to the analysis of a business case within the EV battery end of life management market. As provided in the basic methodology, I will investigate the EV battery industry and shed light to the future demand of not only the batteries themselves but also to the metals that are required to sustain such a rapid increase in li-ion EV batteries. Furthermore, an underlying notion of why I believe there is a strong business case, is the directives and regulations of the European union in regard to recycling. Which will make it hard for the current unethical framework of recycling to continue. In order to facilitate this message, Quotas will be analyzed and whether nations can achieve such quotas without the help of private players in the industry.

Furthermore it is important to gather an understanding of the key stakeholders within the recycling industry in order to facilitate an understanding of why there is in fact an opportunity in EV end of life management.

Literature Review

In order to make this a valid and comprehensive yet also compelling analysis it is of key importance to understand the current state of published works in regard to this papers topic. Therefore this segment will focus on establishing a basic understanding of where the industry stands and where there is a lack of revolving knowledge.

To start this literature review I would like to initially focus on what Li-ion batteries are made of, this will provide a crucial understanding of the core topic and will be interconnected with the next topic worth exploring which would be the need of recycling and repurposing of li-ion EV batteries, this should give the reader a sound understanding of why it is important to think of end of life management.

Within the Li-ion there is an abundance of different chemical bases, as the chemical make of each batterie offers important implications to its life cycle, management and end of life management it is important to analyse the different chemical bases. Let us start by understanding the Li-ion batteries. In order to make this investigation valid we will only focus on the explanation of the most energy dense Li-ion batteries. The chemistry in these batteries is called "Lithium-Nickel-Manganese-Cobalt-Oxide, abbreviated to NMC" NMC batteries are often used for EV purpose since they have a high energy density. Yet the cost of these batteries is quite high compared to similar batteries such as LFP. LFP based batteries are also used in electric vehicles. Their chemistry base is made of "less energy dense but cheaper, Lithium-iron-phosphate" (Rowan Harris, 2022)

To conclude the types of electric vehicle batteries we should also mention LCO batteries, LCO batteries are "Lithium Cobalt Oxide" chemistry based batteries. Furthermore there is also LMO based batteries being considered for EV batteries. LMO batteries are *"lithium manganese oxide batteries" Lithium manganese oxide batteries are notable for their high temperature stability and are also safer than other lithium-ion battery types."* (Pistilli, 2022) To date NMC batteries are also widely used batteries within the EV scene therefore it is noteworthy to include them in this investigation aswell. Nonetheless when looking at the macro factors in EV batteries these batteries "NMC, LFP, LCO and LMO" make up most of the batteries used in EV. (Ulrich, 2021)

Now that we have defined what the main batterie types in EV´s. We should understand some key metrics in order to realize their separate implications on usage, lifetime and their end of life management. The fact that there is a vast amount of different battery types makes it increasingly hard to make a homogenous recycling and repurpose method.

Let us first look at the production rate of each battery kind. This will allow us to later narrow our investigation and not lose scope of the hypothesis of this investigation.

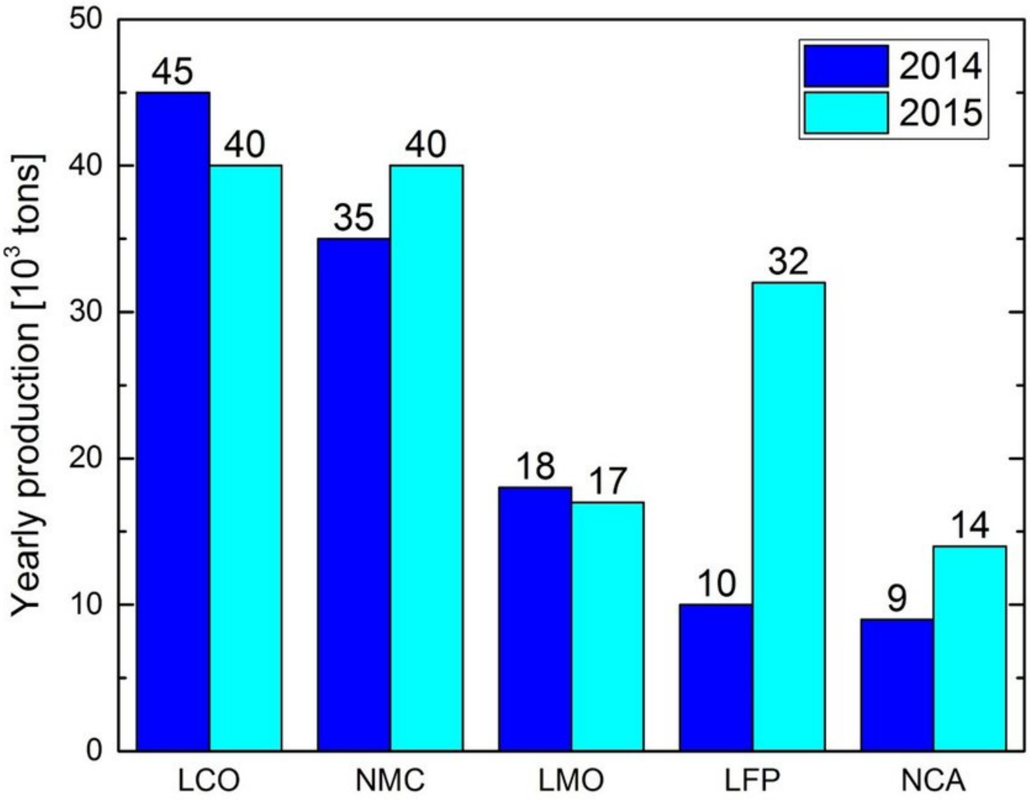


Fig 1. Yearly production of different types of batteries in 10^3 Tons in regard to the sample years, 2014 and 2015. (Wandt, 2017)

Figure 1 shows us the various production volumes of batteries with different chemical bases. This diagram shows data from the years 2014 and 2015. This data lets us decipher that LCO batteries and LMO batteries are the only chemical bases that seem to be losing in total production volume. In order to provide a rational for the rapid increase of production of LFP batteries it is important to consider that they have a much *"safer cathode material than NMC/LCO batteries as they are more temperature resistant, and thus, provide the best thermal and chemical stability."* (Green Cubes, 2020) As safety is a key element when considering the usage of an item we now see (2021) big motor companies such as *tesla using LFP based Li-ion batteries*. (Wayland, 2021) This is due to the fact that the different chemical bases have considerably different thermal runaways. A thermal runway is "*Thermal runaway begins when the heat generated within a battery exceeds the amount of heat that is dissipated to its surroundings. If the cause of excessive heat creation is not remedied, the condition will worsen."* (Mitsubishi, 2022)

Yet many other companies use NMC batteries for different reasons. This provides us with crucial information as we now understand that not all batteries have the same chemical structure.

As this thesis is intended to facilitate understanding of the end of life management of EV batteries it is important to understand materials needed to make these batteries:

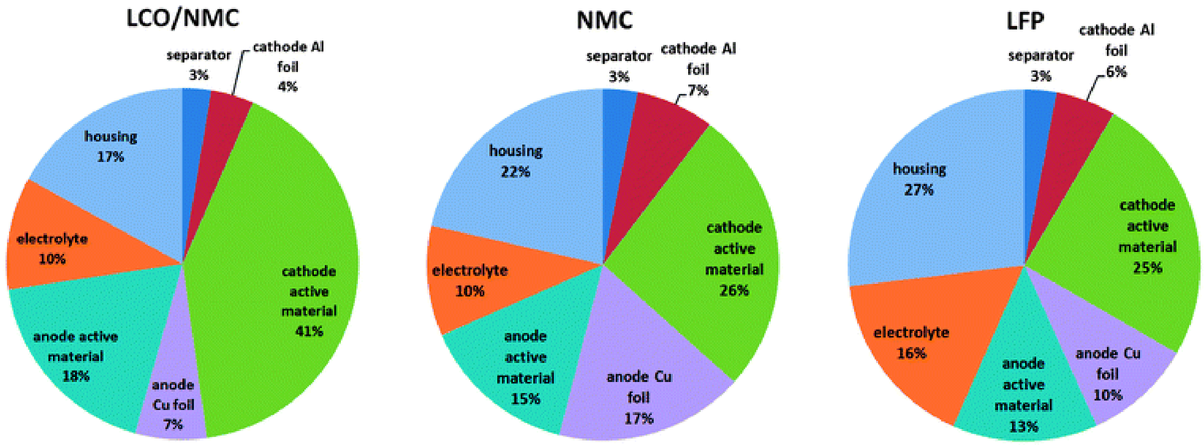


Fig 2. Materials by percentage within each battery type, respectively LCO/NMC, NMC AND LFP. (Golubkov, 2013)

Figure 2 shows us the difference in components used in the three main chemical compositions of Li-ion batteries. This is important as each one will have to be treated differently when recycled since LFP batteries also offer *“high recycling capabilities and high frequency will take precedence over energy density and reliability for the ESS market. Cost and safety will continue to top the mind of battery vendors for multiple applications.”* (Mccaine, 2020) This is a crucial finding, as it has various implications toward the onset of this thesis. Since the repurposing of the different batteries will have to undergo individualistic methods and processes. Providing an interesting basis for Hypothesis 2.

Now that we understand the components and different types (chemical compositions) we can now focus on providing an understanding of how Li-ion batteries function and work, although this does not directly tie in with the subject matter of the thesis, I believe it is important for the context as it is the underlying functionality that will also provide insights on what components of a battery will be able to be recycled and also give concluding evidence on what components decrease the life time of EV batteries.

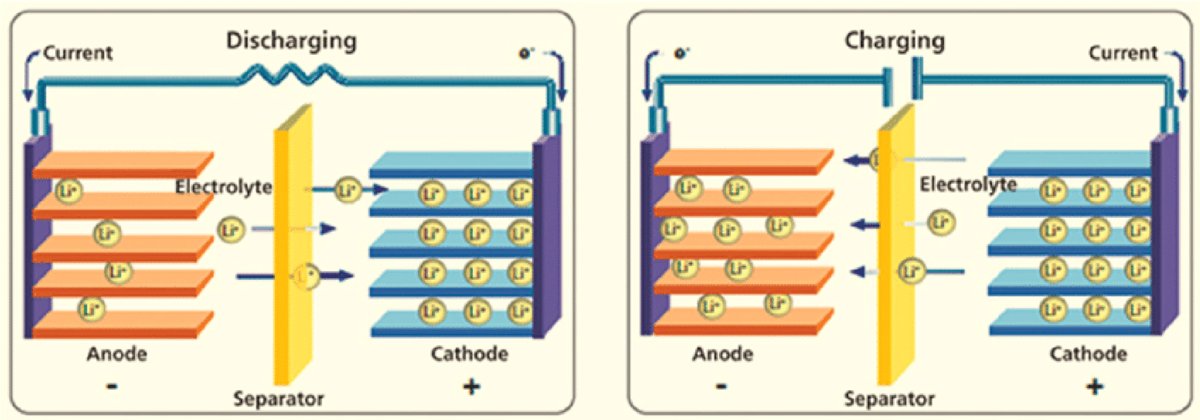


Fig 3. Li-ion Battery Discharging and Charging visualized, - anode, + cathode. (Chawla, 2018)

Li-ion batteries consist of a positively charged cathode, negatively charged anode, separator, electrolyte, and positive and negative current collectors. While discharging, the lithium ions travel from the anode to the cathode through the electrolyte, thus generating an electric current, and, while charging the device, lithium ions are released by the cathode and then fo back to the anode. Figure 3 shows the basic working principle of a Li-ion battery. (Chawla, 2019) Having understood the make and functioning capabilities of Li-ion batteries we can now extend this investigation toward the end of life management of electric vehicle batteries.

Costs of making Li-ion batteries

As we know end of life management has been introduced to the world in order to facilitate a circular economy approach. Yet most of the enthusiasm and incentive has been coming from the government. Which begs to ask the question whether recycling would be profitable. In order to do so it is important to consider the implications of raw material sourcing. We will thus conduct a cost analysis based on the materials used.

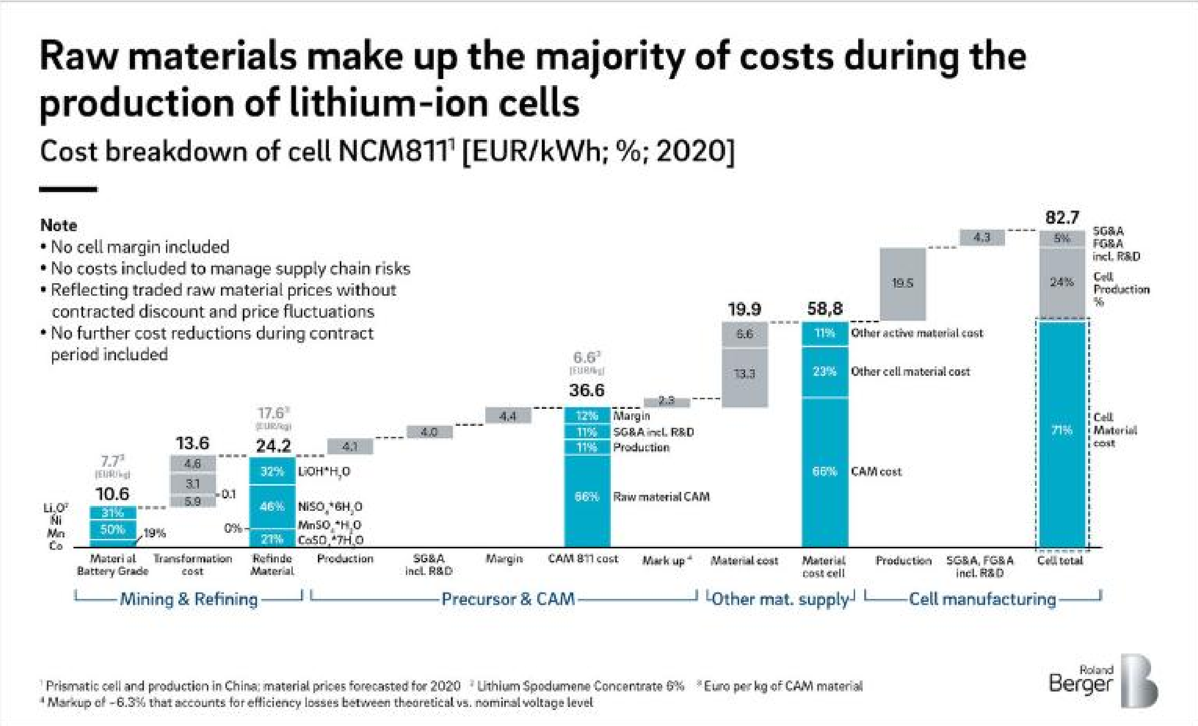


Fig.4 Cost breakdown, from mining and refining to CAM, and cell manufacturing, weighted in EUR/kWh; %; in the year 2020. (Bernhart, 2019)

As we can see from figure 4 above there is an abundance of costs within the raw material and cell material acquisition, when regarding the production of a Li-ion battery cell. If we take a closer look at figure 4 we can Identify the typical costs within every step of the production cycle. Starting with Mining and refining, which as the subject matter incurs shows its most salient cost in refining and grading of the material, the only cost external to the material costs is the transformation cost, this transformation cost is significant as it will be a key metric to regard in the recycling process of li-ion cells, since the cost of transformation in the recycling process has to be within the realm of the cost in the mining and refining process in order to make the recycling economically viable for businesses. This topic is worth analyzing in further detail, this investigation will review this topic in the section of economic viability. The Precursor & CAM section of this cost analysis revolves around the *cathode active material production*. In this section we see that 66% of the underlying costs are raw material costs related to the cathode. When regarding the cell manufacturing of li-ion batteries one might think that the process and engineering of cells would be the highest cost as it takes a long time and needs expertise. Yet if we regard the metrics from figure 4 valid we can see that even in the final process of making a li-ion battery 71% of the costs are revolved around sourcing the raw materials.

Concluding figure 4, we can see that in all steps of production, raw material costs are significant, this translates into the importance of acquiring the raw materials and further elapses into the great opportunity within the recycling market of li-ion batteries and provides further need of investigation into the economic viability of recycled materials.

Raw Materials needed to produce Li-ion batteries

After understanding the dynamics of Li-ion batteries and their externalities. It is important to understand the recycling processes revolving around the end of life management of Li-ion batteries. As we have now provided understanding of: The types of li-ion batteries used within the EV market. This understanding was crucial to the trajectory of this thesis as it allows the reader to grasp what trends are being established. Furthermore, the materials and components used within each battery type have been explored allowing us to formulate an understanding of the resources needed. Connecting these findings with the production rates of each battery type, it would be of importance to understand the raw materials themselves, their availability or consequent scarcity and their cost. Therefore the investigation will now focus a section of the literature review in understanding the raw materials needed for li-ion battery production, as this understanding is crucial for the argument of recycling.

There is a general notion in regard to lithium that we have a deficiency and that there is not enough lithium to sustain the rapid demand of the metal from the increasing electrification of vehicles. This notion is important to investigate as it can have critical impact on the future reliability of li-ion batteries and the EV market in general. (Mathew, 2021)

As this investigation is aimed at the end of life management of EV based batteries exclusively it is important to understand how much of the lithium production is directed at the EV market the following figure brings evidence that the EV market consolidates the majority of the lithium demand, even though the industry is very young.

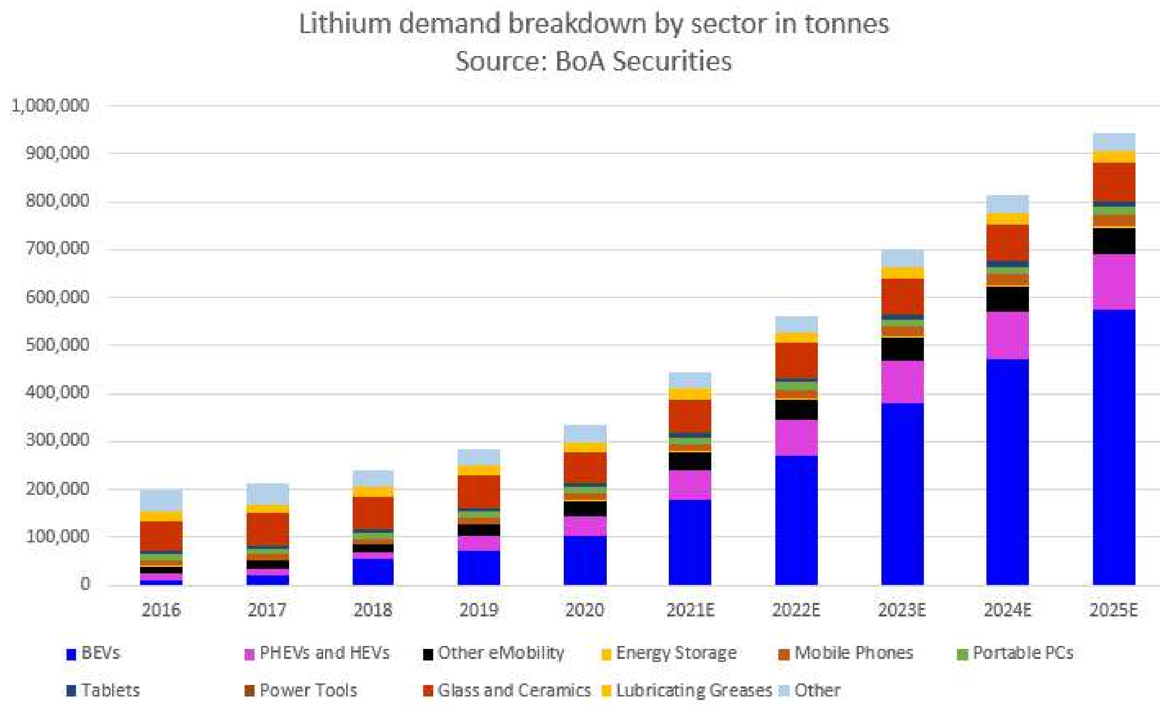


Fig.5 Demand of Lithium in tons, broken down by sector, projected to the year 2025. (Mathew, 2021)

As mentioned in the introduction to this figure we can clearly see that in the year of writing this thesis the electric vehicle market already consolidates more than half of the macro demand of Lithium, this helps us understand the need for recycling of the metals from the perspective of the year 2022. Yet when looking into figure 5 we can see that the model also extrapolated information for the future predictions of the lithium demand. It becomes apparent that there will be more than 500,000 tones of lithium metal produced by the year 2025. This rapid increase will be a huge challenge for the end of life management of this metal. As even today there are huge ethical fallacies involved in the end of life management of lithium and other electronic metals. Given the status quo on end of life management, this huge increase in material will have grave implications, both ethically and industry related. More on this topic in the segment about the ethical implications of end of life management.

Now that we understand the demand of lithium in connection to the electric vehicle market, we need to understand the demand of the other materials and components needed in order to facilitate the production of a battery as the end of life management will need to tackle the majority of the metals and resources within a EV battery in order to be an efficient recycling method.

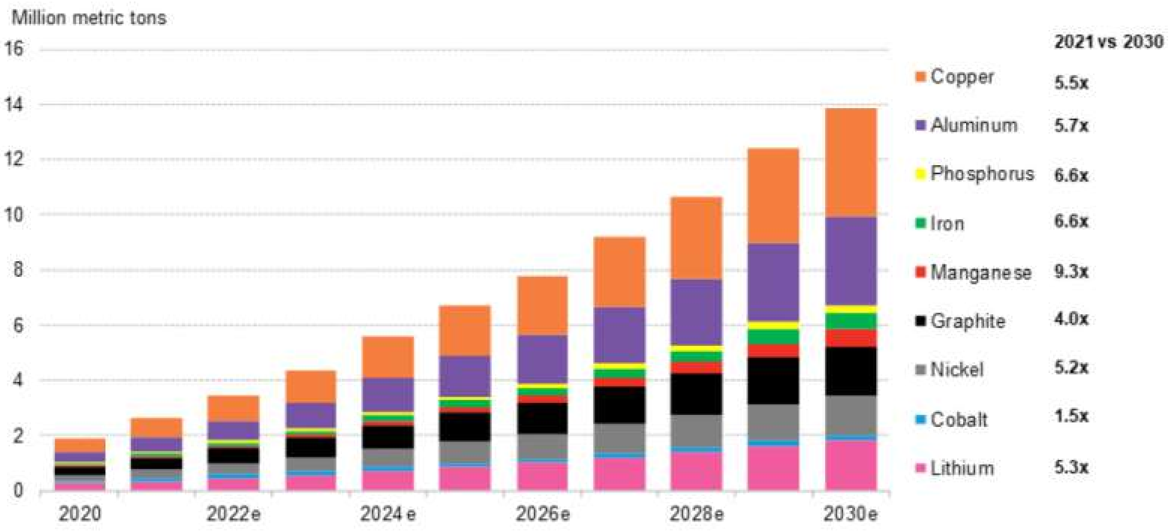


Fig. 6 Metals and components needed to sustain the demand of li-ion battery production, projected to the year 2030 in MMT, million metric tons. (Bloomberg, 2021)

Figure 6 shows a detailed list of the main components used in a li-ion battery. The figure entails details that are valid for this investigation as there is many rare metals involved in the production of li-ion batteries. Which further strengthens the thesis argument that there is an avid need for end of life management not only from an ethical perspective but also from a required capacity point of view. With required capacity I aim to further the argument that many of the resources listed here are resources that are finned and there is only a certain amount of mines that we currently know of. This will mean that when the industry optimizes for complete electrification there will be a need for the metals to be recycled and reused as this will allow the industry to create a secondary supply chain of raw materials.

One can know understand the gravity of the economic argument underlying the need for recycling the metals in an li-ion battery, as the metals are very expensive to source and cause a large amount of CO2 emissions in the creation process, resulting in further taxation and public critique. When regarding the production of li-ion EV batteries and its subsequent production of CO2 one has to face the fact that it costs allot of CO2 emissions. (PolitiFact, 2022) Actually And Nguyen from PolitiFact institute states that *"Production of a lithium-ion battery for an electric vehicle emits carbon dioxide equivalent to operating a gasoline car for about one or two years, depending on where the battery is produced."* (Nguyen, 2021) This quote offers great critique to the argument underlying the electrification of vehicles. Which is to become more CO2 neutral, Yet does this claim actually hold valid, the thesis aims to analyze this claim. In order to do so it is important to note the life cycle production of CO2.

CO2 emissions connected to electrification of mobility

The exact production of CO2 for technical terms, it is important to note that battery production varies in methodology and in manufacturing steps, which consequently alters the CO2 produced by each method. For simplicity sake the thesis will focus on Li-ion production in the U.S.A vs. the production in Asia. It is said that; "*Producing a 75 kilowatt-hour battery for a Tesla Model 3, considered on the larger end of batteries for electric vehicles, would result in the emission of 4,500 kilograms of CO2 if it was made at Tesla's battery factory in Nevada. That's the emissions equivalent to driving a gas-powered sedan for 1.4 years, at a yearly average distance of 12,000 miles, Hausfather said. If the battery were made in Asia, manufacturing it would produce 7,500 kg of carbon dioxide, or the equivalent of driving a gasoline-powered sedan for 2.4 years — but still nowhere near the eight years claimed in the Facebook post. Hausfather said the larger emission amount in Asia can be attributed to its "higher carbon electricity mix." The continent relies more on coal for energy production, while Tesla's Nevada factory uses some solar energy."* (Matousek , 2019) In order to validate that the common fallacy of EV batteries causing as many emissions as diesel cars holds truth, we must include a secondary source, which is the following figure figure 7.

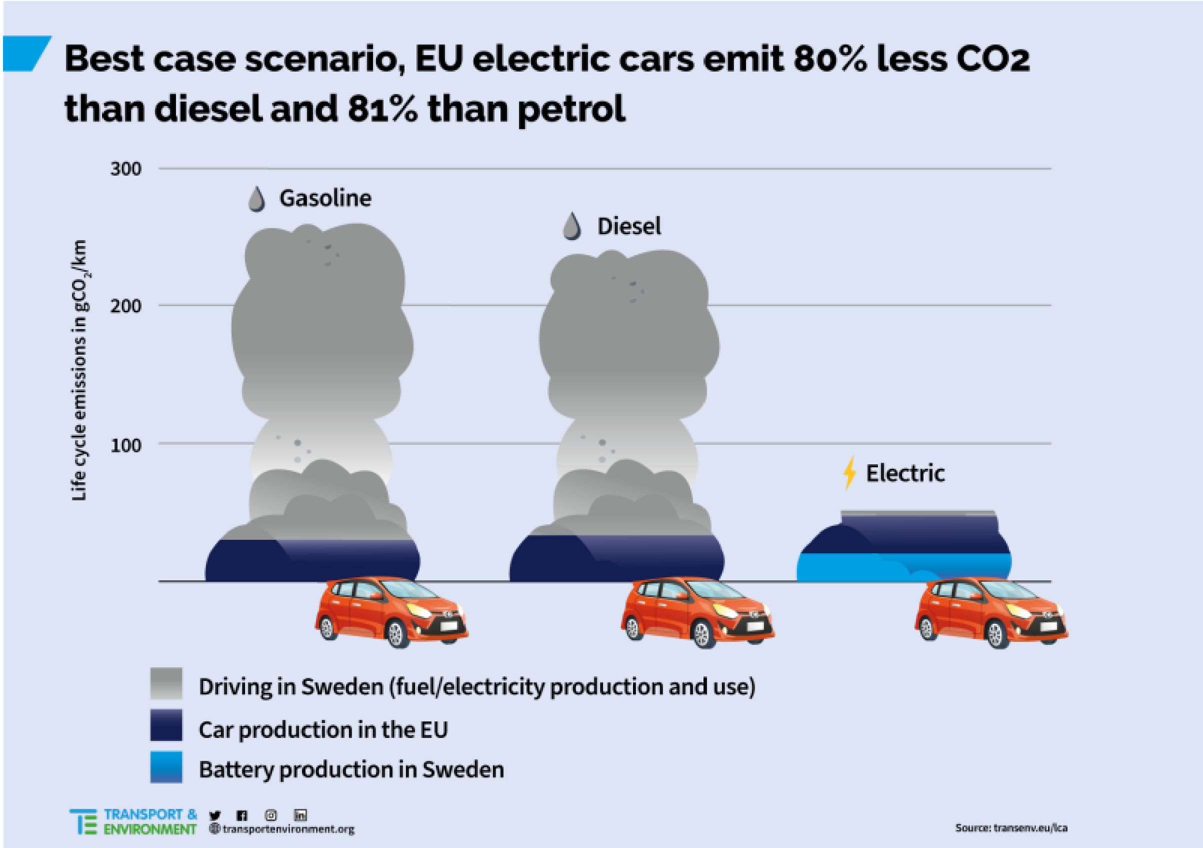


Fig 7 EU electric car emissions, Gasoline vs Diesel vs Electric vehicles. Best case scenario is iterated to be the result of using a good energy mix. Life cycle emissions are given in gCO2/km. (Bannon, 2020)

Figure 7 entails critical information on the fallacy of EV causing the same amount of CO2 as diesel and gasoline engines. What becomes apparent is that as mentioned before it is important to note the origin of where the battery was produced as this has implications on the CO2 output in the manufacturing process. The first finding we can deduct from figure 7 is the fact that electric vehicles do cause lifetime emissions, yet remain lower than those of diesel and gasoline engines. Eoin Bannon states that *“Electric cars in Europe emit, on average, almost three times less CO2 than equivalent petrol or diesel cars.”* (Bannon, 2020). This would make the argument of electrification valid, yet not as significant as many politicians claim. Another element that is not considered here is the energy mix used to fuel the EV´s, this is crucial as the argument is only valid if the energy mix used to fuel the EV is primarily from renewable energy sources. The information derived by Bannon focuses on Sweden as a core demographic for his findings. The energy mix of Sweden has roughly 56% of its entire output from renewable energy sources, in which hydro and wind energy take the biggest share, but is also supported by the bio energy heating. The rest is facilitated through gas and nuclear power. (Sweden Serige, 2021). Having understood the source of figure 7, we must instigate a margin of error when holding this argument valid in a global sense. As the energy mix varies greatly between nations.

As a comparison the article by Bannon underlines another finding in regard to the energy mix, in which he phrases implications on the use of EV batteries in different countries, analyzing these findings will allow us to further a better understanding of how important a nations energy mix is when trying to derive a sound understanding of the lifetime CO2 implications of EV. Bannon goes on to state that; *"Even in the worst case scenario, an electric car with a battery produced in China and driven in Poland still emits 22% less CO2 than diesel and 28% less than petrol, the tool shows. In the best case scenario, an electric car with a battery produced in Sweden and driven in Sweden can emit 80% less CO2 than diesel and 81% less than petrol."* (Bannon, 2020) This analysis provides understanding that due to the fact that Poland has a less renewable energy mix, the lifetime CO2 output of a driven EV increases when compared to the use of EVs in Sweden. Yet the underlying argument that remains is the fact that even under *"worst case scenario"* themes EV still produce less CO2 than its diesel and gasoline counterpart. It is important to state that there is allot of information that suggest EVs are more harmful than diesel or gasoline cars, as one needs to consider elements such as battery replacement every 8 years. Yet it would be misleading to dedicate more time and wording to this section as it is only one element of this investigation.

Having understood the basic notions in regard to lifetime CO2 production and deriving that EV batteries create CO2 yet less than that of its gasoline and diesel counterparts, allows us to continue our investigation.

Recycling Processes of li-ion batteries

Before jumping to far ahead it is important to properly understand the methods of recycling the metals forming the composition of an electric vehicle battery as detailed in figure 6 above. There is two best practices when it comes to the recycling of EV batteries, Hydro process recycling and direct recycling. In this chapter this investigation aims to provide a sound understanding of the two methodologies, which will further develop into an argument that homogenous recycling methods are key and critical to creating a adaptive, efficient and well implemented end of life management system in recycling.

HYDRO PROCESS RECYCLING

Hydro process recycling also called hydrometallurgical, is deemed to be the most appropriate and efficient way of recycling EV batteries. Before understanding the processes singularities and methodologies, we must first establish an understanding of the steps within the process, their advantages and disadvantages.

The thermal process: The thermal process counts as a precursor to most recycling methods involving the reuse of metals. What is achieved by this process? Primarily it is aimed at applying heat to the waste material in order to sanitize it, which provides the function of *"convert the waste to a stable and usable end product and reduce the amount that requires final disposal in landfills."* (Harrison , 2011) How exactly does the process work? I would like to refer to the work by Viraj Gunarathne in this case, as he detailed a perfect description of the process in his book; Handbook of Electronic Waste management. Initially it is key to understand that even the recycling process itself is fraudulent to polluting the environment, as it is mostly done in so called open burning, it is important to note that in this process the common practice is to not include pollution controlling devices, which results in pollutants escaping to the environment, yet due to the fact that it is rather cheap, most countries in the world focus on using this technology in the recycling process. (Singh and Gautam, 2014).

Yet many modern nations implement the use of so called Afterburners, since the thermal process yields many unwanted combustible highly toxic and polluting gases. There is two general types of Afterburners, direct flame afterburners in which the gases are oxidized in a combustion chamber and the latter which are catalytic combustions systems, which revolves around oxidizing the gases in temperatures far below the autogenous ignition point. (Vallero, 2019)

This is valid and worth investigating in the scope of this thesis as the main argument revolves around the need for end of life management systems to decrease the CO2 output of the general electrification. Thus, I dedicate this section to the appeasement of pollutants in the recycling process. As mentioned the most common way of dismantling the toxic pollutants of the thermal process, are direct flame afterburners, these do not only facilitate the retention and dismantlement of gasses but also those of aerosols, vapors, gases and odors that result of the thermal controlling step of the recycling process. (Vallero, 2019)

These afterburners are can be optimized when properly operated, in order to not only be economical but also efficient, it is noteworthy to investigate the economical factor, as the recycling of Li-ion batteries in regard to EV is currently still not economically viable. Therefore it is important to minimize costs at every possible angle during the recycling process. Vallero helps us understand a critical understanding of how to minimize costs in relation to using afterburners to control the production of pollutant gases in the thermal recycling process. Vallero suggests the use of *heat recovery systems:* as displayed in figure 8 it endows: *"This configuration includes a fume inlet to an insulated forced draft fan, a regenerative shell-and-tube heat exchanger, an automatic bypass around the heat exchanger for temperature control (required for excess hydrocarbons in fume steam under certain process conditions), a refractory-lined combustion chamber, refractory, with a discharge stream leaving the regenerative heat exchanger and then the ventilating air heat exchanger for further waste heat recovery."* (Vallero, 2019)

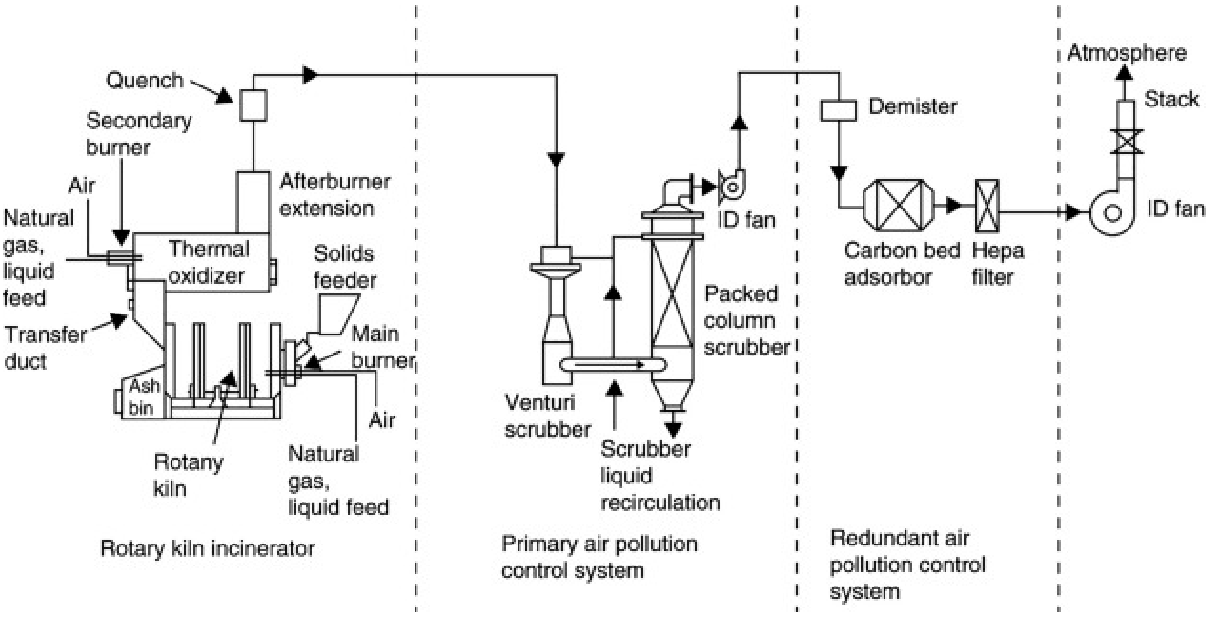


Fig. 8 How afterburners work, read left to right, with the goal of minimizing CO2 production while enabling the recycling method of Hydrometallurgical. (Vallero, 2019)

What is noteworthy is that the catalytic functions displayed in figure 8 above, are also to a certain extent in a much more minimal version implemented in the current diesel and gasoline cars, to reduce the toxic waste stemming from those engines. There is also other ways of dismantling the hazardous waste emerging from thermal treatment such as "thermal plasma technology, yet this is not considered to be a best practice within the industry and thus, will not be investigated in the analysis. Having understood that thermal treatment focuses on "making the waste stable and usable" we can now focus on the next step in the hydro process recycling, which is; leaching.

First it is important to note that after the thermal process has made the waste usable and stable, the next step would be shredding the material and separating the metals, plastics and other components individually, yet these processes are rather simple and thus not worth investigating further, as a basic understanding of separation will suffice. The next step though, condones various methods of leaching.

What is leaching? Leaching refers to the extraction of metals through the action of liquid passing through a substance. In the case of lithium batteries, water would not suffice in separating the materials, therefore a more sophisticated approach is needed, thus, sulfuric acid can be utilized at approximately 80 Degrees, the exact elemental composition of the sulfuric acid is; $C_6H_8O_6$. Due to the vast differences in li-ion batteries, that this investigation mentioned in the above section of "battery types" it is hard to optimize a homogenous method of recycling as the leaching process must be optimized for each battery type. Yet Miamari Aaltonen states the following: *"there are numerous other commercialized positive electrode materials that include lithium nickel manganese cobalt oxide ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$, NMC), lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, NCA), spinel ($Li_2Mn_2O_4$, LMO), and lithium iron phosphate ($LiFePO_4$, LFP) [4]. As a consequence, spent battery waste offers a rich source of both critical (Co) and economically valuable (Li, Ni, Cu) materials"* (Aaltonen, 2017) This proves vital to this investigation, as many of the metals mentioned in figure 6 can be dismantled and recycled. In fact *"nearly all of the cobalt and lithium can be leached out in sulfuric acid"* (Aaltonen, 2017).

After the leaching process, the metals undergo various metal recovery strategies such as; solvent-extraction, electrowinning, bio/chemical sorption and bio/chemical precipitation.

These processes are aimed at allowing precipitation by separating the insoluble residue to separate from the so called pregnant solution containing the metals (Sethurajan, 1970). Subsequently once the separation is conducted the metals can be clustered, sterilized and gathered in order to be reused.

This section has provided the reader with an in-depth understanding of how the hydro process recycling works, Furthermore, it has provided supportive arguments to the context of economic viability and to the fact that although the recycling process condones the creation of pollutants there is fit counter measures to ensure that the recycling process is legitimate and causes no to minuscule harm to the environment, this fact is of great importance to this investigation, due to the fact that if recycling was harmful to the environment an increase in the end of life management of li-ion batteries would not be advised.

DIRECT RECYCLING

The second method of recycling this investigation aims to analyze is the method of direct recycling, which is stated to be *"more efficient than classical methods because it recovers the functional cathode particle without decomposition into substituent elements or dissolution and precipitation of entire particles"* (Sloop and Crandon, 2020) The understanding of the direct recycling method will be paraphrased from the work by sloop and Crandon entirely through their work *"a direct recycling case study from a lithium-ion battery recall"*.

The process of direct recycling focuses on:

1) The extraction of electrolyte with carbon dioxide
2) Industrial shredding
3) Electrode harvesting
4) Froth flotation
5) Cathode healing
6) The rebuilding of cells made from direct recycled cathodes and anodes

The investigation aims at providing a sound understanding of this recycling process and its consequent broken down steps as it will allow the investigation to formulate a better understanding of which recycling process is better equip to take the upper hand in the future.

Direct recycling revolves around three core approaches; cathode-to-cathode, mechanical electrochemical, and cathode-healing technologies. The method is nondestructive and corrects structural and chemical deficits that occur throughout life. Used cathodes, for example, have lithium inventory deficits of 10–15 percent, as well as structural changes that obstruct lithium movement. Cathode-healing restores the lithium capacity/conductivity structure-property correlations in spent cathodes and can be employed on a wide range of lithium-ion battery kinds and combinations. Making this a more homogenous solution to the recycling problem, as hydro process recycling has to be optimized to the different battery kinds. According to modeling, direct recycling is the most cost-effective way to offer low-cost, recycled, EV-relevant material. (Sloop and Crandon, 2020)

The following figure 10 illustrates the Cathode-healing process. CO2 is used to remove the electrolyte from Li-ion batteries, after which the cells are safely shredded. Plastics and metals are removed from battery components, and electrodes are treated hydrothermally. Cathode and anode are separated by froth flotation, then the cathode material is heated to generate healed cathodes. (Sloop and Crandon, 2020) Froth flotation refers to the *"process for selectively separating of hydrophobic materials from hydrophilic."* (Dunram, 2022)

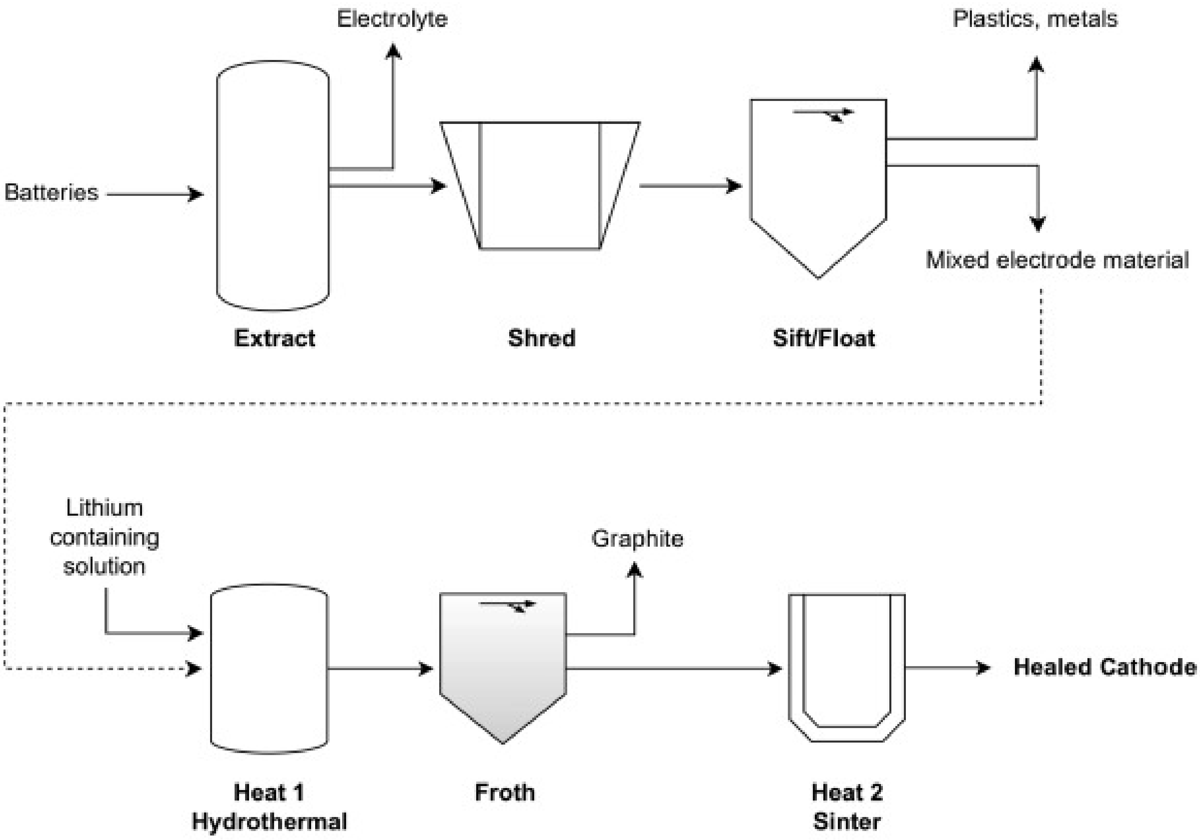


Fig.9 Cathode-healing is a scalable process. CO2 is used to remove the electrolyte from Li-ion batteries, after which the cells are safely shredded. Plastics and metals are removed from battery components, and electrodes are treated hydrothermally. Cathode and anode are separated by froth flotation, then the cathode material is heated to generate healed cathodes. (Dunram, 2022)

Again the great benefit here is the fact that direct recycling does not invoke the need for individual treatment of each battery kind, and allows a process of recycling without dismantling cathode.

The remaining steps in direct recycling in the process of cathode-healing, were Hydrothermal (harvesting of the cathode), separation of carbon and metal oxides through froth flotation, Heating of the LCO which endows hydrothermally treated cathodes being heated under air to 800 degree Celsius, to the recycled graphite preparation which involves rinsing the recovered graphite with nitric acid to dissolve trace metals. (Sloop and Crandon, 2020)

After this process the process of full cell construction accrues, yet this process requires an in-depth understanding I would thus like to motivate the reader to visit the work by Sloop and Crandon in order to achieve a full understanding of this process. What is crucially important to understand is whether the cathode healing process works and if it is viable to ensure the recycling efficiency of li-ion batteries. The following figure shows the need for healing the lithium cobalt batteries, a comparison in voltage between healed and harvested LCOs:

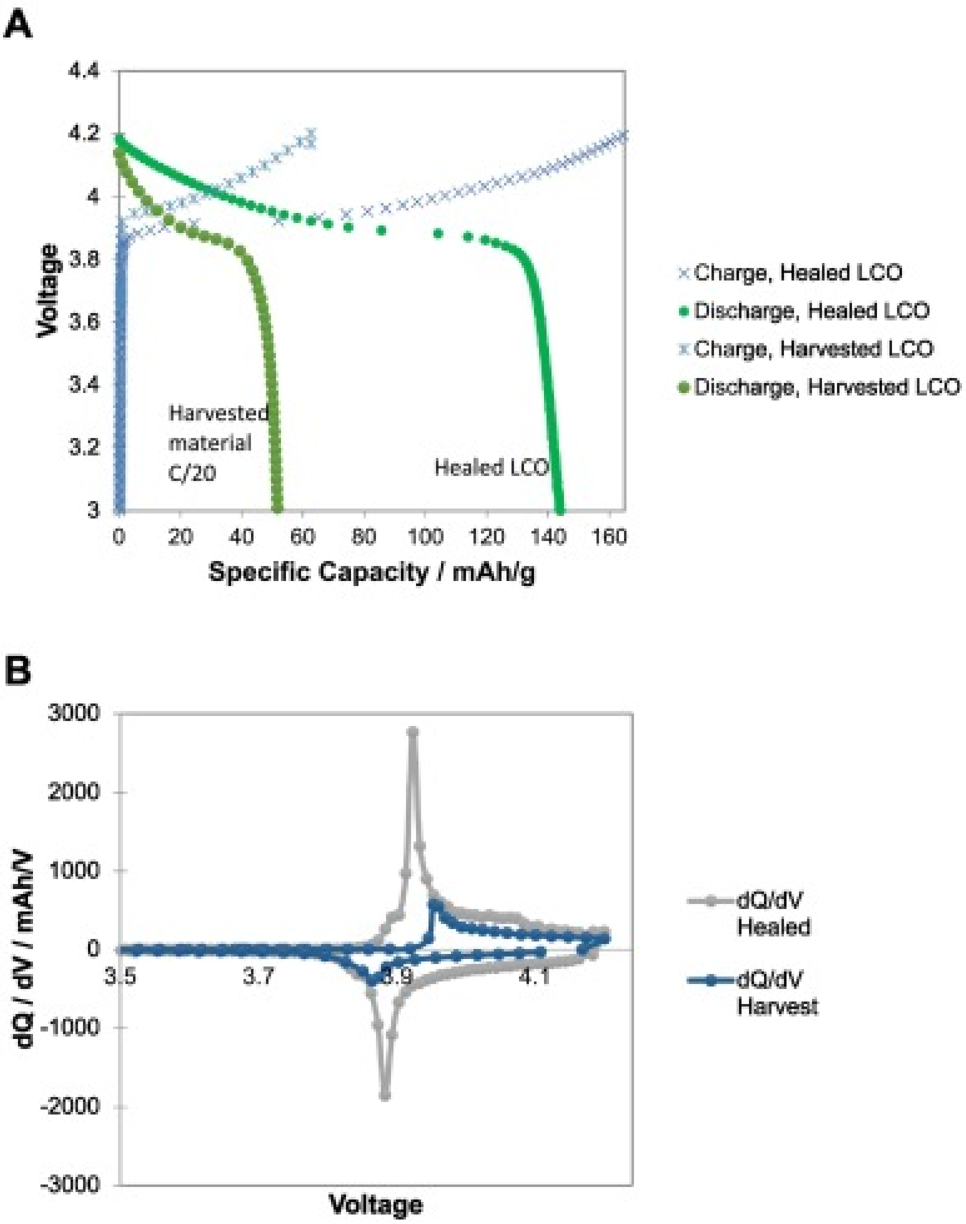


Fig. 10 (a) Voltage vs. Specific Capacity and (b) dQ/dV for harvested and healed LCO. LCO harvested from faded cells has low capacity. The capacity of the healed LCO is 144 mAh/g. The theoretical capacity for LCO is 140 mAh/g. (Sloop and Crandon, 2020)

As seen in graph a LCO harvested from faded cells has low capacity with an mAh/g of roughly 52 vs. The capacity of the healed LCO is 144 mAh/g. (mAh/g = millampere hours per gram, a measure of energy density). (Sloop and Crandon, 2020)

Concluding one would have to analyze the specific capacity as presented in figure 11 of a healed LCO at 144 mAh/g and the discharge current density, in order to conclude whether direct recycling or in this case cathode healing is efficient and works.

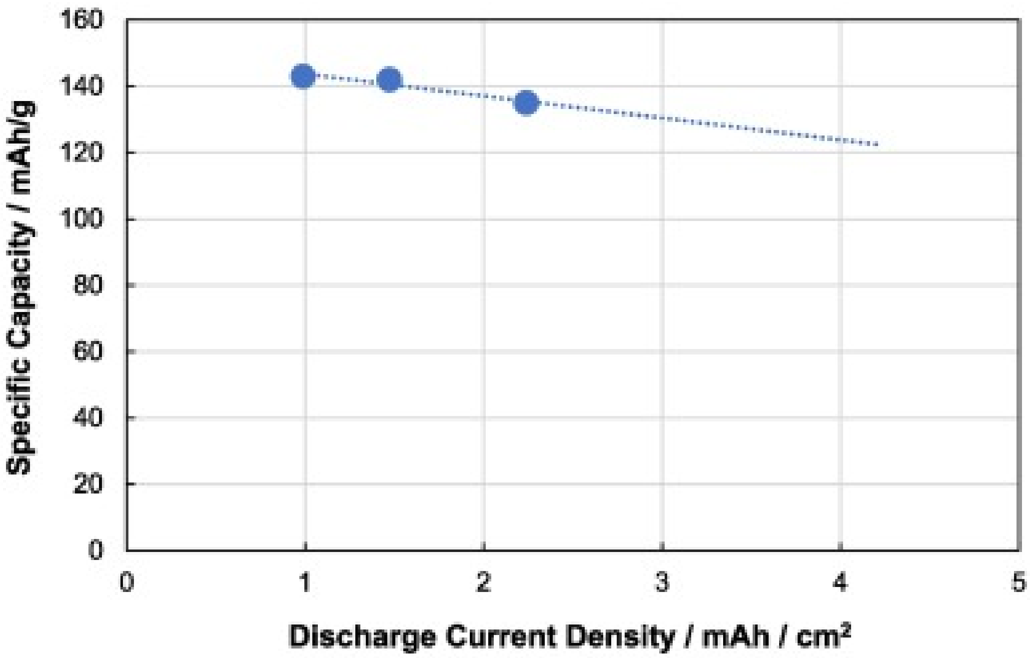


Fig 11. Rate capability for healed LCO against Li metal. The healed LCO maintains specific capacity as the current density increases, which provided confidence to build full cells against graphite. These are equivalent to C/12, C/8 and C/5.

Healed LCO's rate capability against Li metal. As the current density grows, the healed LCO maintains specific capacity, giving us the confidence to create entire cells against graphite. Furthermore The full cell composed of new graphite and healed LCO demonstrated good capacity retention. Figure 11 specific capacity vs. cycle number shows that healed LCO retained 80% of capacity after 160 cycles. (Sloop and Crandon, 2020)

Concluding one can state that direct recycling works, yet it is important to state that the first charging cycles show high capacity for both electrodes, yet later cycles show a greater capactity loss, this is most likely due to impurities in the recycling process. Yet one can generally say that direct recycling is applicable and works, furthermore it has advantages due to its homogenous applicability in terms of battery kinds, Thanks to the work of Sloop and Crandon we now understand the different recycling processes and their advantages and disadvantages.

Having provided an understanding that there is effective ways of recycling li-ion we can now lead this investigation to the status quo of recycling. As this is crucial for the effectiveness of this investigation and its validity in proposing a potential business opportunity. It is important to note that the scope of this investigation remains the European union therefore the following section is most saliently focused on the review of E waste in Europe and its consequent end of life management.

STATUSQUO OF RECYCLING

To make this a fair investigation it is important to go back in history, as the EV battery recycling market is rather young, thus one must first understand the development rate of the recycling output. Dramatically less than 1% of lithium from various applications was recycled globally in 2011. (Aaltonen, 2017) This is an appalling statistic, as one might be led to wonder what happens with the lithium that reaches its end of life cycle. To further capitulate on the fact that there is hardly anything being done to this day, it is worth mentioning the fact that: *"99% of lead-acid batteries in the United States are recycled. Yet only about 5% of lithium-ion batteries are currently recycled, according to the DOE"* (Wallace, 2021).

In the next step it is important to understand how much li-ion batteries are actually available to be recycled, and whether the majority of which come from the EV industry or related industries.

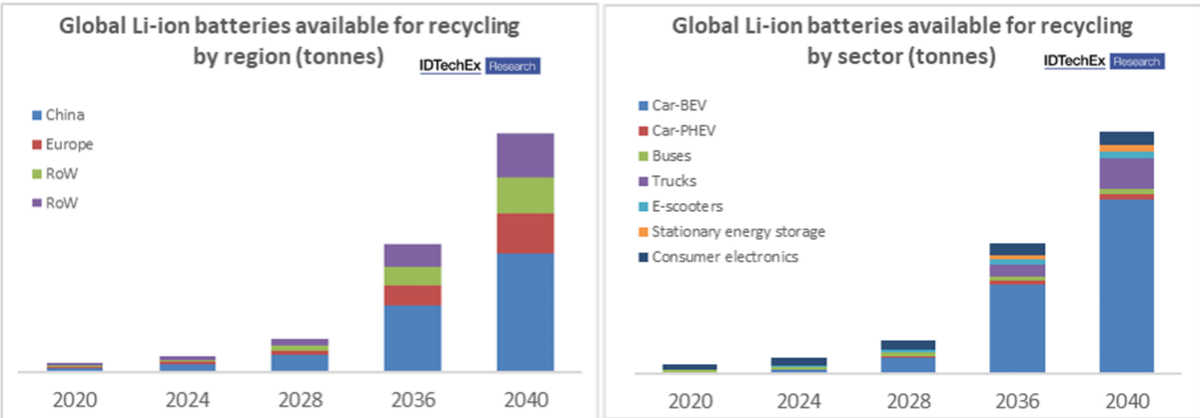


Fig 12. Graphs showing the projected amount of li-on batteries available for recycling, by sector and country. (IDTECHEX, 2020)

Each of the important markets - China, Europe, and North America - will be examined, with information on market size and value provided. China is the world's largest market for Li-ion battery recycling: by 2040, China will recycle almost half of the world's wasted Li-ion batteries, or 4.3 million tons. Although most Li-ion batteries available for recycling in the early 2020s come from consumer devices, the electric vehicle sector will dominate and considerably drive the Li-ion battery recycling business from 2025 onwards. (Holland, 2020)

As figure 13 and consequently the work by Dr.Holland, so prominently displays, there is a huge volume increase expected to happen within the “available li-ion batteries” furthermore what we can clearly derive is that the future available market of li-ion batteries will be almost completely sourced through EV batteries. This provides further support to the salience of this investigation. The fact that China will be responsible for recycling the majority of li-ion will also provide a reasonable ground for the European union to expand their recycling initiatives as an over dependence to another nation will never be profitable or reliable.

There is not yet a huge surplus of li-ion batteries available for recycling it is important to note that optimizing the industry to do so is key, as the infrastructure requirements of li-ion batteries are vast and thus cost and time extensive. Furthermore the world can no longer turn a blind eye on the unethical recycling methods of electronic waste.

Unethical practices

Figure 13. Child labor in the recycling process of E-waste. Source: (TCO, 20169

Pictures like these expose the sad but upmost truth, that most of the western world's e waste ends up in so called LEDC countries, there has been claims of Children being used to labor, especially in India and Africa. The conditions are severe and can cause major health issues due to the hazardous and toxic fumes they produce, the investigation has talked about the potential to recycle without causing harm to the environment and without spreading pollutants in the air. Yet without the investment and recognition of the ethical fallacies there is hardly any hope that the management of waste will change. This claim is further supported by Figure 15:

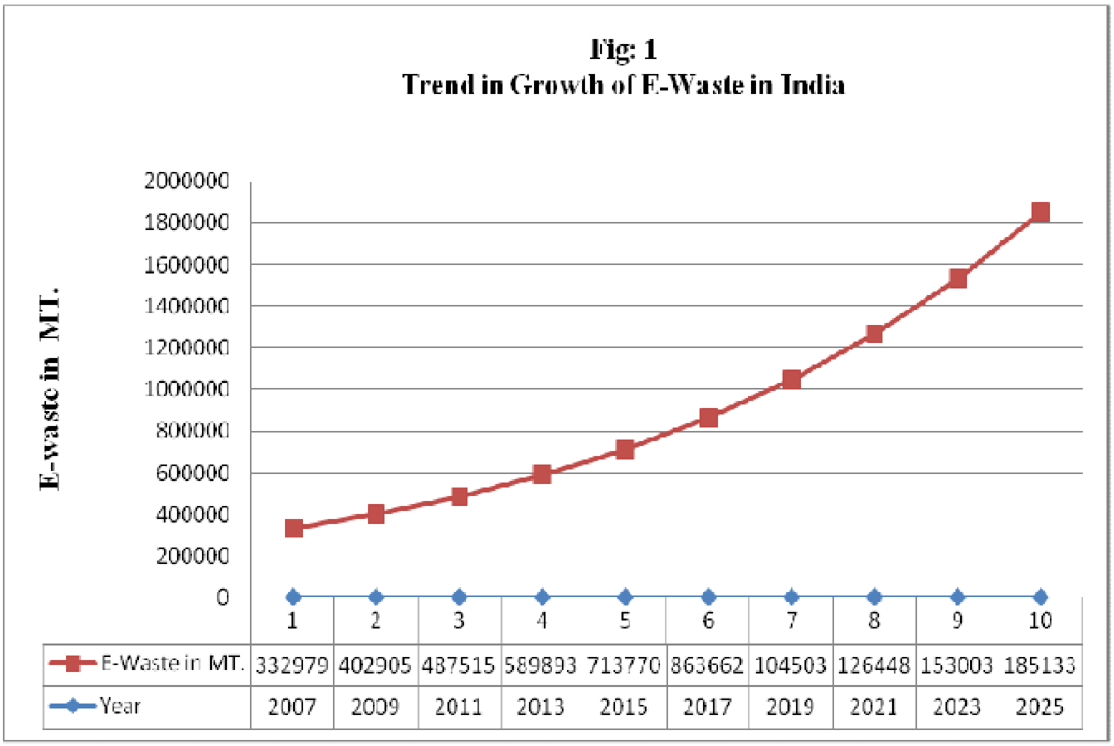


Fig 14. E waste in Million tons, over a time frame from 2007 – 2025. (ResearchGate, 2018)

Figure 15 shows the trend of growth in E waste arriving in India. As li-ion belongs to the e waste family we can comprehend an understanding that allot of the li-ion that will arrive at its end of life time, will end up in India or Africa, causing harm, and polluting the environment. It is therefore crucial that western countries build the right infrastructure.

As reports suggest that; E-waste recycling poses health problems in other countries as well. Several studies conducted in Guiyu, China, the world's largest e-waste recycling hub, demonstrate that local residents are suffering from significant digestive, neurological, pulmonary, and bone issues. Eighty percent of Guiyu's children have respiratory problems and are at risk of getting lead poisoning (McAllister, 2013). Developing countries are popular destinations for industrialized countries to export their e-waste to since the garbage may be recycled at a reduced cost due to lower labor costs. Low pricing may appear attractive to foreign investors, but they come at a tremendous cost to workers' health, the general public's health, and the local environment. (Dawson, 2016)

The much graver consequence is that there is hardly any action being taken to fight these backward and harmful antics within the management of e waste, A few organizations in India are taking action by offering information on toxics and e-waste, and they are also looking into new ways to strengthen their system and strive toward environmental justice. Other international organizations, such as Networks for Environmental Advocacy in San Jose, California, are also working toward same aims. The International Solid Waste Association, SWA of North America, and the Environmental Protection Agency are among the others. Some global networks, such as BAN, are working particularly to prevent e-waste exporting, with the goal of prohibiting all types of "toxic trade" between countries (Pinto, 2008).

Even though the afore mentioned information is in regard to the existing E waste, and figure 13 shows us that there is hardly any li-ion based e waste on the market yet it is important to understand the current framework in order to facilitate the need for change in the future. Yet in order to really understand the ethical framework within the dismantling of li-ion it is also important to consider the implications when mining the li-ion metals.

Lithium-ion technology has drawbacks, both for individuals and for the environment. The basic minerals, primarily lithium and cobalt, require a lot of energy and water to extract. Furthermore, the labor is done in mines, where workers, including children as young as seven, are frequently exposed to hazardous conditions. Policymakers, industry leaders, and researchers must address these issues promptly in order to mitigate the unintended repercussions of a critical technology. Accelerating battery reuse instead of, or in addition to, recycling or landfill disposal is one critical intervention that requires more research. (Taylor, 2021)

Although the production of the metals needed for electrification is important to understand, it is not of basis to this investigation, therefore no further time will be spent on investigating the supply end of things.

Economics of Recycling

Next it is important to explore the economics of recycling and whether it is worth exploring. In order to provide an understanding it is important to first understand the macro outlook in the li-ion market.

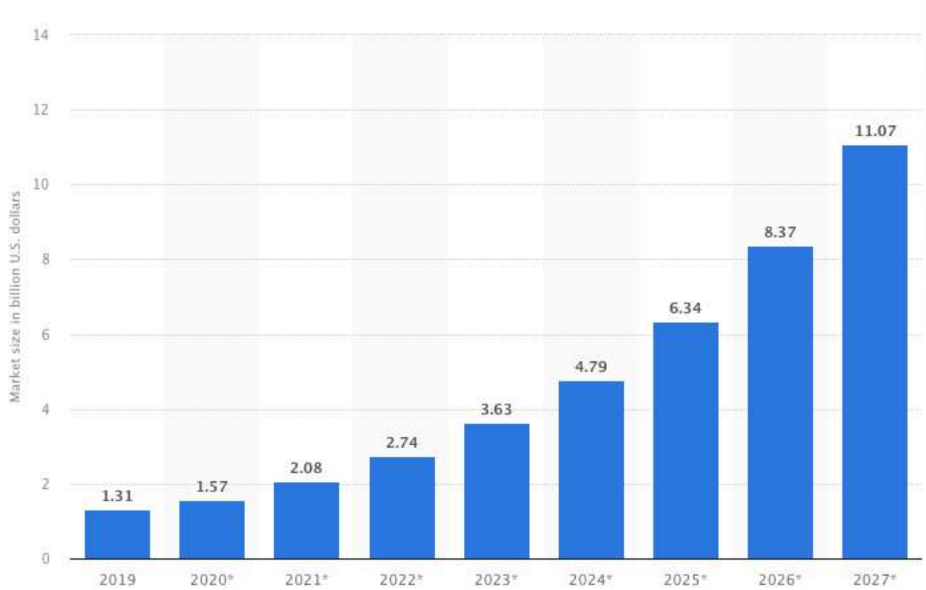


Fig.15 Ion lithium recycling market size in billion USD, in the years 2019 – 2027, (Statista, 2020)

Given the data presented in figure 16 it become apparent that the market size is correlated with the huge increase in li-ion production as stated in figure 5. Which allows us to further an even better understanding of the framework of end of life management and why it is significant to both the private and the public sector.

To further expand on the topic it is important to recap a sound understanding of where lithium is being produced and where currently in the year 2022 recycling facilities are engaging the process of end of life management for li-ion EV batteries. This is important to this investigation as the economic viability is a crucial and decisive factor in the establishment of a sound end of life management system for EV li-ion batteries.

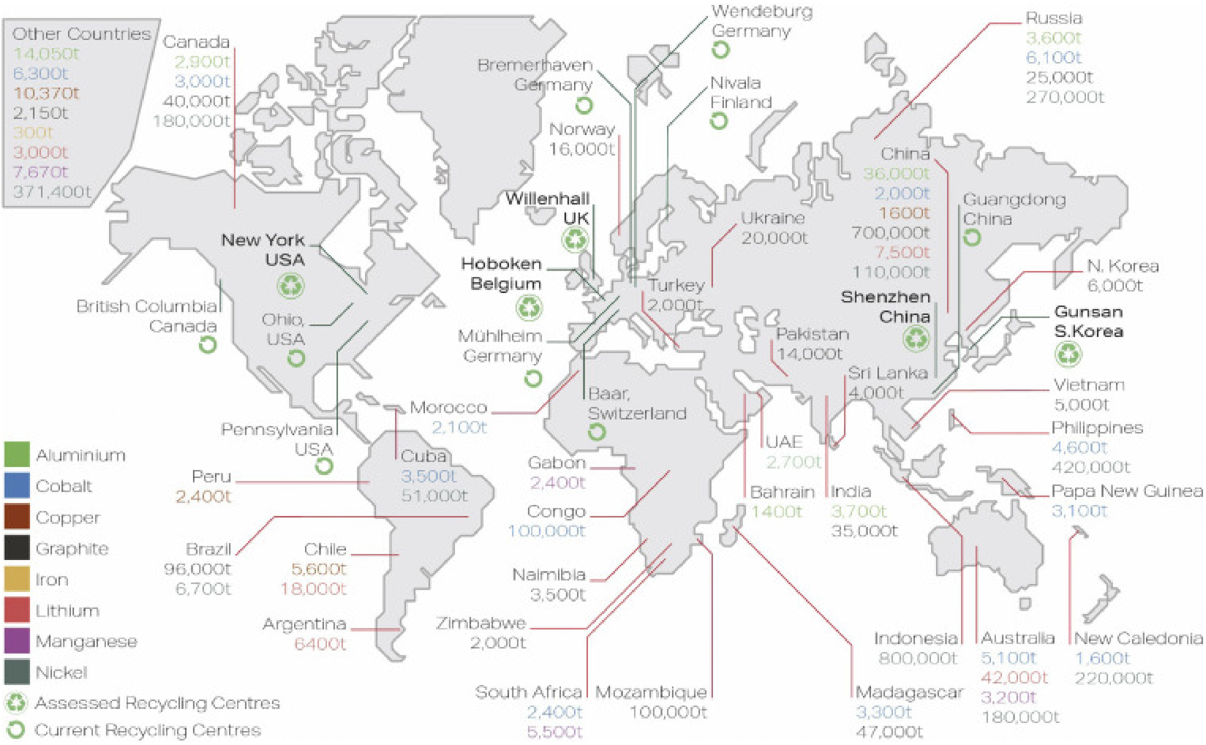


Fig. 16 In 2019, global mine production for raw minerals contained in LIBs (Mineral Commodity Summaries 2020, 2020) and the locations of a selection of LIB recycling plants (Mineral Commodity Summaries 2020, 2020). The recycling facilities in bold are the ones that were evaluated in this study. (Science Direct, 2020)

This figure has been included due to the before mentioned reasoning but even more importantly due to the fact that li-ion batteries are large and heavy, the weight of a standard Tesla Model 3 battery is 540 Kg, Yet this is deemed to be one of the rather light EV li-ion batteries, the Model X battery is already reflected to weigh over 800 KG, this is a huge and gullable challenge for the end of life management of these batteries, due to the extensive costs of logistics in moving the batteries to the purposed recycling facilities. (Casper, 2021)

Given figure 17 most of the active recycling facilities are within Europe and the United States of America, with a further potential for assessed recycling centers in the east. China is the only country with an active recycling facility in Asia. Which is the facility in Guangdong China. What is important to note is that there is no recycling facilities within the eastern European Countries, yet these countries fall under the directives of the European Union which is worth investigating due to the fact that allot of taxation is to be expected in the next years, thus eastern

European nations are expected to follow suit by electrifying their vehicles. Leading to the question where these li-ion batteries will be recycled? As the logistics to facilities in the east will be to costly to endure.

To further understand the economic viability of recycling, and why this investigation only analyzed the Hydrometallurgical and Direct method of recycling, It is important to validate the claim of logistics being the biggest Burdon in establishing a profitable business case in recycling.

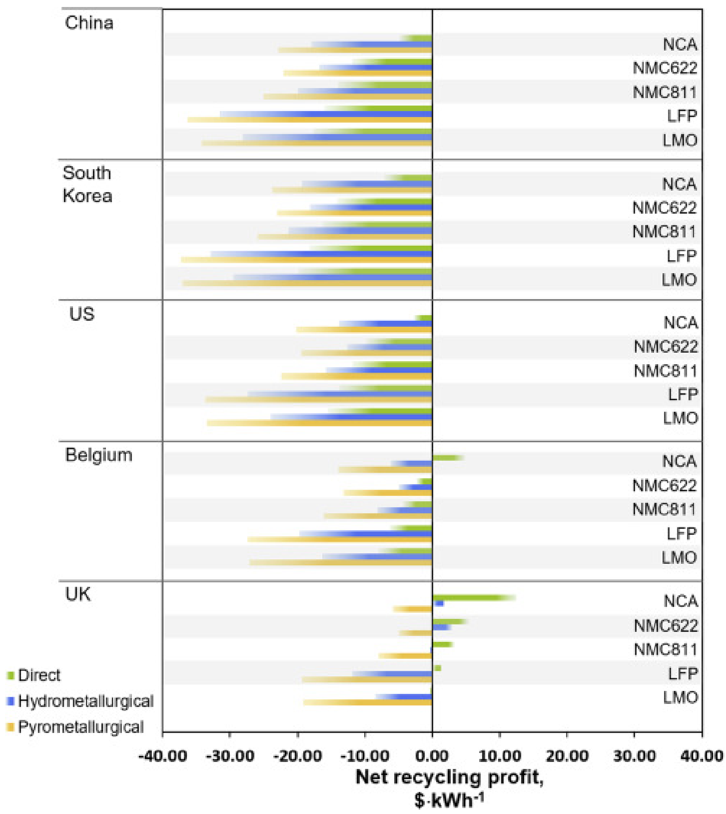


Fig 17. With rising transportation costs, EV battery net recycling profits are expected to rise. (Lander, 2021)

Using reported transportation costs, net recycling revenues in $kWh1 were compared for five nations. Overall losses are represented by bars pointing to the left, while overall profits are represented by bars pointing to the right. (Lander, 2021) The net profit is measured in Dollars per kWh.

To expand on the validity of the figure above one must take into account the transportation costs; Shipping from the UK collection location to South Korea and China costs 1.24 $kWh, Belgium and the UK 0.39 $kWh, and the US 1.55 $kWh, according to reported transportation costs for 8,000 tonnes cells Transportation accounts for 7–13 percent of total recycling costs in China, South Korea, and the United States, depending on the recycling process, and about 2% in Belgium and the United Kingdom. The overall transportation costs increase dramatically when the EverBatt transportation fees are used instead of the above quotes in the cost model (Figure S3B). In this scenario, shipping to China costs 28.02 $kWh1, shipping to South Korea costs 26.62 $kWh1, and shipping to the United States costs 18.08 $kWh1. Transportation costs 6.22 $kWh1 and 0.83 $kWh1 to Belgium and the United Kingdom, respectively. This raises China's transportation cost contribution to >70%, South Korea's to 65–70%, the United States' to 50%, Belgium's to 20–25%, and the United Kingdom's to 5%. Only in-country recycling in the UK and direct NCA recycling in Belgium are profitable at this point. For all chemistries and recycling techniques, recycling abroad becomes uneconomic. To make direct recycling of an NCA pack economical in China, for example, transportation costs would have to fall by more than 60% to around 10.50 $kWh1. (Lander, 2021)

To be profitable, shipping costs for other battery chemistries or pyrometallurgical recycling would need to be reduced much more. The difference in transportation costs between the quoted costs and EverBatt could be due to the fact that EverBatt's transportation cost is from 2015 and is based on the US average, whereas the costs based on quotes are current and specifically given for transportation from a collection site in the UK to a recycling site. (Lander, 2021)

Lader goes on to iterate that even though at the moment there is margins that would indicate that it is not yet profitable, there will be in the future to what she calls “profitability through scale” In which she iterates the significance of economies of scale; A sensitivity analysis was performed for the recycling cost and NRP (Net recycling profit) as a function of the yearly cell throughput in a UK recycling facility for an NCA battery pack to assess the impact of economies of scale for recycling profitability. With volumes of 1,000 to 15,000 tonnes per year, the estimated recycling cost drops dramatically. According to the findings, the hydrometallurgical procedure is marginally less expensive than pyrometallurgical and direct recycling. The disparities in the recycling processes are more obvious when it comes to the NRP, with direct recycling yielding the biggest profit. The pyrometallurgical, hydrometallurgical, and direct recycling processes all have breakeven points of 17,000 tonnes per year, 7,000 tonnes per year, and 3,000 tonnes per year, respectively. (Lander, 2021)

Raw material prices, in turn, are influenced by mining companies' investment cycles, gaps between finance and delivery of raw materials, and geopolitical concerns that can disrupt supply. Because cobalt is the most precious ingredient in current battery chemistries, the current trend of moving away from high cobalt content and toward Ni-rich and LFP battery chemistries will have a significant impact on recycling profitability. Compares the economies of scale for an NCA battery with and without money produced from recovered cobalt to demonstrate this. In this scenario, the profitability criterion for pyrometallurgical recycling rises to >50,000 tonnes per year and for hydrometallurgical recycling to around 17,000 tonnes per year. (Lander, 2021)

These findings are made clear in the following figure:

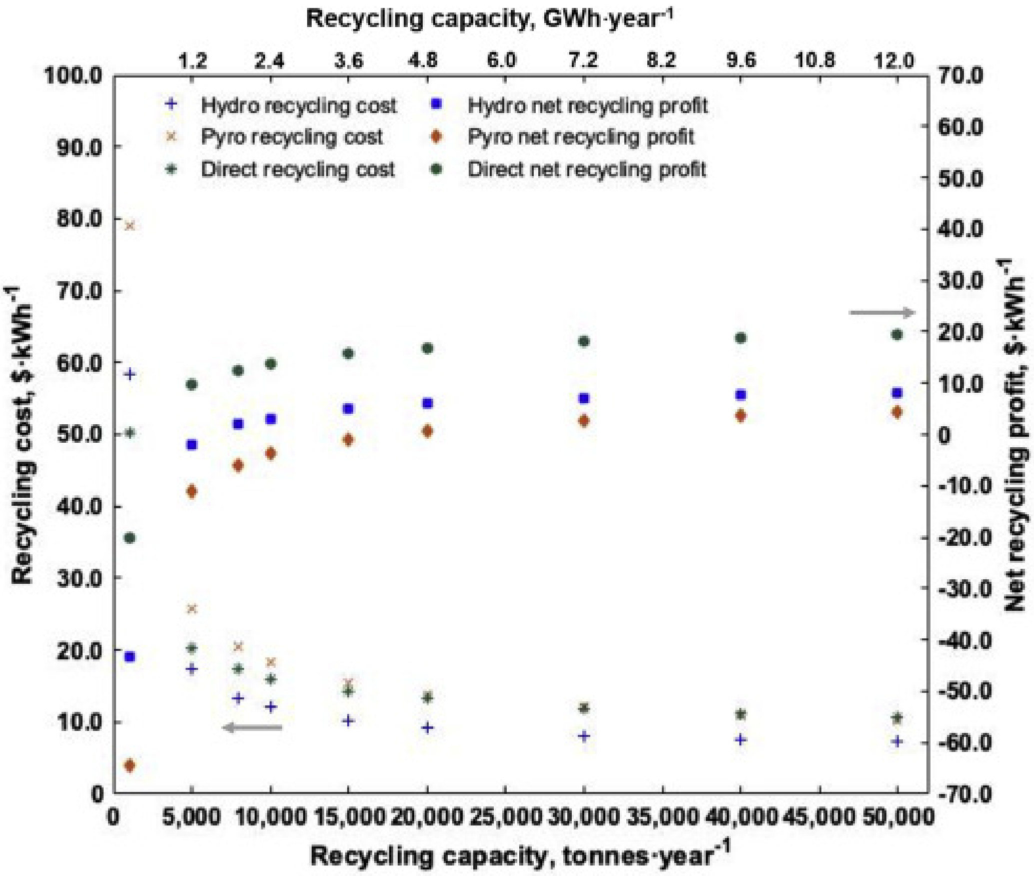


Fig. 18 Economies of scale in recycling, displaying profitability and loss margins, as given by the unit metric USD – kWh -1. (Lander, 2021)

Understanding that economies of scale are crucial to the economic viability of recycling and consequently the end of life management of recycling, is crucial for this investigation. One might question whether such economies of scale will work in the environment we are currently working in today. Given the huge increases in li-ion batteries as seen in figures 5 and 16 it becomes more than apparent that there will be more than enough material inflow to appropriate working economies of scale. As given by the graph above done by Lander, profitability really starts to work closer to recycling capacity of 50,000 tones per year. This has many implications, firstly, it will mean that there will only be limited space in the industry, providing huge barriers of entry for new businesses. Secondly, the logistical implications of the supply chain must be efficiently managed, as they account for the main costs after the capex investment for the infrastructure. This was crucial to this investigation as it allows us to provide decisive findings for hypothesis 3.

Repurposing li-ion batteries

Repurposing batteries, is a underlying argument that many specialists suggest can reduce the overall CO2 impact of li-ion batteries. Many believe this to be a solution to minimizing the emissions connected to electrification entirely. This investigation stipulates that repurposing is a mechanism to prolong the life of EV li-ion batteries, yet cannot replace the ultimate process of recycling.

Initially it is important to understand the real impact of repurposing li-ion batteries, in this case the investigation refers to the work by Cornell university.
Cornell University researchers published a study recently that details strategies to sustainably repurpose spent lithium-ion electric vehicle batteries to reduce their carbon impact, which was partially sponsored by the US National Science Foundation. The researchers looked into how lithium-ion EV batteries' energy output and environmental impact are influenced by battery chemistry, reuse, and recycling.

According to the study, if a lithium-ion EV battery is reused before being recycled, its carbon footprint might be decreased by up to 17%. Batteries with insufficient energy storage capacity can be converted to store wind and solar power. The findings will aid in the development of lithium-ion batteries for electric vehicles that are built for long-term performance rather than short-term efficiency.

"What to do with all of these retired electric vehicle batteries is going to be a significant issue," one of the study's authors, Fengqi You, said. In terms of how batteries are made, used, and recycled, the researchers examined environmental and economic concerns.

"Today's lithium-ion batteries are engineered for performance rather than recycling or reuse," You explained. Lithium-ion batteries typically have a lifespan of 12 years or fewer before they lose their ability to power a car. "Right now, there's very little discussion on how to improve battery design for recycling or reuse from an environmental standpoint."

The demand for recycling facilities that can dismantle li-ion electric vehicle batteries and extract the basic materials inside is currently outstripping supply. That demand will only increase in the coming years due to the volume of spent batteries that will need to be recycled. (Macaine, 2021)

This review by the national science foundation again proves this thesis rhetoric that we will have to optimize our recycling capacities in order to sustain the huge demand in li-ion batteries. Yet more crucially it extrapolated evidence that , repurposing could actually reduce the lifetime carbon footprint of li-ion batteries by an astounding 17% which would be a significant decrease.

Challenges of repurposing

Repurposing is challenging as its impacts and implementations depend highly on the chemistry behind each of the li-ion batteries. As already mentioned in the section on types of li-ion batteries there is a multitude to be considered here. Furthermore aspects such as battery design, disassembly mechanism make it hard to efficiently repurpose li-ion batteries.

This section will primarily focus on the work by J. Pyper, in which she provides a sound understanding of the challenges and current developments within the industry of repurposing li-ion batteries.

Previous research has emphasized the necessity of LIB design for recycling. Standardized battery design with a simple disassembly mechanism, such as cell-to-pack technology, can assist address automation and robotic disassembly difficulties while also increasing recycling efficiency. LIB recycling can eliminate several complicated separation operations, which would result in reduced yield and product purity, by using automated disassembly instead of shredding . Furthermore, switching aqueous binders for polyvinylidene fluoride (PVDF) binders not only benefits the environment, but also simplifies material recovery and improves the economic feasibility of LIB recycling. Materials with higher purity and yield might be recovered with less energy and chemical inputs using an optimized LIB design for automated disassembly and recycling, resulting in additional economic and environmental benefits. (You, 2021)

Another challenge revolving around second life phasing and repurposing of li-ion batteries is the fact that li-ion batteries that have been retrofitted for reuse require substantial testing and improvements to assure that they will work reliably in their new role. In order to succeed, the embryonic second-life battery sector requires a continuous supply of batteries, client demand, and investment. (Pyper, 2020)

The wide variety of electric vehicle battery packs on the market adds to the difficulty of processing and reconfiguring the batteries for new applications, as it necessitates extensive reverse engineering even before the battery testing process can begin. Smartville Energy, a spinoff from UC San Diego's Center for Energy Research, has created a battery reconditioning technique that experts believe is vital to bringing the technology to scale.

Smartville's uniquely engineered power converters and conditioning process purposefully slows the battery testing process to balance the health of the batteries across the entire system, rather than speeding it up like RePurpose and other companies in the space do. Because the battery health check entails charging and discharging the batteries multiple times over several weeks, this process generates an extra revenue stream by selling electrical services from the batteries while they are being tested. (Pyper, 2020)

"All of those varied batteries from different vehicles, makes and models, as well as power-coupling formats, are brought into the same modular architecture by our control and power electronics design," stated Smartville CEO Antoni Tong. "Then, through the conditioning process, each of them is cycled in a way that improves uniformity, and those operations are coordinated with a grid service at the same time." (Pyper, 2020)

Another California business, ReJoule, which earned $2 million from the EPIC program, takes a unique method to optimizing second-life batteries that begins within the vehicle. The battery system can be optimized over its entire life by using ReJoule's technology on a new battery, allowing it to last even longer. (Pyper, 2020)

"The notion is that once our battery management system is installed in the car and we have this real-time state-of-health measurement, transitioning from a first-life to a second-life application will be lot easier," said Steven Chung, founder and CEO. (Pyper, 2020)

"We wouldn't require any further testing; we wouldn't have to remove the battery from the vehicle, bring it to a certain test center, perform the testing, and then transport it to whatever second-life application," Chung explained. "It might be a lot more efficient." (Pyper, 2020)

This section provided this investigations outlook on hypothesis 1 with critical insights that will provide a sound understanding to proving or disproving said hypothesis, the many challenges within the repurposing framework of li-ion batteries will prove insightful in many regards.

Status quo of second life / repurposing li-ion batteries

Lithium-ion batteries that have been reused or "seconded" still have a lot of life left in them, but the idea of employing them in stationary applications has yet to gain hold. New research, increased interest in the automobile business, and a developing startup ecosystem imply that this may be changing now. (Pyper, 2020)

It is stated that even some of the big car makers such as GM are exploring the idea of repurposing EV batteries.

Creating a circular supply chain for EV batteries, according to Dane Parker, GM's chief sustainability officer, is one of the company's primary efforts to lessen its environmental footprint, he said in an interview at the company's EV Day event earlier this year. He claims that GM's new Ultium battery pack was developed with second-life applications in mind, and that the company is actively working with partners to establish a business case for battery reuse. He stated of second-life batteries, "We honestly believe it's very viable." "If you build them with that goal in mind, it'll be a lot easier to integrate later." That's exactly what we're doing right now." (Pyper, 2020)

GM isn't the only EV manufacturer paying attention to the second-life battery market. In 2015, Nissan was one of the first major automakers to test second-life electric vehicle batteries in a grid-scale storage system. During an 18-month pilot project with Pacific Gas & Electric in the same year, BMW tested used batteries in demand response events. Daimler AG also announced intentions to construct a 13-megawatt-hour second-life battery storage unit at a recycling factory in Lünen, Germany, in 2015. Mercedes-Benz Energy, a division of Daimler, teamed up with Beijing Electric Vehicle, one of China's top EV manufacturers, last year to develop an energy storage system based on discarded EV batteries. Rivian, an American electric truck business, developed its battery packs from the start to enable end-of-life repurposing as simple as possible, even if it hasn't entered the stationary storage area directly. Proterra, an electric bus maker, followed a similar technique. (Pyper, 2020)

Economics of repurposing

Automakers aren't the only ones that are interested in second-hand batteries. According to Mathews, a rising number of project developers are beginning to regard second-life battery storage as a method to lower the capital costs of commercial and grid-scale battery installations. This indicates a departure from the modest domestic and off-grid battery applications for which recycled batteries were first evaluated. (Pyper, 2020)

Mathews and five other current and former MIT researchers concluded in a study published in Applied Energy that lithium-ion batteries could have a profitable second life as backup storage for grid-scale solar photovoltaic installations, where they could operate for a decade or more in this less-demanding role. (Pyper, 2020)

The findings are based on a thorough examination of a hypothetical grid-scale solar farm in California, which included real-world data on solar power availability, battery degradation, and other variables. If the reused batteries were 60% or less of the original battery pricing, Mathews and his co-authors estimated that a system of second-life battery installations combined with a 2.5-megawatt solar project would be a successful investment. By the mid-2020s, a McKinsey study estimated that second-life batteries might offer a cost advantage of 30 to 70% over new battery alternatives. (Pyper, 2020)

According to the same McKinsey estimate, the supply of used electric vehicle batteries might reach 100 gigawatt-hours per year by 2030, meeting half of the projected global demand for utility-scale energy storage in that year. (Pyper, 2020)

Survey Analysis

Now that we have provided an understanding of the economics revolving the end of life management of Li-ion batteries and provided sufficient understanding that there is profits to be made, especially regarding the establishment of economies of scale. This investigation will now analyze a primary source survey that will shed light on the mindsets of a random sample set of 52 people. This is crucial to this investigation as the argument of recycling depends highly on the subsidiary funding of governments (Walker, 2022) , especially in the early steps of establishing the required supply chain and infrastructure needed to facilitate an efficient recycling framework. Since all European nation states live under democratic rule, it is of interest to understand what the citizens think and understand in regard to recycling.

In order to make this a unbiased sample set and reduce the margin of error, a group of 54 people was examined. Before analyzing the results of the survey it is important to understand the theoretical framework behind the questions:

General question reasoning

What is your Age?

- Appropriate in order to understand how differently generations might think of the problem of recycling, it is especially important to include young; 20 – 30 year old's as the electrification will be critical to their lives.

What is the highest level of school that you have completed?

- It is furthermore interesting to see a correlation between understanding the theme of recycling from the point of view of education, as this will give crucial understanding of whether the government needs to provide more knowledge to people with a lack of higher education.

Do you believe the future of mobility (Cars, Trucks) will be Electrified?

- The aim of this question is to provide an understanding of the general notion of electrification and whether people see the electrification as a trend with an end, or whether they see electrification as something that is here to remain and impact our future lives, this will provide a basis for establishing a business case in hypothesis 3.

Do you believe electric vehicles are better for the environment than diesel or petrol engines? (year 2022)

- The underlying argument of electrification is to reduce CO2 in mobility, in the literature review of this thesis we have provided sound understanding that stipulates that electric vehicles are in fact better for the environment, yet this depends highly on the energy mix fueling the vehicles, and the lifetime usage, from mining to end of life management. Understanding what the status quo thinks of this notion is crucial for the longevity and success of electrification.

Do you know how Lithium-Ion based batteries are made?

- This question is aimed at analyzing whether people understand the harsh conditions that pressure the supply chain of li-ion batteries such as rare metal shortages and the mining process of said metals, since the investigation has proven that mining such metals can produce high levels of CO2, which again questions the underlying argument of why the world is electrifying their vehicles.

Do you know how long a lithium-ion electric vehicle battery can be used? (on average)

- Since all hypothesis investigated in this thesis are reliant on the establishment of waste, more precisely li-ion waste, it is important that people know that li-ion batteries have an expiration date, which is reached after roughly 7 – 8 years, if people don't understand this fact, they might underestimate the need for proper end of life management mechanisms, thus, oppose subsidy expansions into the field of waste management.

Do you know what end of life management is?

- This is a very basic, yet crucial question to ask, as it is the substance of this investigation.

Do you agree/disagree: We currently recycle our electric waste, ethically and efficiently?

- As the literature review identified, our current system of end of life management and the general notion of recycling electric waste is the opposite of ethical and efficient, it is important to understand whether people know of this fact. As otherwise they would be sufficiently pleased with the continuation of the current status quo of recycling electric waste.

Do you agree/disagree with this statement: As long as CO2 emissions are not produced in a given City/Area, the City/Area can be deemed emissions free?

- Since there is many city and country plans that are aimed at going CO2 neutral within the next 20 years, it is of significance to understand the posed question, as the electrification of vehicles might not cause CO2 emissions within the location of usage, but through the literature review in this investigation it has become apparent that in supply chain management, and end of life management, there are considerable amounts of pollution and CO_2 emissions being produced. If the status quo agrees with the mentioned statement then current political promises might hold truth of emission free cities, yet it boils down to the fact that we live under one ozone layer and live on one planet, thus emissions must be reduced through a global effort rather than having signal nations on the forefront of climate neutrality.

Analysis of survey findings

Having understood the theoretical framework behind the questions of the survey, the next section of this investigation is dedicated at iterating the results of the survey. Henceforth answering the substance of the questions, outlining important facts in regard to the hypothesis set to be questioned.

Initially it is key to understand the sample set, 54 participants were recorded, of which 18 were aged 18-24, 32 were aged 25 – 34, 2 were aged 35 – 44 and 2 were recorded to be over the age of 55. This is an indicator that the sample set is broad and therefore significant, yet does show that the mean candidate was aged in the demographic from 25 – 34.

When regarding the educational level of the participants, these results were collected: The majority of participants (25/54) had a Graduate level degree, a close second are individuals with a bachelor's degree amounting to (11/54). 14 individuals did not yet have any college degree, within the sample set there was also one outlier, who stipulated he/she had no degree or school diploma. Given the results one has to concur that this is a highly educated sample set and thus does not represent the mean of the general population in Europe as the mean percentage for European nation states lies at 40%. Given the data, this sample set exceeds this mean, as 70% of recorded answers are individuals with a higher education. This is critical to understand, as we cannot presume that the results of the survey study are representative.

The first interesting question to analyze is that of whether people generally believe that "the future of mobility will be electrified". Interestingly enough there is a discrepancy, 16 people answered that they do not believe the future of mobility will be electrified. Interestingly enough the majority of people answering no, were classified as having a graduate degree or at least some college experience. The majority of the sample set stated that they do believe that future mobility will be electrified. Understanding the fact that even under the higher educated there is not yet a homogenous understanding of the future of mobility is interesting to our analysis. As this could affect the purchase rates of vehicles and thus have impact on the production numbers of li-ion batteries and their subsequent end of life management. Yet one must state that the majority of answers indicated that the future of mobility will be electrified. Which proves critical to this investigation as it allows us to continue a reasonable investigation into the three hypothesis.

In order to further appropriate the need for end of life management mechanisms, the following question was asked toward our sample set. The question at hand was: Do you believe electric vehicles are better for the environment than diesel or petrol engines? (year 2022) This question showed very interesting results. Since the spread within the answers was almost equally equated between yes and no. 34 people answering with yes and 24 people answering with no. a fascinating result, since most of main stream media supports the fact that electrified vehicles are better for the environment. Regarding the fact that we have a highly educated sample set, it is possible to entertain the fact that many of the individuals within the sample set have been confronted with the statistics in regard to CO2 emissions during the mining process and the wasteful and outdated end of life management of e waste.

In order to investigate this notion further, I chose to interview two of the individuals in the sample set, One who answered yes and one who answered no, they will be referred to as candidate x and y respectively with candidate x answering yes and candidate y answering with no. First I asked why they chose their respective answers. Candidate x who had 2 years of college experience, stated that he believed they were better for the environment since they did not produce emissions while the vehicle was being operated, quite literally pointing out the fact that there was no exhaust on the vehicle. This answer gives us an indication on how people measure the fact of low emissions, in this case it was measured from the "point of touch" meaning as soon as the consumer uses the vehicle. There was no regard given to the emissions caused in the creation process and in the end of life management of the vehicle. Contrarily individual y stipulated a very sound and reasonable answer to why he indicated that electrified vehicles are in fact not better for the environment. Stating that the main reason for this was the logistical problem from creation to assembly to recycling. As we know from our analysis in the literature review this is a very valid point. Yet no regard was given to the problematic emission heavy mining and disablement process.

To further investigate the notion of why the majority of individuals answered yes to the previous questions of: “Do you believe electric vehicles are better for the environment than diesel or petrol engines? (year 2022)” It was necessary to find out whether the sample set knew how Li-ion batteries were produced. Interestingly there was a significant correlation between people answering yes to Question 4 and people answering no to questions 5. Allowing us to understand that most people regarded electric vehicles to be better for the environment because they did not know about the mining process of metals required for li-ion. This validation is supported when regarding Question 8 which asked “Do you know what end of life management is?” in which the same people who answered yes to question 4 answered no to question 8, again corroborating the notion that people only measured the emissions and contribution to the environment during the usage of the vehicle. This fallacy is a contributing reason to why the end of life management of li-ion batteries is so backward and not up to date to the expected production cycles of li-ion batteries.

The highest spread of all was found in question 9, “Do you agree/disagree: We currently recycle our electric waste, ethically and efficiently?” In order to visualize the response spread I have chosen to include the following figure stipulating the questions answer spread:

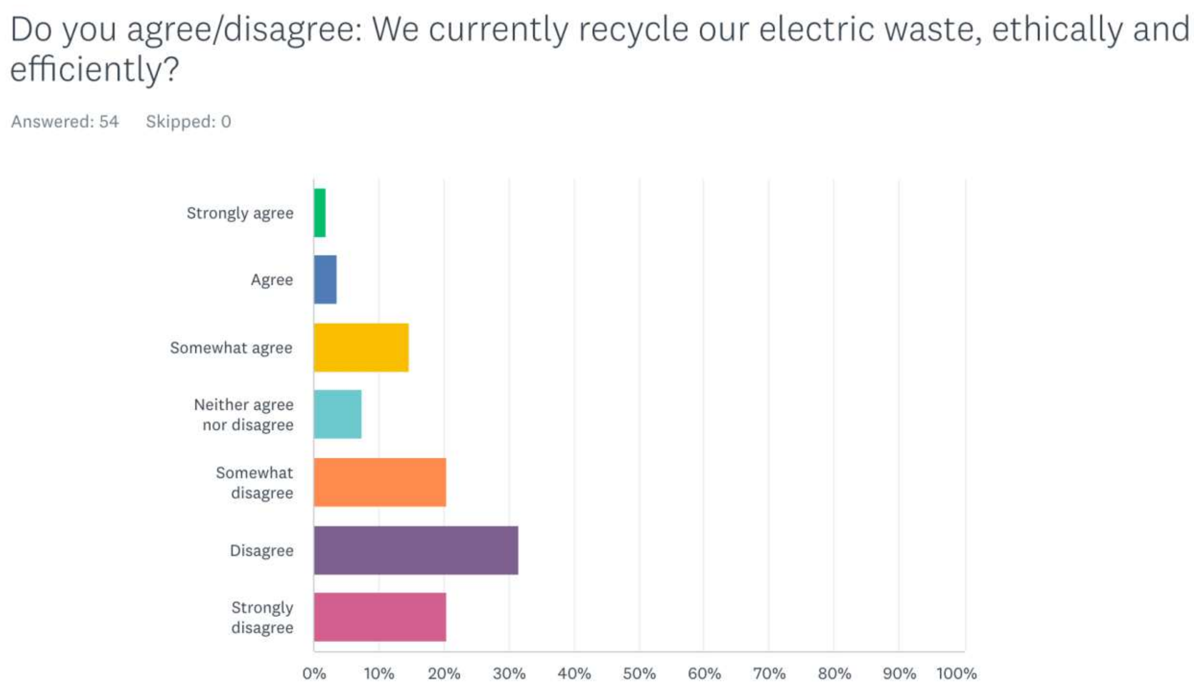


Fig. 19 Answer spread to Do you agree/disagree: We currently recycle our electric waste, ethically and efficiently?".

Although the majority of answers falls under the attributed category of "disagree" there are many individuals whom believe that our current recycling procedures are ethical and efficient. This obstructs in some sense the underlying arguments within this thesis, which primarily stress the importance of establishing new and efficient models of recycling. Yet the majority of the sample stated that they disagree, when further investigating, there is a correlation between highly educated people believing we currently do not recycle ethically and efficiently.

The last question in the survey and most definitely the most crucial in regard to this thesis is: Question 10: "Do you agree/disagree with this statement: As long as CO2 emissions are not produced in a given City/Area, the City/Area can be deemed emissions free?" in which 50% stated that they do not agree, this is crucial as many cities have begun planning "going emissions free" by 2030 or 2040, Yet the goods used and consumed within the city are not accounted for within the stipulations of going emissions free. Stipulating that many cities actually agree with the fact that as long as CO2 emissions are not produced in a given City/Area, the City/Area can be deemed emissions free. One factor to consider here is the current framework of outsourcing our waste to landfills in LEDC countries. After having conducted an analysis into the damaging and unethical practices of outsourcing our waste, one must stipulate that those emissions have to be attributed to the country of origin. This shows relevance since almost 50% of our sample set disagrees with question 10.

Concluding, we have gathered more than enough evidence within this primary source survey that suggests end of life management of li-ion batteries needs to be increased and optimized, furthermore, we now have an understanding of the fact that highly educated people know of the fact that current recycling practices are not only inefficient but also unethical and therefore need replacing.

Conclusion

Through the numerous findings within this investigation, I have managed to gather assortments of empirical evidence that help understand the rational of end of life management within the li-ion battery market, these have established grounds on proving or disproving the three Hypothesis claimed in this thesis paper.

Hypothesis 1:

“Repurposing of Electric vehicle batteries will only work if the industry creates a viable tracking framework revolving around metrics such as; quality, energy density, Cost.” This claim holds truth when regarding the findings within this paper.

Repurposing is at a very early stage. As suggested by J. Pyper. Even though there is a multitude of companies involved in the process of repurposing batteries. There is an abundance of issues revolving around the aspect of second life and repurposing, starting from the lack of knowledge of the status of the battery. As Pyper states “The wide variety of electric vehicle battery packs on the market adds to the difficulty of processing and reconfiguring the batteries for new applications, as it necessitates extensive reverse engineering even before the battery testing process can begin.” (Pyper, 2021)

This reverse engineering can prove to be a challenging factor, yet when not knowing the status of quality, energy density and chemical composition the repurposing of batteries can become a time and cost extensive problem, which would slow down any factor of success.

Furthermore, Standardized battery design with a simple disassembly mechanism, such as cell-to-pack technology, can help tackle the challenges in automation and robotic disassembly and improve recycling efficiency. (You, 2022)

I propose a simple system of so called tracking of the li-ion battery, which is conducted during the time a vehicle is being serviced at a dealership. This could perfectly work in combination with the technology introduced by Rejoul and Smartville. After the testing for quality and energy density, the information would be relayed to a data base in which interested buyers of the battery can track the proposed metrics and thus provide an efficient understanding on how to reverse engineer the battery to fit the second life purpose. Furthermore, it would also allow the next use case to derive critical understanding of whether the battery is still worth repurposing or not.

Consequently, I can state that Hypothesis 1, holds truthful. Although one can critique the fact that it requires even more than a tracking mechanism to make the repurposing economically viable and efficient, such as the before stated need for a standardized battery design and a facilitation of an easy disassembly mechanism.

Hypothesis 2:

"The reuse (Recycling) of EV batteries and their subsequent components will be inevitable. Hydrometallurgical recycling in combination with Direct recycling will be key to facilitate a economically viable framework." To provide sound understanding of the conundrum, it was initially important to understand the processes of recycling and the demand for scarce metals within the production of li-ion batteries.

Understanding that many metals in regard to li-ion battery production are scarce and that current mining rates won't be able to facilitate a generous enough supply and demand equilibrium (Casper, 2021). One understands the importance of recycling. Furthermore, even when repurposed batteries will lose voltage capacity and thus quality to ultimately be inefficient to a rate in where the prolonged life no longer makes economical sense. (Pyper, 2021)

Although “Direct cathode recycling is the most environmentally favorable technology of LIB recycling, in concordance with previous findings” (You, 2022) Hydrometallurgical recycling will be needed aswell as it is the most profitable form of recycling li-ion (Lander, 2021).

Since profitability is crucial, I can iterate that although direct recycling is more efficient and less polluting, hydrometallurgical recycling will be key in providing a sound and efficient recycling framework.

Consequently, I can state that hypothesis 2 holds validity. Although in order to facilitate a truly economically and process efficient recycling methodology it will require a homogenous recycling method in the future, making one of the processes, direct or hydrometallurgical redundant.

Hypothesis 3

“There will be an opportunity to establish a sound and reliable business case in regard to EV end of life management within the European union.” In this case the investigation conducted an analysis of the current recycling framework, the projected increases in demand and the overall profitability within the current li-ion recycling framework.

Although one must stipulate that generating profitability in the current li-ion recycling market is not an easy task, it is possible. Especially when regarding the notion of increased economies of scale which result in the projected increases of li-ion production. (Casper, 2021)

Not only has this investigation proven that there is profits to be made in the recycling of li-ion batteries, it has furthermore proven the fact that the current industry is at the very early stage. Furthermore, when regarding figure 17, it becomes apparent that there is currently only a very limited number of recycling facilities, especially in the European region. If we take into consideration that “logistics account for the primary cost in the recycling process” (Casper,

2021) A well placed recycling plant, with access to shipping and rail transportation roots could in fact prove to be very profitable and necessary.

Additionally, this investigation has shed light on an additional economically viable income stream within the repurposing of li-ion, "If the reused batteries were 60% or less of the original battery pricing, Mathews and his co-authors estimated that a system of second-life battery installations combined with a 2.5-megawatt solar project would be a successful investment. By the mid-2020s" (Pyper, 2021) Yet this aspect of profitability is not directly related to the hypothesis since recycling concurs to be different than repurposing, I included it in the evaluation of hypothesis 3 since it would allow a company that is willing to position itself within the EV recycling market to establish more than one stream of income.

Another notion that supports hypothesis 3 is the fact that the EV market within Europe seems to be one of the fastest growing, which is a direct result of political factors and the benefit of high income states. "The European electric vehicle (EV) market experienced unprecedented growth in 2020, posting a 143% increase in sales of passenger electric cars from 2019" (Bernard, 2021)

Subsequently, with regard to increases in li-ion production especially in relation to EV, the fact that there is profitable recycling methods such as the hydrometallurgical method, in connection to the predicted affiliations with strong economies of scale one can state that hypothesis 3 holds valid. Yet one has to be realistic here, the infrastructural requirements will endow a huge amount of capital expenditure (CAPEX) and the fact that there will be huge barriers of entry to the market, make it highly unlikely for any new companies to emerge in the li-ion recycling market. As there are already quite a few multinational, stock listed recycling companies, ready to pursue such investments.

List of Figures

Key Definitions

Lithium-ion (Li-ion) Battery:

Lithium-ion (Li-ion) batteries are rechargeable batteries that are utilized in electric cars and a variety of portable electronics. They have a higher energy density than standard rechargeable lead-acid or nickel-cadmium batteries. This allows battery makers to save space, resulting in a smaller battery pack overall. (mdpi, 2008)

EV Battery:

A battery used to power the electric motors of a battery electric vehicle (BEV) or hybrid electric vehicle is known as an electric vehicle battery (HEV).
(Science Direct)

Recycling:

The process of transforming waste resources into new materials and things is known as recycling. This notion frequently includes the recovery of energy from waste materials. The ability of a substance to reclaim the qualities it had in its original form determines its recyclability.

End of Life management:

End of life management (EOL) focuses on, what happens to a product after it has expired its use. This step can involve replacement, repurpose or recycling of the product when associated correctly.

Circular Economy:

A manufacturing and consumption strategy that emphasizes the sharing, leasing, reusing, repairing, refurbishing, and recycling of existing materials and products for as long as possible.

Cathode:

The electrode of an electrochemical cell at which reduction occurs: a : the negative terminal of an electrolytic cell. b : the positive terminal of a galvanic cell.

Thermal runway:

Thermal runaway begins when the heat generated within a battery exceeds the amount of heat that is dissipated to its surroundings. If the cause of excessive heat creation is not remedied, the condition will worsen.

Energy density:

The amount of energy that can be stored in a given system, substance, or region of space. Energy density can be measured in energy per volume or per mass. The higher the energy density of a system or material, the greater the amount of energy it has stored.

Abbreviations:

Li-ion batteries:

“A lithium-ion (Li-ion) battery is an advanced battery technology that uses lithium ions as a key component of its electrochemistry. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons.” (Clean energy institute / University of Washington)

Battery types:

NMC:

“In short, NMC batteries offer a combination of Nickel, Manganese and Cobalt. They are sometimes known as Lithium Manganese Cobalt Oxide batteries. NMC batteries have a high specific energy or power. This limitation of either 'energy' or 'power' makes them more common for use in power tools or electric vehicles” (Accardo, Dottelli, 2021)

LFP:

The lithium iron phosphate battery or LFP battery is a type of lithium-ion battery using lithium iron phosphate as the cathode material.

NCA:

Lithium Nickel-Cobalt-Aluminum Oxide (NCA) is used as the cathode material for lithium ion batteries, and is mainly used in electric automobiles.

LMO:

A lithium ion manganese oxide battery (LMO) is a lithium-ion cell that uses manganese dioxide, MnO. 2, as the cathode material. They function through the same intercalation/de-intercalation mechanism as other commercialized secondary battery technologies, such as LiCoO.

BEV:

BEV (Battery electric vehicle) These are your pure electric cars. These cars are powered by rechargeable battery packs, with no secondary source of power. These cars plug into an electricity source to recharge.

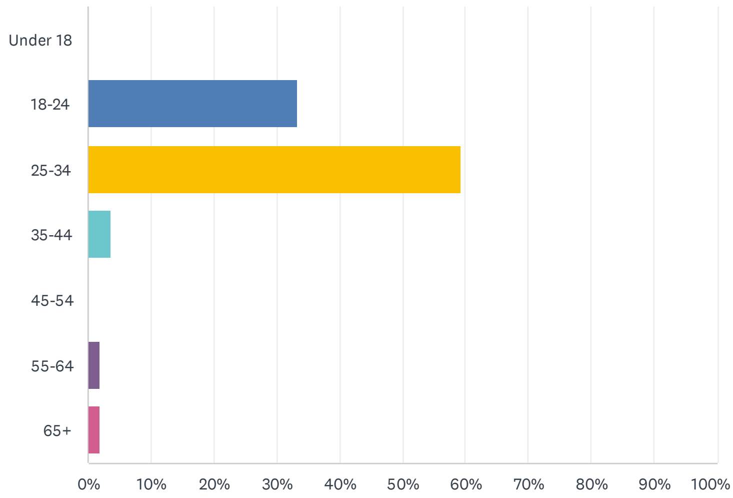
NRP: Net recycling profit

Appendix

Survey Findings

Q1 What is your age?

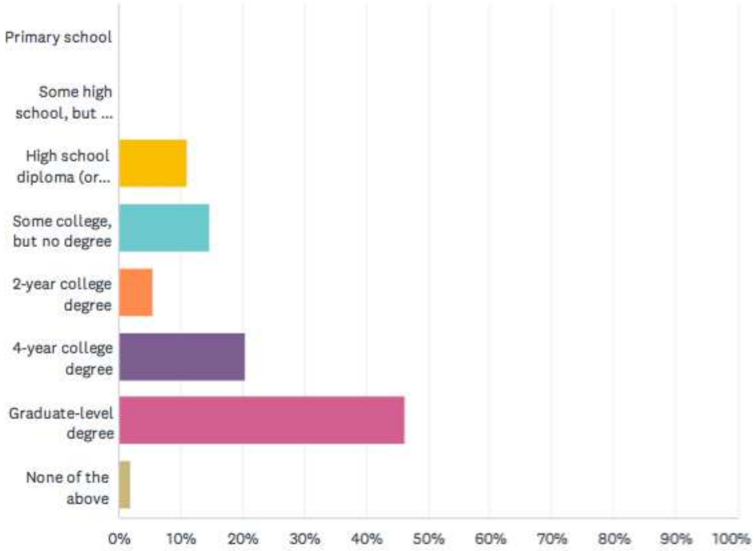
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Under 18	0.00%	0
18-24	33.33%	18
25-34	59.26%	32
35-44	3.70%	2
45-54	0.00%	0
55-64	1.85%	1
65+	1.85%	1
TOTAL		54

Q2 What is the highest level of school that you have completed?

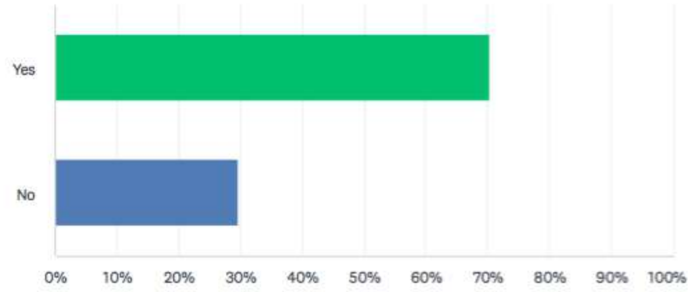
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Primary school	0.00%	0
Some high school, but no diploma	0.00%	0
High school diploma (or GED)	11.11%	6
Some college, but no degree	14.81%	8
2-year college degree	5.56%	3
4-year college degree	20.37%	11
Graduate-level degree	46.30%	25
None of the above	1.85%	1
TOTAL		54

Q3 Do you believe the future of mobility (Cars, Trucks) will be Electrified?

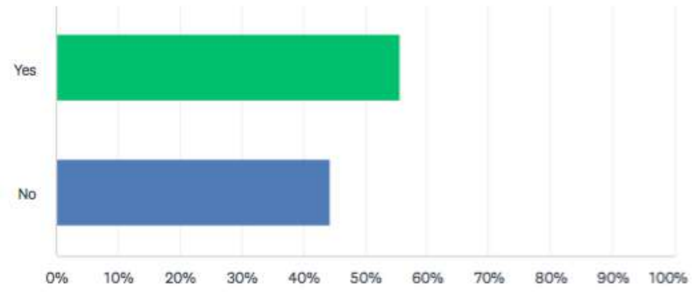
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	70.37%	38
No	29.63%	16
TOTAL		54

Q4 Do you believe electric vehicles are better for the environment than diesel or petrol engines? (year 2022)

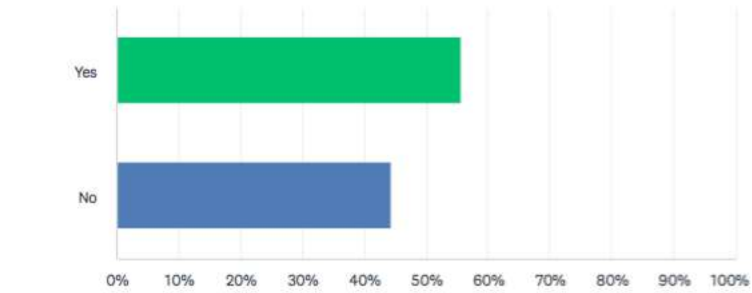
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	55.56%	30
No	44.44%	24
TOTAL		54

Q5 Do you know how Lithium-Ion based batteries are made?

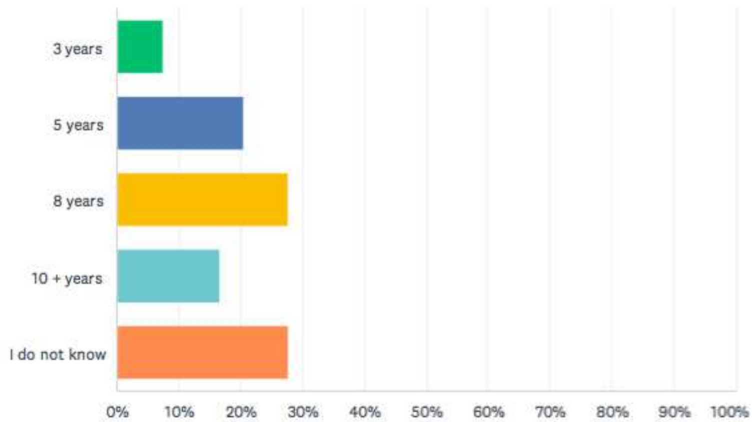
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	55.56%	30
No	44.44%	24
TOTAL		54

Q6 Do you know how long a lithium-ion electric vehicle battery can be used? (on average)

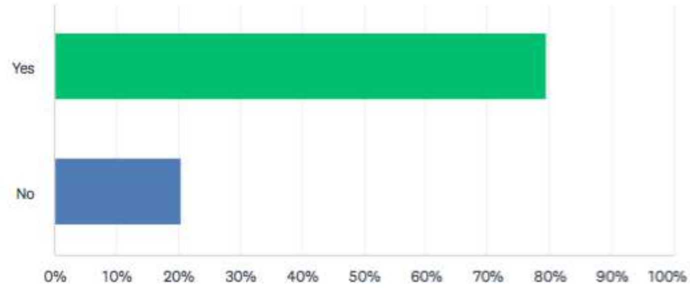
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
3 years	7.41%	4
5 years	20.37%	11
8 years	27.78%	15
10 + years	16.67%	9
I do not know	27.78%	15
TOTAL		54

Q7 Do you know what is meant by the term: circular economy?

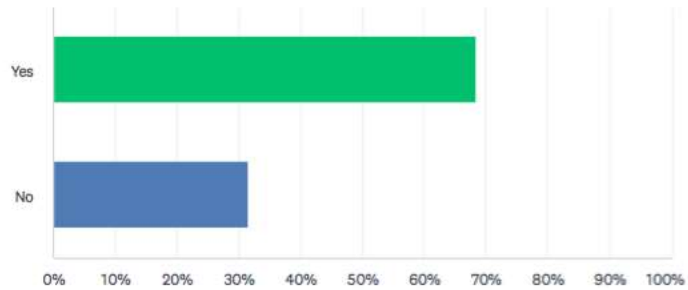
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	79.63%	43
No	20.37%	11
TOTAL		54

Q8 Do you know what end of life management is?

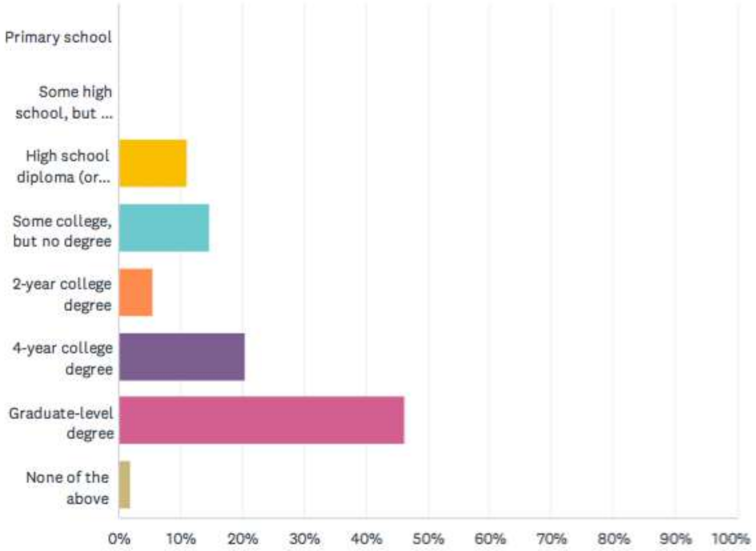
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	68.52%	37
No	31.48%	17
TOTAL		54

Q2 What is the highest level of school that you have completed?

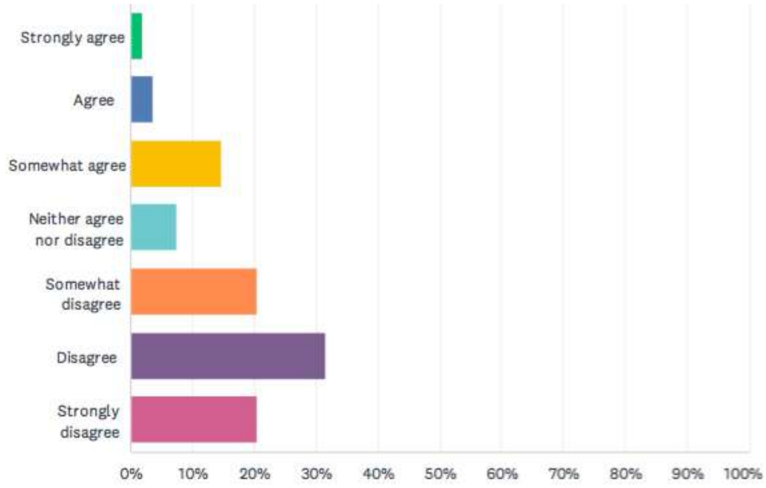
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Primary school	0.00%	0
Some high school, but no diploma	0.00%	0
High school diploma (or GED)	11.11%	6
Some college, but no degree	14.81%	8
2-year college degree	5.56%	3
4-year college degree	20.37%	11
Graduate-level degree	46.30%	25
None of the above	1.85%	1
TOTAL		54

Q9 Do you agree/disagree: We currently recycle our electric waste, ethically and efficiently?

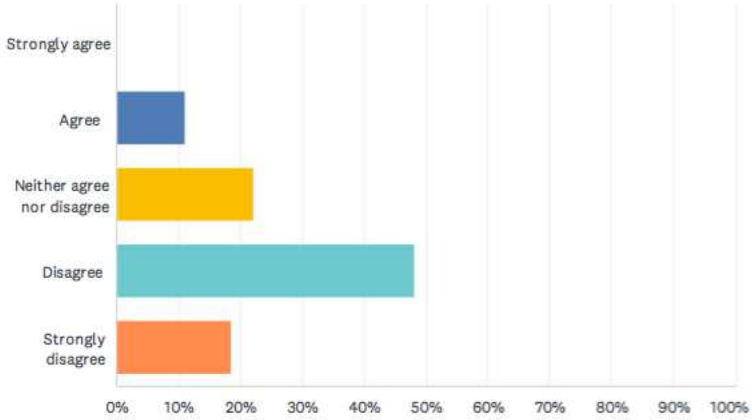
Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Strongly agree	1.85%	1
Agree	3.70%	2
Somewhat agree	14.81%	8
Neither agree nor disagree	7.41%	4
Somewhat disagree	20.37%	11
Disagree	31.48%	17
Strongly disagree	20.37%	11
TOTAL		54

Q10 Do you agree/disagree with this statement: As long as CO_2 emissions are not produced in a given City/Area, the City/Area can be deemed emissions free?

Answered: 54 Skipped: 0



ANSWER CHOICES	RESPONSES	
Strongly agree	0.00%	0
Agree	11.11%	6
Neither agree nor disagree	22.22%	12
Disagree	48.15%	26
Strongly disagree	18.52%	10
TOTAL		54

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