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EV battery state changes & RL considerations

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EV battery state changes & RL considerations

By

Muhammad Nadeem Akram

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2020

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January 14, 2020
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ABSTRACT

Electric Vehicles are becoming trendy and proved to have no harmful exhaust like traditional fuel-powered vehicles which makes them one of the best solution to reduce greenhouse gas emissions. As the world shifts towards electric vehicle adoption, we will need efficient power sources to provide enough capacity for all these vehicles to function. Lithium-Ion batteries are the driving force behind this new trend. The goal of this research is to analyze the lifespan and long-term ratio composition of Lithium-Ion batteries in electric vehicles by developing two models, an Absorbing Markov Chain model, and a Markov Chain Steady-State Census model. A sensitivity analysis is also conducted to alleviate the scarcity of enough input data. The models show that the lifespan of the new batteries can be extended by 4.5 years, which will have a positive environmental impact and reap economic benefits. Further, the long term composition of batteries in New, remanufactured, repurposed and recycled states can be projected. The increasing demand for EVs globally has created a necessity for more batteries to power them, and these batteries require materials to be made. By considering reverse logistics processes, it is possible to recycle batteries and recover the valuable materials. Not only does this support the environment, but given the rising demand and finite raw material supply, there is an opportunity to capture the economic benefit of recycling. From this research, the recovered materials cobalt, lithium, and nickel are calculated, and this is especially important for the optimal planning of sustainable manufacturing.
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# TABLE OF CONTENTS

DECLARATION OF ORIGINALITY .................................................................................................. iii

ABSTRACT ....................................................................................................................................... iv

ACKNOWLEDGEMENTS .................................................................................................................. v

LIST OF TABLES ............................................................................................................................. ix

LIST OF FIGURES .......................................................................................................................... x

LIST OF ABBREVIATIONS .............................................................................................................. xi

CHAPTER 1 ....................................................................................................................................... 1

INTRODUCTION ............................................................................................................................. 1

1.1 Background ............................................................................................................................. 1

1.2 Research Objective .................................................................................................................. 4

1.3 Research Purpose ..................................................................................................................... 5

1.4 Limitations ............................................................................................................................... 5

1.5 Thesis Outline .......................................................................................................................... 6

CHAPTER 2 ....................................................................................................................................... 7

LITERATURE REVIEW ..................................................................................................................... 7

2.1 Lithium-Ion Batteries ................................................................................................................. 7

2.1.1 Working Principles ................................................................................................................ 8

2.1.2 Cell Construction .................................................................................................................. 9

2.1.3 Degradation .......................................................................................................................... 11

2.2 Remanufacturing ...................................................................................................................... 12

2.3 Repurposing ............................................................................................................................. 16

2.4 Recycling .................................................................................................................................. 19

2.4.1 Recycling Processes .............................................................................................................. 21
4.11 Assumptions ........................................................................................................58
4.12 Consideration of Sustainability .........................................................................59
  4.12.1 Cobalt ........................................................................................................60
  4.12.2 Lithium ........................................................................................................61
  4.12.3 Nickel ........................................................................................................61
4.13 Recycling Efficiency .........................................................................................62
4.14 Volume of Raw Materials in EOL EV Batteries ..................................................62
4.15 Electric Vehicle and Battery Capacity ...............................................................62
4.16 Sensitivity Analysis ...........................................................................................64
  4.16.1 Results ........................................................................................................68

CHAPTER 5 ...............................................................................................................77
CONCLUSION .........................................................................................................77

References: ..............................................................................................................80
Vita Auctoris ............................................................................................................92
LIST OF TABLES

Table 1: Summary of Literature Review ................................................................. 31
Table 2: Lifespans of LIBs in EVs and Other Applications ................................. 51
Table 3: Lifespan Probabilities of LIBs in EVs .................................................... 52
Table 4: Environmental Benefits ........................................................................ 55
Table 5: Long Run Ratio Composition of LIBs ..................................................... 59
Table 6: Capacity and Total Number of EOL LIBs in mid-2042 .......................... 63
Table 7: Recovered Materials .............................................................................. 64
Table 8: Value of Recovered Materials ................................................................. 64
Table 9: Lifespans of LIBs in EVs and Other Applications (sensitivity analysis) .... 69
Table 10: Lifespan Probabilities of LIBs in EVs (sensitivity analysis) .................... 70
Table 11: Long Run Ratio Composition of LIBs (sensitivity analysis) .................. 71
Table 12: Environmental Benefits (sensitivity analysis) ...................................... 73
Table 13: Capacity and Total Number of EOL LIBs (sensitivity analysis) .......... 75
Table 14: Recovered Materials (sensitivity analysis) .......................................... 76
Table 15: Value of Recovered Materials (sensitivity analysis) ............................ 76
LIST OF FIGURES

Figure 1: Schematic of a Lithium-Ion Battery (Le, 2016)............................................. 9
Figure 2: Circular Economy Reproduced and Modified from Elia et al. (2017).............. 20
Figure 3: Process Flow of Forward and Reverse Logistics ........................................... 27
Figure 4: RL Process Flow of LIB Remanufacturing, Repurposing and Recycling ...... 28
Figure 5: States of a LIB’s Life Cycle ........................................................................... 38
Figure 6: Triangular Distribution, f(x) vs Number of Years ........................................ 46
Figure 7: Transition Probability Diagram ...................................................................... 50
Figure 8: Projected Global EV Stock ........................................................................... 53
Figure 9: Lithium-Ion Battery Market ........................................................................... 57
Figure 10: Assets Recovery ......................................................................................... 60
Figure 11: Lifespans of LIBs in EV and Other Applications .......................................... 69
Figure 12: Long Run Ratio Composition of LIBs .......................................................... 71
Figure 13: Environmental Benefits ............................................................................. 74
Figure 14: Total Number of EOL LIB and Capacity ..................................................... 75
Figure 15: Value of Recovered Materials ..................................................................... 76
LIST OF ABBREVIATIONS

DRC - Democratic Republic of Congo
EOL - End of Life
EPA - Environmental Protection Agency
EV - Electric Vehicle
GHG - Green House Gases Emission
GWH - Giga Watt Hour
HEVs - Hybrid Electric Vehicle
LCE - Lithium Carbonate Equivalent
Li$^+$ - Lithium-Ion
LIBs - Lithium-Ion Batteries
NMC - Nickel-Manganese-Cobalt
PHEVs - Plug-in Hybrid Electric Vehicle
RL - Reverse Logistics
SEI - Solid Electrolyte Interphase
SOH - State of Health
WH - Watt Hour
CHAPTER 1
INTRODUCTION

1.1 Background

Electric Vehicles are becoming more popular each passing day. In fact, these battery-powered modes of transportation are attracting the automobile and technology industries, and general public too (Bernhart, 2013). Since there is no harmful exhaust like traditional fuel-powered vehicles, Electric Vehicles (EVs) are an environmentally optimal solution to reduce greenhouse gas emissions. These emissions have been proven to induce climate change, and the rise in heat may make it difficult for organisms to normally survive in the coming years. In fact, from 1990 to 2012, there was a 41% increase in greenhouse gas emissions across the world (Samimi and Zarinabadi, 2012). In the US, about 28% of greenhouse gases come from the transportation sector (Jenn et al., 2016), which means that some changes need to be made regarding the emissions from vehicles. Taking the health impacts into account, EPA (2009) found that the tailpipe emissions that come from vehicles can cause cardiovascular and respiratory problems, along with sooner deaths from both short- and long-term exposure. Essentially, vehicles powered by current fuels (i.e. gasoline) have lasting impacts on both humans and their surroundings. However, electric vehicles can change this: the US Department of Energy (n.d.) say that while gasoline, hybrid, and plug-in hybrid vehicles produce 11,435 pounds, 6,258 pounds, and 6,044 pounds of carbon dioxide per year respectively; fully electric vehicles produce 4,352 pounds per year. Even considering the energy needed to make and power electric vehicles, Wilson (2013) made final estimate that in the US, 300g CO$_2$e/km come from gasoline vehicles while electric vehicles produce about 202g CO$_2$e/km. This is a huge environmental improvement in
relation to today’s standard vehicles, so if we prioritize shifting to EVs, the world can stay in livable conditions for much longer. On the topic of the benefits of EVs, Malmgren (2016) conducted an experiment that looked at seven comparisons between an electric vehicle: the 2016 Nissan Leaf (with a 24kWh battery pack), and a gasoline vehicle: the 2016 Honda Civic. Among the seven comparisons were of fuel costs and maintenance costs. The results were that EVs save $4,130 from fuel and $1,488 from maintenance throughout their Lifespans. Currently, although the down payment of EVs may seem high, it is a great investment in the long-run; once other costs become lower, EVs may become the better option to choose when comparing with today’s gasoline vehicles. Through forecasting, it is projected that in the year 2030, the global annual sales of passenger EVs will rise to 28 million (Bloomberg New Energy Finance, 2019). We would need very efficient power sources to allow all these vehicles to function, and Lithium-Ion batteries are the solution to this matter. Fabricated in the 1980’s, Lithium-Ion batteries first made their appearance for commercial use in the 1990’s (Nishi, 2001). With their high energy densities, low self-discharge, exceptional cycle lives, and very low damage to the environment, LIBs are becoming increasingly used worldwide, and the best choice for use in hybrid electric vehicles and electric vehicles (Wang, 2011; Lee, 2011). Lithium-Ion batteries have great efficiency, light weight, small volume, low maintenance, and are very reliable (Raszmann, et al., 2017; Ordonez, et al., 2016). These batteries are so crucial to EVs, that they account for up to 40 percent of the entire vehicle cost, with the material to make the batteries being the main expense (Nelson, 2009). Although our focus is on EVs, the use of Lithium-Ion batteries is not exclusively for them. This technology has been tested and can be used in a wide variety of appliances, from laptops to pacemakers, portable electronic devices,
aerospace systems, or power storage for sustainable energy sources (e.g. solar and wind turbines) (Dubarry et al., 2014).

There is always competition when it comes to management and quality of processes in the business sector: companies are constantly adjusting and improving organizational processes to meet optimal standards. This has led to the analysis of these processes becoming a large academic field, where people are required to utilize large amounts of data to create statistical models and evaluate them to see what can be perfected (Davenport, 2006; de Vries, 1999). A prominent and relevant method to develop a mathematical model to calculate the lifespan of LIBs of an EV is Markov Chains. These are mathematical models that use concepts of probability to describe how a system changes from one state to another. Markov processes have applications in modeling and analysis of a wide range of trends in many fields, including linguistics, biology, political science, medicine, economics, computer science, etc. The Markov property is applied to predict the future if one knows the current state, even when there is no information of its past states. Markov chain models are tools that allow process managers to yield planning results and what-if analyses in a short amount of time (Suri and Tomsicek, 1998). For industries, this is important, as the competitive nature of businesses requires reducing time used for demanding tasks, one of which is information collection of current processes and improvements upon them. The proposed mathematical model is expected to calculate the lifespan of LIBs of an EV and establish the steady-state census of the EV batteries. With a booming industry, these batteries are becoming important parts of our everyday transportation. This places a need for us to monitor and accommodate for any anomalies regarding warranty, demand, and inventory of LIBs.
When these batteries reach their end of life it is not wise to dispose of them. This is because they contain valuable materials such as cobalt, nickel, aluminum, lithium, and copper. Moreover, they harm the environment when they are dumped into landfills. After using LIBs in both EV and post vehicle application, through reverse logistics we can bring back these batteries to recycling facilities and extract those valuable materials to assist in sustainable manufacturing.

1.2 Research Objective

- The objective of this thesis is to develop an evaluating model of the electric vehicle Lithium-Ion batteries lifespan in order to identify the utility time of the LIBs for full term usage, new, remanufacturing, repurposing and/or recycling by using an absorbing Markov chain state transition probabilistic model, and;

- To develop a long run ratio composition model of electric vehicle Lithium-Ion batteries that can be used in forecast operations based on new battery injection quantity/number.

Research Contribution

The outcome of this research would contribute in the following aspects:

1. To develop a state transition probability matrix for Lithium-Ion batteries.
2. To develop an absorbing Markov Chain Model for the expected lifespan for all new, remanufactured, and repurposed LIBs.
3. To develop a probability ratio of electric vehicle LIBs which can be used as a prediction model.
4. To develop a steady-state census model to estimate the composition of the EV LIB market in the long run.
5. To investigate the environmental impacts that would take place when LIBs improve their Lifespans.

6. To consider the sustainability of raw materials after LIBs go through reverse logistics process.

1.3 Research Purpose

Climate change is a huge environmental challenge in addition to pollution. Although any form of effect is produced in certain area, the effect is extended globally. Likewise, any contribution to reduce such negative impact will be reflected towards the whole globe. The purpose of this thesis is to study the lifespan probability of new LIBs which can be remanufactured and repurposed using an absorbing Markov chain model in order to provide a decision making and projection values that can be used in favor of production optimization and extended life cycle efficiency management. This can serve the optimum goal of sustainable manufacturing and minimizing the environmental impact of Lithium-Ion batteries made for next generation’s automotive industry.

1.4 Limitations

This research is relatively new and studying new market topic of next generation transportation system is difficult. Thus, the empirical study in this field is relatively limited. Furthermore, the data used in this study is obtained from interviews with experts in the field of servicing LIBs and from the published literature due to the limitation in access to real market data. However, it is believed that the developed model can be validated by using actual data.
1.5 Thesis Outline

The remainder of the thesis is organized as it follows. Chapter 2 presents a literature review about Lithium-Ion batteries, working principal, cell construction, degradation, remanufacturing, repurposing and recycling, along with Markov chains, reverse logistics and research gaps. Chapter 3 provides the problem statement, research motivation, and research approach. Chapter 4 displays an absorbing Markov chain model and Markov chain steady-state census model to evaluate the lifespan of LIBs and their market composition in the future. Chapter 5 ends the thesis with the conclusion, and future potentials.
CHAPTER 2

LITERATURE REVIEW

2.1 Lithium-Ion Batteries

Throughout history, humans have always wanted to progress in technology, and through this advancement, we have become the dominant species on earth. From ancient times to modern day, transportation has played a pivotal role in the human revolution. The automobile was and still is the prime mode of transportation for the people around the world. Most vehicles that we use today are powered through burning gasoline and different oils. This has always been a concern to environmentalists, as the exhaust that is produced through these combustion vehicles is carbon dioxide, and because it is being released straight into the air, a lot of environmental damage takes place. On top of this, there are many health concerns related to this excess carbon dioxide in our environment, as oxygen becomes less abundant in the air. Since the world today has become very dependent on fossil fuels, they are decreasing in quantity rapidly. In fact, the U.S alone uses an average of 19.96 million barrels of oil daily (U.S. Energy Information Administration, 2018). Due to this and global warming issues, people are turning to Electric Vehicles (EVs) as an alternative for conventional oil-powered vehicles. Three types of electric powered vehicles are being produced today: Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs).

One of the most essential parts of any Electric Vehicle is the Lithium-Ion battery, as they provide exceptional performance due to their high energy density and advanced gravimetric and volumetric properties (Delacour and Safari, 2012; Tredeau and Salameh,
The cost of just the battery of the vehicle approximates to nearly 40 percent of the entire vehicle price (Nelson, 2009).

When the Lithium-Ion battery in an EV has completed its lifespan, it cannot just be easily disposed of, as the materials they are composed of are highly valuable, and sometimes hazardous to the environment. Due to this, methods of reusing these batteries have become economical, such as: remanufacturing, repurposing, and recycling (which we will be targeting). Resource depletion is becoming more drastic, as the extraction of the materials used in manufacturing has seen a tremendous increase; with these methods, we can reduce this and help the environment by reducing batteries in landfills.

2.1.1 Working Principles

Before we discuss remanufacturing, repurposing and recycling processes, we must look at how Lithium-Ion batteries work, what they are made of, and how they gradually degrade in performance within an EV. A Lithium-Ion battery consists of cells which are comprised of a cathode, an anode, two current collectors, an electrolyte, a separator and a cell casing (Dahn and Ehrlich, 2011). The basic working mechanism of a Lithium-Ion battery is that electrons are forced to move between the anodes and cathodes of the cells. Lithium atoms release electrons onto the anode, resulting in positively charged Li-ions being left behind. The movement of electrons between anode and cathode takes place through an external circuit. Simultaneously, due to electrical attraction, the Lithium-Ions move in the electrolyte towards the cathode passing the separator.

The movement of Lithium-Ions towards the cathode (which has a positive charge) occurs because of the potential difference. This is necessary, as if the cathode were to become
negatively charged – and thus repel electrons – the whole current would cease to flow (Hoyer, 2015; Maehlib, 2012). This entire procedure is reversed when the system is charging.

2.1.2 Cell Construction

The most important and costly units in LIBs are the cells themselves. In LIBs, there are subunits called battery modules, which are essentially multiple cells clustered together using plastic casing and various circuitry. There are four types of cells that can be used in LIBs: cylindrical, prismatic, button and pouch cells.

The essential elements of Lithium-Ion cells are an anode, a cathode, an electrolyte and a separator (Zeng et al., 2014; Korthauer, 2013). The anode is a graphite-covered copper foil, as carbon is often the active element used for battery anodes (which is connected to the copper with a polymeric binder) (Zeng et al., 2014). The cathode is an aluminum foil coated with a material that is electrochemically active (which has many available options). The key component for this material is a lithium-transition-metal-oxide (LiMO2), and Kang et al. (2006) have listed different types of cathode material for LIBs available in the market.
which can be used for automotive application like: lithium cobalt oxide (LiCoO2), lithium manganese oxide (LiMn2O4), lithium nickel oxide (LiNiO2), lithium vanadium oxide (LiV2O3), and lithium iron phosphate (LiFePO4). Some examples of these cathode materials in use in the automobile industry are the Tesla Model S, which uses lithium cobalt oxide (Lucas, 2012), the Coda Sedan, which utilizes lithium iron phosphate (Schneider, 2007), and the Nissan Leaf, which takes the option of lithium manganese oxide (Hernandez, 2011). With the help of binders, all the active electrode material is fastened onto their respective electrode.

To allow the ions to move between electrodes, an electrolyte is needed. Bernardes et al. (2004) explain that energy is created when the ions diffuse by moving through the electrolyte from the anode to the cathode (or vice-versa). There are various elements to an electrolyte of a LIB, like: lithium salt (with lithium hexafluorophosphate, or LiPF6, being the most used). Also, a mix between either linear, or cyclic carbonates (or both) are used to make a solvent that the salt gets dissolved in (like ethylene carbonate (EC), propylene carbonate (PC), and dimethyl carbonate (DMC), with polyvinylidene fluoride (PVDF) being an organic binder). Along with all of this, other additions can be made to the electrolyte like phosphonates and carbonates to allow for better cell efficiency and safety (Heelan et al., 2016; Sloop, 2010; Grützke et al., 2015). Finally, the separator is a film-like polymer that can be made of microporous polyolefin (Dahn and Ehrlich, 2011). It is put between the anode and cathode so that direct contact does not occur, as this would cause short-circuiting (Zeng et al., 2014).
2.1.3 Degradation

All batteries go through a type of aging called degradation, where the materials of a battery like the electrolyte, anode or cathode material deteriorate over its lifespan (Christophersen et al., 2007). Every time a battery goes through charging and discharging, the degradation process becomes faster, and the subsequent cycles affect the battery more. As a battery degrades, three key performance factors are affected: energy efficiency, power, and capacity.

Energy Efficiency Fade: this is the loss of energy efficiency of a battery over time due to the surface layers that are created onto the anode and cathode (Abraham et al., 2005). What these layers do is block reactions with the electrolyte, which create electrical impedance in the cells of the battery and decrease its efficiency (Andersson et al., 2002).

Capacity Fade: this is the loss of energy capacity of a battery over time. It is mainly due to a solid electrolyte interface passivation layer forming on the anode-electrolyte interface, which is caused by its consumption of Lithium-Ions (Arora et al., 1998).

Power Fade: this is the loss of available power in a battery due to the increase in internal impedance over time. Since solid electrolyte interfaces forming on the cathode-electrolyte interface, also increase resistance of the transportation of ions, it can be noted that they also promote power fade (Wang et al., 2005).

In the application of an EV, there are four resulting impacts caused by capacity fade and power fade. First, a lower capacity means an increase in an EV’s charging time when going through a drive cycle. Second, a lower capacity is linked to an EV driving for lower distances before switching to charge-sustaining mode (the energy saving mechanism of an EV). Third, a lower power output means that the minimum voltage limit for driving an EV
and the maximum voltage limit for charging an EV are both decreased. This causes a decrease in the maximum discharge and charge power of the battery and ultimately less acceleration power when driving and less ability to regain power when needed. Finally, a lower power output would also play a role in decreasing the capacity of an EV, because meeting a certain power output would require more electricity to offset the lower terminal battery voltage (Arora et al., 1998; Abraham et al., 2005).

The main factors that impact battery degradation are high temperatures during a drive cycle, charging rates that input too much power at a time, deep depths-of-discharges (the amount of energy used after a single charge), and by cycling to extreme state-of-charge points (Zhang and Lee, 2011). That being said, it is possible to lessen the effect of these factors by implementing some countermeasures. For instance, keeping depths-of-discharges under 60% and by keeping temperatures 35°C or cooler can help decrease the rate of degradation in a battery (Millner, 2010). By taking all of this into account, designing an electrical system around different degradation countermeasures to increase system lifespans is absolutely crucial. Customer satisfaction is immensely based upon how well an EV can counteract loss of capacity and loss of power, as these affect the most basic and essential tasks of any vehicle (acceleration/performance of the vehicle and driving range).

2.2 Remanufacturing

Remanufacturing is defined by Lund (1984) as “an industrial process to recover value from the used and degraded products to ‘like-new’ condition by replacing components or reprocessing used component parts.” It is usually known to be a very environmentally friendly choice to reutilize a product that has reached its end-of-life (Gutowski et al., 2011). This process is a highly exercised method in the automobile industry to recover parts. In
fact, almost 80% of all automobile components are in some way shape or form remanufactured; this makes up for 2/3 of all remanufacturing and is a multi-billion-dollar industry not only in the US (with $53 billion), but across the world (with over $100 billion) (Gutowski et al., 2011). This highly efficient process is quite profitable, as remanufactured products can be sold to extend life cycles of products; reuse of products through remanufacturing has grown to be a large market (Ayres et al., 1997).

The focus of our research is to develop an evaluating model of the electric vehicle Lithium-Ion batteries lifespan in order to identify the utility time of the LIBs for full term usage, remanufacturing, repurposing and/or recycling of Lithium-Ion batteries in EVs; it is noted that the remanufacturing and reuse of LIBs in EVs is different from traditional recycling and remanufacturing. A method that is orderly and systematic is needed so that managing the used vehicle battery subsystems becomes possible. Usually, the process is diagnosis, disassembly, testing, sorting, reassembly, and finally retesting; however, this is not as easy as the conventional processes for remanufacturing. One crucial aspect of this remanufacturing process that has been recognized is managing multiple LIBs that have reached their end-of-life sustainably. Having said that, there are still many issues regarding this: it is not understood completely, and methods that have been created to solve different related problems are flawed (Jin, 2012).

Due to limited and expensive resources, the construction of LIBs being in separate parts (cells), and the possible resale market, there is a great need for EV battery remanufacturing. Warranties usually last 8 years or 160,000 kilometers for LIBs in popular EVs like Tesla, Kia, Nissan Leaf and Chevy Bolt, but there is a chance of failing the batteries within warranty period. When an LIB ceases to function in an EV, the resources available inside
still hold high value, and it is not optimal to simply dispose of these batteries, so through
remanufacturing, it is possible to make use of those materials and greatly reduce the total
life cycle costs of LIBs (Jin et al., 2013; Jin et al., 2011).
Foster et al. (2014) analyzed the cost-benefit of remanufacturing, repurposing, and
recycling Lithium-Ion batteries. They looked at capital costs for equipment, factory
facilities, and other expenses like labour and materials. They found that a remanufactured
battery can be made for 60% of the cost of a brand-new battery. For repurposed batteries,
while looking at research and development costs along with the various other expenses,
they found that LIBs can be repurposed (at lowest price) for $114.05/kWh. Finally, they
looked at all the costs for recycling, and it is not economically feasible currently; however,
if lithium-salts have a x20 increase in market price to about $98.60/kg in the future, then it
may be deemed economic.
Standridge and Hasan (2015) looked at the manufacturing capacity needed to support EV
LIBs in applications after end-of-life through remanufacturing, repurposing, and recycling.
They used a mathematical model to analyze their data and then examined the results. What
they found was that if EOL LIBs are taken for remanufacturing instead of disposal, then in
2030, the demand for new LIBs can decrease by about 25%.
There is some uncertainty as to when one should remanufacture an LIB of an EV. Zhang
et al. (2014) take this problem and determined the optimal point as to when LIBs should
be remanufactured. They focused on battery degradation through multiple cycles and
realized that there are three working stages and two turning points of an LIB, where after
the second point, drastic discharge capacity reductions and extreme impedance increases
occur. This results in internal destruction of the battery which leads to it reaching its end-
of-life faster. Due to this causing remanufacturing complications, the authors concluded that the best time for a battery to be sent for remanufacturing is after 500-550 cycle times. In a paper by Ramoni and Zhang (2013), the issues of recycling EOL LIBs and alternative options for reusing them are discussed. The paper analyzed various problems regarding recycling that may need further research, and then proposed an economically feasible, and innovative strategy to remanufacture batteries. It first looked at how over the time, layers called solid electrolyte interface (SEI) form over the electrodes of a battery. These reduce both the power and capacity of a battery, and therefore decrease a battery’s lifespan. The solution was to disassemble the battery, use laser technology to remove the solid electrolyte interface, and then reassemble the battery; compared to manufacturing a brand-new battery, this is much more cost effective and environmentally friendly solution.

Kampker et al. (2016) evaluated the overall effectiveness of remanufacturing EV LIBs. They used two mathematical models to determine if a circular economy with LIBs is feasible and if remanufacturing is sustainable and economically efficient. The outcome was that through remanufacturing LIBs, the best-case scenario is $68/kWh cost savings. Furthermore, in a circular economy, remanufacturing would bring reduced GHG emissions and resource consumption, which overall improves the environment.

Ramoni et al. (2017) further looked at using laser technology to ablate solid electrolyte interface (SEI) from electrodes of an EV LIB. They used laser fluence ranging from 0.308 to 2.720 J/cm², and they also used analytical tools such as a scanning electron microscope, atomic force microscopy, X-ray powder diffraction, X-ray photoelectron spectroscopy, and electrochemical measurements to see if the electrodes were still in working condition. They found that through this process, not only was the SEI successfully removed, but the
electrodes themselves did not structurally change and still worked decently. This can allow LIBs to be remanufactured more efficiently, and EVs can therefore become less expensive. Also, resource extraction can be reduced and ultimately reduce harm on the environment. A paper published by Casals and Garcia (2016) examined remanufactured batteries and their management, along with the issues accompanied with them. It looked at the various kinds of batteries, their collection, their remanufacturing processes, problems regarding them, and potential solutions to said problems. The result was a wide range of different solutions to various problems, each with their own positive and negative impacts. The paper said that although businesses that work with reusing or remanufacturing would face difficulties in some aspects, the outcome would greatly improve the environment and the economy.

Lin et al. (2018) addressed cost-effectiveness to remanufacture LIBs in EVs at an enterprise level instead of just a laboratory scale. They proposed a closed loop supply chain network model for the remanufacturing of LIBs that also accounted for various quality levels of spent battery returns. The profit increase that they found by integrating remanufacturing into LIB supply chain networks is 9.81-30.93%.

2.3 Repurposing

As the world is striving to create less damaging, much greener energy sources and generators, some countries especially in Europe have made some goals to promote saving the environment. Some examples are Denmark, who is investing a lot of resources in making half of their electricity solely from wind, and Netherlands, who raised subsidies in producing renewable energy (IEA, 2013). These objectives placed by countries to increase
the production and integration of renewable energy would need quite efficient energy storage systems to hold and sustain the energy generated (Lymerpopoulos, 2014).

Since LIBs are degenerative, the criterion that must be passed is that over 80% of a battery’s original capacity must be available, or else it is not permitted to be used in EVs (Warner, 2013). Basically, when 20% of a battery’s original capacity is lost, a LIB battery is said to have reached its end-of-life (Monsuru, 2012). When this criterion is met, the battery must be extracted from the EV for other uses. From there, it has to be taken for repurposing, which is a process that disassembles a LIB into its cells and reconfigures them so that they may be used for different applications. Many repurposed EV batteries are mostly used as stationary energy storage systems in homes, offices, or even power plants (Haruna et al., 2011). Repurposed battery packs are advantageous to consumers, as they reduce emissions, and provide a renewable energy source. The expected 8-year lifespan of Lithium-Ion batteries can also be increased by almost 10 years when repurposed for stationary applications (Walker et al., 2015). More advantageously, since the original cost of new LIBs in EVs is exceptionally high, repurposing batteries splits the cost between the initial and latter consumers (over its 18-year total life-span), (Neubauer and Pesaran, 2011).

As said by Shokrzadeh (2012); Cready (2003); and Bibeau and Molinski (2010) repurposed batteries could be utilized in different storage applications like a grid system, electric supply, ancillary services, and renewable integration. For example, it is challenging to manage energy from wind turbines when the wind has many irregularities, so repurposed batteries can possibly support this at a lower cost than conventional techniques (Bibeau and Molinski, 2010).
Casals et al. (2019) found how long second-life EV batteries would last through a model. They looked at four applications for these second-life batteries: Fast EV Charge, Self-Consumption, Area Regulation, and Transmission Deferral. What they considered as their primary input for the model was what current load the batteries should go through for each application. Change in State of Health, Depth of Discharge, and current rates, at every instant was considered to calculate the aging of the batteries. The four applications are discussed as follows:

*Self-Consumption:* In this second-life battery application, batteries are reconfigured to store about 6 kWh of solar energy generated on building rooftops. In this scenario, it was calculated that if a battery was repurposed this way, it would run for 12 years.

*Area Regulation:* In this second-life battery application, the Self-Consumption scenario is added onto by implementing a grid stability service. In this scenario, a repurposed battery would run for six years.

*Transmission Deferral:* In this second-life battery application, batteries support grid transformers by providing additional electricity when the transformers cannot provide sufficient amounts to the area. Batteries charge during off-peak hours (generally at night) and run when electricity is needed. In this scenario, second-life batteries would run for 12 years.

*Fast Electric Vehicle Charge:* The authors studied three Fast EV chargers connected to a grid with a limit of 70 kW. When many EVs arrive in short periods of time, it was found that an added 20 kW are necessary to meet sufficient energy demands. Instead of spending money on increasing grid capacity, this second-life battery application completes the
additional demand during peak times. In this scenario, a repurposed battery would run for 30 years.

Bobba et al. (2018) looked at if environmental benefits were present when EV batteries were repurposed if they were used as energy storage systems in three scenarios: a house that used photovoltaic self-consumption as its power, a house that was connected to a grid system, and a house that used a diesel generator. They used a life cycle assessment to analyze different situations that were possible with a battery’s life cycle. What they found was that there were environmental benefits depending on if there were specific conditions being met. Furthermore, they state that much more research needs to be conducted for analyzing the sustainability of repurposing batteries currently or in the future.

2.4 Recycling

Recycling, as defined by The Battery directive (Council Directive 2006/66/EC) is “the reprocessing in a production process of waste materials for their original purpose or for other purposes but excluding energy recovery.” Worrel (2014) explains that when it comes to recycling, there are two levels: high level recycling, and down cycling. High level recycling is when the returned materials are close to the original materials in terms of quality; however, down cycling is when the returned materials are of less value and quality than the original materials.

As we constantly extract and use resources from the Earth, they cannot regenerate fast enough to meet demands many years from now. Due to this, the values of materials are drastically increasing, and it is becoming costly to buy them for different applications. Recycling these materials is a great way to counteract this, as one can recover the materials by processing existing products and extracting them. Currently, LIBs consist of highly
valuable materials, and can be recycled for reuse or reselling. Today, recycling battery materials is very strongly driven by prices (Kumar, 2014); usually, companies will only recycle batteries’ components if it will profit them through reselling. Through recycling LIBs, some materials that can be recovered are cobalt, nickel, copper, lithium, and aluminum. Globally, lithium is rising in demand and therefore becoming costly (Gains & Nelson, 2009), and this means that it is a wise choice to start focusing more on recycling lithium in the near future.

A crucial part of recycling is circular economy. In a linear economy, materials are used and disposed off right after their initial use, but a circular economy strives to keep materials in cycle for as long as they hold value (Worrel, 2014).

![Circular Economy](image)

Figure 2: Circular Economy Reproduced and Modified from Elia et al. (2017)

The figure shows the processes connected to one another in a circular economy: Material Input, Design, Production, Consumption, and Recycling which is considered the end-of-life phase, and is connected directly to material input, thus closing the loop for material use (Jawahir et al., 2016; Elia et al., 2017).
Right now, there are quite a few rules and regulations about the disposal of LIBs. The United States Environmental Protection Agency (EPA) regulates the disposal of batteries in large quantities under the universal rules of hazardous waste (40 CFR PART 273) (GPO, 2012). Different states have to make their own guidelines as to how to dispose of LIBs, as the federal government does not regulate it themselves (GPO, 2012). Gaines (2014) has noted that only two states are considering LIBs as hazardous waste that need to meet the requirements of packaging, labelling and shipping: California and New York.

2.4.1 Recycling Processes

The current most popular and used recycling processes for batteries are Umicore VAL’EAS, Sony-Sumitomo, and Retriev Technologies (Toxco). They are explained in the following sections.

2.4.1.1 Umicore VAL’EAS

Through Umicore, many of the traditional processes of recycling batteries can either be omitted or simplified. This process focuses on recycling the battery materials that are deemed the most valuable, like cobalt and nickel. Umicore utilizes both pyrometallurgical and hydrometallurgical processes to extract these materials. By beginning with pyrometallurgical treatment in a single shaft furnace, there isn’t a need for releasing excess electricity left in a battery (discharging). Along with this, because aluminum and iron are basically viewed as excess materials, there’s no need to separate them through crushing either, as they are slagged during the smelting process anyway (Georgi-Maschler et al. 2012; Cheret and Santén 2007).

First, the batteries are taken apart and then put into a furnace with coke, slag formers and possibly limestone and silicon oxide; air is delivered into the furnace from the bottom
(Vezzini, 2014; Cheret and Santén, 2007). Through gradual heating from 300°C, to 700°C, to 1200° - 1450°C, the electrolyte is evaporated, the plastic is pyrolyzed, and the materials inside the furnace are smelted respectively (Vezzini, 2014). After this treatment, the result is an alloy consisting of copper, cobalt, nickel, lithium, and a small amount of iron; and a slag consisting of aluminum, silicon, cadmium, manganese, lithium, the rest of the iron, and REEs (Vezzini, 2014; CEC, 2015). From here, the slag is downcycled because the materials it is comprised of are not of interest (but it is possible to recover the lithium in the slag if need be). What Umicore focuses on is the alloy, and hydrometallurgical treatment takes place to extract its materials. There are two leaching phases: one to extract the copper and iron (though it is not publicly known what the leachant consists of), and another to extract nickel (II) hydroxide and cobalt (II) chloride (through hydrochloric acid).

2.4.1.2 Sony-Sumitomo

The companies Sony and Sumitomo Metals Mining Company made a joint effort to create a process solely to recover the cobalt oxide inside Lithium-Ion batteries. The batteries are first heated in a furnace at 1000°C, and when the cells open, inflammable parts of the battery (like lithium, fluoride, organic solvents, and plastic casing) become fly ash. The result is an alloy consisting of iron, copper, and aluminum which can be separated magnetically (Sonoc et al., 2015). What is left from that is a powder that has the active cathode material along with either graphite or carbon (depending on the battery), and this is finally taken out through hydrometallurgical treatment to extract the cobalt (Ekermo, 2009).
2.4.1.3 Retreiv Technologies (Toxco)

Combing mechanical and hydrometallurgical processes, this process is owned by Retreiv Technologies in the U.S. (Gaines and Dunn, 2014). First, any electrical energy that was previously in the batteries is taken out through cryogenically cooling them at around -200°C (Gerogi-Maschler et al., 2012). With this, any possible explosion hazard through lithium being at room temperature is mitigated. From this, the batteries are taken for shredding, and are crushed using a hammer mill. These small pieces are then brought to a shaker table, and then water is added. An alkaline solution is added in order to both neutralize the acid compounds and to hydrolyze the organic solvents, resulting in homogenates. The lithium salts that are created through this are separated from the plastic and metallic materials. Finally, this semiliquid-substance has sodium carbonate added to it, which allows the precipitation of lithium carbonate that can be purified and then recrystallized (Tedjar and Founadraz, 2010). As our focus is LIBs in EVs, recycling is a great way to recover and make use of materials in LIBs. Having said that, only about 5% of LIBs are recycled globally, leaving 95% that are either sent to landfills or not even collected (Heelan et al., 2016). Recycling is not only a viable option to reduce environmental damage, but it is also attractive in an economic sense due to cobalt becoming increasingly expensive (Li et al., 2013). Also, as cobalt and lithium are becoming less abundant in different sources, recycling LIBs can greatly reduce the sharp decrease in availability of these materials.

A paper written by Bahaloo and Mousavi (2017) looked at a bioleaching method using the organic acids produced by Aspergillus niger to recover valuable metals from LIBs. Through response surface methodology, they examined the effective factors of sucrose
concentration, initial pH, and inoculum size to optimize organic acid production. LIBs are leached through organic acids produced biogenically through pulp densities. The results of their research were that when the pulp density was 2%, the metal recovery was 100% of the copper and lithium, 77% of the manganese, and 75% of the aluminum; and at 1% pulp density, 64% of the cobalt and 54% of the nickel was recovered.

Wegener et al. (2015) proposed a system that could aid the disassembly for recycling EV batteries. They suggested while a human does the complex tasks of disassembly, a robot could assist them by doing the simple tasks like removing screws and bolts. What they found was that such a robot would require three things: a systematic method for removing the screws and bolts, a way to change screwdriver bit depending on the type of screw or bolt on the EV battery, and a way to gather information to locate the fasteners. The result was that, although successful, the robot consumed lots of time when doing the tasks; the authors said that more research would be required for an auto-detection system to be implemented and to function but is a feasible solution.

Heelan et al. (2016) stated that the current recycling process for LIBs in EVs and the industry as a whole is flawed. They said that the materials recovered from present recycling are not viable for direct use in new EV batteries, especially when the sole focus is to recover large quantities of cobalt to make a substantial profit. They then stated that a new recycling process must be introduced so that the recovery of more valuable materials, and at a greater efficiency can be achieved. They noted that if a closed-loop recycling process was implemented, many batteries would be safe from being disposed off annually. An example they proposed was from the Worcester Polytechnic Institute, and the technology that they
used could recover LiNi$_x$Mn$_y$Co$_z$O$_2$, a cathode material in EV LIBs; this makes the recovery more valuable, and the whole process more economically feasible.

A paper written by Zhang et al. (2018) studied the different stages in EV battery recycling, i.e., disassembly, material detection, and recovery; and its two main aspects, the mechanical procedure, and the chemical recycling. They noted the different gaps of current recycling technology like the complexity and safety of disassembly, and the instability of the chemical materials in EV batteries (to name a few); and proposed a framework for the recycling process to eliminate or improve upon these gaps. The framework they provided includes both a semi-automated mechanical procedure, and an enhanced chemical recycling process; the traditional framework and this framework were compared, and it was found that the latter resulted in more efficient and effective recycling, and it was much more environmentally friendly.

### 2.5 Essential Cathode Material (Cobalt)

Vehicles are increasing in demand with each passing day, and along with that, batteries for said vehicles are also becoming more of a need. Through forecasting, it is projected that in the year 2030, there would be 100 million electric cars around the world. For this, a capacity of 1300GWh of Lithium-Ion batteries would be needed. Of these batteries, an essential element required in their manufacturing is cobalt, which is used in the cathode. To support the demand for electric vehicles and battery production, in 2030, 156 000 metric tons of cobalt will be needed. (Bloomberg New Energy Finance, 2017). The fact of the matter is, in 2016, about 55 to 60 % of the world’s cobalt production was derived from the Democratic Republic of Congo (DRC) (Bloomberg New Energy Finance, 2017). With
DRC’s troubled government system, many problems can arise from depending solely upon them to meet our cobalt needs.

By 2025, a large amount of Lithium-Ion batteries will be available, and if these are recycled properly, about 20% of worldwide cobalt demand that has been predicted can be met (Zacune, 2000). In simple terms, a lot of the cobalt that we take for granted that’s produced in the DRC can be reused. This can significantly reduce our dependency upon them to produce cobalt, and the prices can be stabilized and drastically lowered.

2.6 Reverse Logistics

The history of Reverse Logistics dates back to quite a while before modern-day engineering, but its roots are embedded into the American Civil War. At the Civil War’s end, General William T. Sherman had noticed that in order for his soldiers to be successful in moving through dangerous territory, he would have to prioritize supply and mobility, and “supply his soldiers on the march” (Robinson, 2014). From these roots came returns and refunds, along with recycling and recovery policies. In fact, in 2001, the European Union made a goal to recover or recycle 50 to 65 percent of packaging waste, which conveyed to the other countries that they will have to emulate these standards if they wish to do business with them (Robinson, 2014). This is also prevalent in companies today, as they are always striving to find better ways to improve their systems and work upon any issues. Utilizing material, machine, and man in the most efficient, optimal way possible is what we call logistics. The definition of Reverse Logistics from The Council of Logistics Management comes from the paper “Going Backwards: Reverse Logistics Trends and Practices” (Rogers, Tibben-Lemke, 1998). It is defined as:
“the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.”

Figure 3: Process Flow of Forward and Reverse Logistics

Figure 4 describes the life cycle of any product from its material state to disposal. The first step in forward logistics is that materials are extracted from the Earth. These materials are then brought to manufacture individual components of a product and then assembled in a certain facility. This is then brought for distribution, which is where a customer takes the product for utilization. When the product becomes obsolete for the customer, it can be returned, through which Reverse Logistics begins. As stated by Lambert et al., (2011) Reverse Logistics has four primary steps: gatekeeping, collection, sorting and disposal. The product is inspected for its condition, classified and sorted accordingly, and then altered for reuse applications. Once the product goes through all the phases of Reverse Logistics, it can no longer be used in applications and must, therefore, be disposed of.
Below is a process flow that displays all the tasks that occur when an LIB is remanufactured, repurposed, or recycled through reverse logistics.

![RL Process Flow of LIB Remanufacturing, Repurposing and Recycling](image)

**Figure 4: RL Process Flow of LIB Remanufacturing, Repurposing and Recycling**
2.7 Markov Chain

Markov chains are an important part of stochastic processes. Markov processes have applications in modeling and analysis of a wide range of trends in many fields, including linguistics, biology, political science, medicine, economics, computer science, etc. The Markov property is applied to predict the future if one knows the current state, even when there is no information of its past states. When studying Markov chains there are two different types: Discrete-Time Markov Chains and Continuous-Time Markov Chains. The former refers to when the chance of moving to another state depends solely upon the present state (states being the conditions that something can be in). A continuous-time Markov chain changes at any time. Poisson process is an example of continuous-time Markov chain, usually it is practiced in queuing theory (Andersson, 2004). We have focused on discrete-time Markov chains in our thesis.

In this thesis, we have utilized a Markov chain model, but more specifically an absorbing Markov chain model. This is defined as the following:

When a state \( i \) is impossible to leave in a Markov chain, it is called *absorbing*, i.e. \( P_{ii} = 1 \). An absorbing Markov chain is one that has a minimum of one absorbing state that can be reached from all other states. As an absorbing Markov chain has both transient states and absorbing states. Moreover, a Markov chain steady-state census model to estimate the composition of electric vehicle Lithium-Ion batteries market in the long run is developed.

To sum up the literature review in this chapter. It is observed that Lithium-Ion battery lifespan got very high attention from more than 30 research papers and articles. The following table summarizes some research of focus with author name, main objective, result, their main concerns of the research (remanufacturing, repurposing, recycling),
extended life cycle analysis and modeling techniques. In summary, the mathematical models are listed for the first four papers, the testing techniques in the following six papers and finally the recycling processes are shown for the last four papers.
Table 1: Summary of Literature Review

<table>
<thead>
<tr>
<th>S. No</th>
<th>Author</th>
<th>Literature Review</th>
<th>Results</th>
<th>Remanufacturing</th>
<th>Repurposing</th>
<th>Recycling</th>
<th>Extended life cycle analysis</th>
<th>Modeling Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foster et al. (2014)</td>
<td>Examined the cost benefit of remanufacturing, repurposing, and recycling LIBs.</td>
<td>They found that remanufacturing an LIB takes 60% of the cost to make a brand-new battery including all expenses.</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>A long-range energy alternative planning system (LEAP) MODEL</td>
</tr>
<tr>
<td>2</td>
<td>Lin et al. (2018)</td>
<td>Analyzed remanufacturing LIBs at the enterprise level instead of the laboratory level.</td>
<td>In an enterprise environment, the result they found was a 9.81-30.93% profit increase through remanufacturing LIBs.</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>Mixed Integer Nonlinear Programming (MINLP) Model</td>
</tr>
<tr>
<td>3</td>
<td>Standridge and Hasan (2015)</td>
<td>Analyzed the manufacturing capacity needed to support EV LIBs in applications after end-of-life through remanufacturing, repurposing, and recycling.</td>
<td>They found that in 2030, if all LIBs are taken for remanufacturing, the demand for new LIBs would decrease by 25%.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The Capacity Planning Mathematical Model</td>
</tr>
<tr>
<td>4</td>
<td>Kampker et al. (2016)</td>
<td>Observed the overall effectiveness of remanufacturing LIBs.</td>
<td>The best-case scenario was cost savings of $68/kWh for remanufacturing LIBs, and the GHG emissions for creating new batteries would be greatly reduced.</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>Business Model and Use the formula for the abiotic depletion potential (ADP) for the consumption of resources</td>
</tr>
<tr>
<td>5</td>
<td>Casals and Garcia (2016)</td>
<td>Analyzed remanufactured batteries and their management, along with issues present with them.</td>
<td>They concluded that although businesses may struggle with managing remanufactured batteries, the impact on the economy and the environment is very positive.</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>Presents principal challenges, faced during business done with reuse LIBs</td>
</tr>
<tr>
<td>6</td>
<td>Bobba et al. (2018)</td>
<td>Analyzed if there were any environmental benefits regarding repurposing of EV batteries and their use in three scenarios: houses using PV self-consumption, a grid-connection,</td>
<td>There are environmental benefits if specific conditions are met, but it is stated that more research is required.</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>Proposed method is based on comparing the LCA impacts of different scenarios.</td>
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<tr>
<td></td>
<td>Authors (Year)</td>
<td>Description</td>
<td>Methodology</td>
<td>Tools</td>
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<td>7</td>
<td>Ramoni and Zhang (2013)</td>
<td>Looked at some issues regarding LIB recycling and proposed an innovative remanufacturing strategy.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Laser cleaning, Analytical tools: scanning electron microscopy (SEM), Atomic force microscopy (AFM), X-ray powder diffraction (XRD)</td>
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<td></td>
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<tr>
<td>8</td>
<td>Ramoni et al. (2016)</td>
<td>Proposed laser treatment as a strategy to remanufacture LIBs and looked at its effectiveness.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Battery testing system and internal resistance meter</td>
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<td>9</td>
<td>Zhang et al. (2014)</td>
<td>Discussed the optimal point at which an LIB should be remanufactured.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Battery testing system and internal resistance meter</td>
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<tr>
<td>10</td>
<td>Casals et al. (2019)</td>
<td>Found how long second-life EV batteries would last through a model.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Electric battery-aging model which simulates the battery capacity fade through its use.</td>
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<tr>
<td>11</td>
<td>Wegener et al. (2015)</td>
<td>Proposed an automatic system for disassembling EV LIBs using both humans and robots.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Proposed a hybrid human-robot workstation</td>
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<tr>
<td>12</td>
<td>Heelan et al. (2016)</td>
<td>Explained the issues with the EV battery recycling industry and process.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Physical and hydrometallurgical Process.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>13</td>
<td>Bahaloo and Mousavi (2017)</td>
<td>Investigated a bioleaching method involving the organic acids produced by Aspergillus niger.</td>
<td>Laser cleaning method to remove SEI</td>
<td>Bioleaching Method</td>
<td></td>
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<tr>
<td>14</td>
<td>Zhang et al. (2018)</td>
<td>Looked at the issues related to the mechanical procedure and chemical recovery of the recycling</td>
<td>Laser cleaning method to remove SEI</td>
<td>Semi-automatic mechanical procedures and enhanced chemical recycling</td>
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</tbody>
</table>
2.8 Research Gap

From the literature review it has been found that limited research was concerned about evaluating the whole extended lifespan of LIBs so far. In addition, Markov chain method has not been used to calculate the probability of the lifespan. So, it is believed that the need for the evaluation of the utility time of LIBs of an electric vehicle for extended lifetime usages, New, Remanufactured, Repurposed is an important subject.

It was likewise discovered that the published research suggests no steady-state census for to estimate the composition of LIB market in the long run which found highly possible.
CHAPTER 3

RESEARCH STATEMENT

After reviewing the Markov chain, remanufacturing, repurposing and recycling of Lithium-Ion batteries of an electric vehicle literature in chapter 2 and by understanding the present needs, the research problem has been identified as follow.

3.1 Research Problem

To develop an evaluation method for the extended lifespan of Lithium-Ion batteries to be remanufactured or repurposed originally manufactured for electric vehicles. Also, to develop a long run ratio composition model of electric vehicle Lithium-Ion batteries that can be used in forecast operation based on the amount of new batteries entering the market.

3.2 Research Motivation

The purpose of this research is to provide a viable assessment to extend the life of LIBs. The estimate can be basically used by car manufacturers, battery manufacturers, battery remanufacturers, stationary application users, recyclers, life cycle sustainability evaluators and government concerned bodies. By extending the lifespan of Lithium-Ion batteries, a positive impact on the environment as well as a substantial economic benefits can be achieved in recovering the most valuable materials such as Lithium, Cobalt and Nickel. Economic and environmental benefits will reduce the effect of the short lifespan of LIBs. It is believed that growth of LIBs manufacturing is overestimated according to operational qualitative and quantitative forecasting methods. This might lead to many complications for car manufacturers as well as Lithium-Ion batteries manufacturers. This can be due to the fact that forecasting methods have some inaccuracies that could result in huge global downturns, as in the famous 2008’s recession. A steady-state census would be a necessary
measure of any prediction to be considered; taking into account many emerging
technologies that might claim market share from LIBs such as fuel-cell technology.

3.3 Research Approach

Based on research gaps presented earlier in Table 1, this research has stepped forward to fill the gap by using information from the literature and through interviews. The topic to work in this research is narrowed down to develop an evaluating model of electric vehicle Lithium-Ion batteries lifespan full-term usage and long run ratio composition. A deep review of the literature on the topic is completed in order to develop sufficient knowledge about previously published research papers. Next an absorbing Markov chain state probabilistic model is developed to calculate the lifespan of Lithium-Ion batteries for the full-term usage, New, Remanufacturing, Repurposing, and Recycling. Furthermore, Markov chain steady-state census model is also developed to find the long run ratio composition of Lithium-Ion batteries. In order to fill the gaps and achieve the research objective, this research may also contribute in Lithium-Ion battery sustainability, extended lifespan assessment as a decision-making assistance, and environmental impacts. As an aid for the contributions mentioned above, reverse logistics can also play a key role in improving the shortcomings present in LIB life cycles. Through reverse logistics processes, EOL batteries can be returned to facilities at which they are sorted; batteries in good and moderate conditions are sent for remanufacturing or repurposing, and batteries in poor conditions are sent for recycling. These latter batteries go through processes that recover materials that can be reused in battery production, which thus benefits the economy and contributes to sustainability.
CHAPTER 4

METHODOLOGY

4.1 Markov Chain

The Markov chain process is very significant in the study of uncertainties in any recurring events, (Wu and Shieh, 2005). It is also used in the examination of any stochastic system in both short- and long-term. A statistical model is one that, through a specific probability, changes over time and is essentially stochastic. The Markov property is present in the stochastic process if only the last state is recalled. This model presumes that the current state of the system changes over time from the original state, and the probability can tell us the change from one state to another.

4.2 Principle of Markov Chain

Serfozo, (2009) has defined Markov chain as follows:

A stochastic process $X = X_n$, $n \geq 0$ with finite set $S$ is Markov chain for any $i, j \in S$ and $n \geq 0$ if,

$$P \{ X_{n+1} = j | X_0, \ldots, X_n \} = P \{ X_{n+1} = j | X_n \}$$

$$P \{ X_{n+1} = j | X_n = i \} = p_{ij}$$

$P$ = probability measure

$p_{ij}$ = transition probability from state $i$ to $j$

(The probability of each individual transition is established through observation).

$$\sum_{j \in S} p_{ij} \leq 1$$ (the sum of all transition probabilities will be 1 at any state)

The equation above is compliant with the Markov property, which says that:

- At any time: $n$, the future state is $X_{n+1}$
- $X_{n+1}$ can only be found using the current state $X_n$
• $X_n$ is independent of all the states that come before ($X_0$, $X_1$, ..., $X_{n-1}$)

• $X_n$ is an element of $S$

As said before, state $S$ is finite and countable, which means that $S$ can be written as the following:

$$S = \{S_1, S_2, S_3, ..., S_r\} \text{ or } S = \{1, 2, 3, ..., r\}$$

With this, a matrix that contains all transition probabilities can be written as follows:

$$P = \begin{bmatrix}
    P_{11} & P_{12} & \cdots & P_{1r} \\
    P_{21} & P_{22} & \cdots & P_{2r} \\
    \vdots & \vdots & \ddots & \vdots \\
    P_{r1} & P_{r2} & \cdots & P_{rr}
\end{bmatrix}$$

The sum of transition probabilities in any row is 1, thus $P$ is a stochastic matrix. If $p_{ii} < 1$, it is a transient state, and if $p_{ii} = 1$, it is an absorbing state. In the Markov chain, it is impossible for an entity to return into the transient state if it enters the absorbing state. A Markov chain has at least one absorbing state and any entity can reach in from all the transient states, (Sericola, 2013).

**Notation:**

The symbols used in the model are explained below:

- $s$ number of transient states
- $r$ number of absorbing states
- $p$ transition probability between states $i$ and $j$
- $Q$ probability matrix of transitions between transient states
- $R$ probability matrix of transitions from transient states to absorbing states
- $I$ Identity matrix
- $E$ matrix of expected number of times in (transient) state $j$, given starting state $i$
A matrix of probabilities of absorption in (absorbing) state $j$, given starting state $i$

### 4.3 Absorbing Markov Chain

This research presents absorbing Markov chain modeling approach. The proposed absorbing Markov chain mathematical model is expected to evaluate extended lifespan of Lithium-Ion batteries that are in states new, remanufactured, and repurposed. It also gives the probability for how long new and remanufactured battery will remain in good working condition at EV.

As an absorbing Markov chain has both transient states and absorbing states, it would be optimal to reconfigure the transition probability matrix into the following (White, 1970):

$$
P = \begin{bmatrix}
Q & R \\
0 & I
\end{bmatrix}
$$

Where:

- $Q$ = matrix that represents transitions between transient states
- $R$ = matrix shows transitions from transient state to absorbing states
- $0$ = matrix consisting of zeros
- $I$ = identity matrix

### 4.4 Transition Probability Matrix

A transition probability matrix is created on the basis of information identified in the literature review and interviews with industry experts, by examining the percent chances of an LIB staying in each state (New, Remanufactured, Repurposed, and Recycled).

![Figure 5: States of a LIB’s Life Cycle](image-url)
Below are the details that led us to create the above Transition Probability Matrix.

**Category 1. New Battery** (or first row of the matrix, \( P \))

In each of the many electric cells in LIBs, there consists an anode, a cathode, an electrolyte, and a separator (Armand and Tarascon, 2008; Balbuena and Wang, 2004). The two electrodes, the anode and cathode, go through a reduction-reaction and an oxidation-reaction respectively. This means that the cathode takes electrons and the anode gives electrons. While charging, Lithium-Ions move onto the surface, through the electrolyte, and onto the negatively charged electrode. The metal used as the electrode increases in electrons, which then get transferred to the circuitry outside. While discharging, this process is reversed (Dhameja, 2001; Axsen et al., 2008; Tarascon and Armand 2001; Balbuena and Wang, 2004).

A study done by Manthiram (2011) states that in a high voltage LIB, the reaction between the cathode surface and the electrolyte is a major issue, as through cycling, SEI (solid electrolyte interphase) layer is formed on the cathode. This impacts the movement of ions through pore plugging, and it also results in resistance across the electrical paths that lead to the cathode. Furthermore, because of the decreased movement speed of Lithium-Ions, SEI also deteriorates the internals of the cell, and thus resulting in capacity fade. Another study displayed a first-principles model that described the growth of a passive SEI layer on electrodes. They found that the thickness of the layer of SEI grows with the square root of
time (Ploehn et al., 2004). Zhang et. al. (2013) found that the loss of Li\(^+\) due to the formation of a film on the electrodes resulted in capacity fade.

Below are the details that led us to create the entries in category 1 new battery.

**(Element)\(_{11}\) New-New**

Evidently, a lifespan of 8 years’ battery warranty is considered by automaker on their vehicle (Ahmadi et al., 2017). Many EV batteries that are warranted for 8 years or 160,000 km (ex. Nissan Leaf, Tesla, Kia, Hyundai Ioniq and Chevy Bolt) may stop working within the warranty period. In this research, we are looking for the duration of a battery’s warranty period in which the battery stays in a good condition. Smart and Schey (2012) analyzed that electric vehicles are driven an average of 48 km daily (about 17,500 km annually) in the US. Hou et al., (2013) also observed the daily electric vehicle kilometers travelled in Beijing (China), and concluded that the average kilometers travelled by vehicle daily was 46.35 kilometers, and 68.2% of travels did not exceed 50 km. If we base our mileage on these calculations (48 km daily), the warranty of 160,000 km is covered by electric vehicle which have higher battery capacity like Tesla, Nissan leaf plus, Chevy Bolt and Kia soul. However, many other factors including EVs that have less battery capacity (Hyundai Ioniq 2019, BMWi3 2019), extreme weather conditions and driver patterns may affect the possibility that batteries will cease to function within the warranty period which is explained below:

Zhang et al. (2014) studied the best point before one should remanufacture an LIB. They found that when a battery is charged and discharged repeatedly, two turning points of an LIB can be seen regarding the impedance. The first turning point presents a sharp increase in impedance due to the rapid SEI formation; then the SEI layer formation slowed down
for a period of time, which kept the battery in normal working conditions; and finally, the second turning point led to a further drastic increase in impedance due to severe damages in the internal circuitry of the battery. They concluded that the optimal point before a battery should be remanufactured is 500-550 cycles of charging and discharging to avoid irreversible damage in the LIB. For our calculation we consider 550 cycles before a battery needs to be remanufactured.

Warranty (160,000 km) can be considered as conditional probability $A$ and $S_1$, $S_2$, $S_3$, $S_4$ $S_5$ $S_6$ are the individual occurrences.

$A = \text{Warranty (160,000 km)}$

$n = \text{Electric Vehicle car brands}$

**Tesla Model S 2019 ($s_1$):** Range per cycle is 386 km (Lambert, 2018)

Total distance traveled in 550 cycle = 212,300 km

$p(S_1) = 1 \quad P (S_1|A) - \text{Bayes’ Rules}$

**Hyundai Ioniq 2019 ($s_2$):** Range per cycle is 200 km (Edmunds, 2019)

Total distance traveled in 550 cycle = 110,000 km

$p(S_2) = 0.6875 \quad P (S_2|A)$

**BMW i3 2019 ($s_3$):** Range per cycle is 246 km (Korosec, 2018)

Total distance traveled in 550 cycle = 135,000 km

$p(S_3) = 0.8438 \quad P (S_3|A)$

**Nissan Leaf 2019 ($s_4$):** Range per cycle is 360 km (Lambert, 2018)

Total distance traveled in 550 cycle = 198,000 km

$p(S_4) = 1 \quad P (S_4|A)$

**Chevy Bolt 2019 ($s_5$):** Range per cycle is 383 km (Chevrolet Pressroom, 2019)

41
Total distance traveled in 550 cycle = 210,650 km

\[ p(S_5) = 1 \quad P(S_5|A) \]

**Kia Soul 2019 (s_6):** Range per cycle is 448 km “New Kia Soul” (2019)

Total distance traveled in 550 cycle = 246,000 km

\[ p(S_6) = 1 \quad P(S_6|A) \]

We assume a uniform distribution for six equal occurrences.

\[
P(A) = \frac{(p(S_1) + p(S_2) + p(S_3) + p(S_4) + p(S_5)) + p(S_6)}{n} = \frac{1+0.69+0.84+1+1+1}{6} = 0.92
\]

There is an 92% chance that the new battery will stay in this state (New).

**(Element)_{12} New-Remanufactured**

GM wrote in the manual (see page 322) of its new Chevy Bolt 2016 that “Depending on use the battery may degrade as little as 10% to as much as 40% of capacity over the warranty period.” (Trek, 2016)

Williams (2019) states that cold and hot temperatures can reduce the performance and life of electric vehicle battery. This effect of temperature is not permanent and the battery range return to normal when there is normal temperature. A study done by AAA used a machine called dynamometer to test the cars. The researchers tested the cars at different temperatures of 20°F and 95°F. They found that if the temperature is 20°F, the driving range of the vehicle reduces to 12% and if the interior heater is used, that range drops to 41%. When driving in 95°F the range reduces by 4% and with use of air conditioner its range drops to 17%. Although this impact of temperature on the battery might not be permanent, but it may affect the battery life through increasing the number of charge-discharge cycle for the same period of time. Approximately 8% of new EVs during the
warranty period experience faults related to their LIBs and need to be remanufactured. Considering all the information mentioned above and with the opinion of the industry expert, we reach the conclusion that with a 6% probability the state of a new battery will transit to the state (remanufacturing).

(Element)\textsubscript{13} New-Repurposed

As discussed above, 2% of new batteries may lose their storing capacity to 80% or less (extra usage, extreme weather condition and driving patterns) during the warranty period and need to be repurposed.

So, there is 2% probability that a new battery will transit to this repurposed state.

(Element)\textsubscript{14} New-Recycled

Walker et al. (2015) state that expected 8-year lifespan of Lithium-Ion batteries in the EVs can also be increased by almost 10 years when repurposed for stationary applications. So, during the warranty period the probability of losing all of its storing capacity of a new Lithium-Ion battery of an EV is zero excluding the manufacturing fault.

Category 2. Remanufactured (or second row of the matrix, P)

If a battery stops working or shows signs of failure during warranty period, there is a possibility of four major faults as proposed by Liang (2018): Electronic components, frame/enclosure, battery cell physical failure, and battery cell degradation failure.

When a battery stops working during its warranty period, one can take the battery for remanufacturing. Argonne National Laboratory Center for Transportation made an assumption that if a battery’s reason to be remanufactured is that the cells in the battery have stopped working, only 10% of them have actually ceased to function; by replacing them, the battery can be brought back to life, (Standrige and Corneal, 2014).
Ramoni (2013) presents that the equation for energy of an LIB is:

\[ W = \frac{nEF}{\sum R} \]

and the equation for power of an LIB is:

\[ P = \frac{VI}{\sum R} \]

\( W \) = specific energy of battery cell  
\( P \) = specific power of battery cell  
\( E \) = electromotive force  
\( F \) = the Faraday constant (96500 C/mol)  
\( V \) = working voltage  
\( I \) = working current  
\( \sum R \) = internal resistance

From the equations above, we can note that increasing internal resistance leads to a decrease in specific energy and power. Thus, fade in capacity in a battery can be quantified by measuring the increase in internal resistance resulting from the growth of an SEI layer on the surface of electrodes through cycling between charging and discharging (Monsuru, 2013; Abraham et al., 2007). When a battery is remanufactured at any point of its lifespan, whether that be any of the four faults identified above, SEI still exists on the electrodes because of prior use of the battery when it was in good condition. This causes impedance, and thus reduces the remanufactured battery’s lifespan.

(Element) Re manufactured - Remanufactured

Qualitative data yet are classified confidential according to EVs maintenance centers. Despite the fact that interviews have been conducted (by the author of this research work) with service centers or companies A, B, and C, located in the province of Ontario. On the
basis of information from published research by Liang (2018), the following faults were concluded:

1. **Electronic Components**: This includes failures in the Battery Management System (BMS).

2. **Frame/Enclosure**: This includes cracks, leaks, and other physical damage to the battery’s frame.

3. **Battery Cell Physical Failure**: This includes physical damage to the internals of battery cells.

4. **Battery Cell Degradation Failure**: This includes malfunction through extended usage.

Furthermore, with information collected from industry experts in the fall of 2019, we reached the conclusion that batteries require remanufacturing due to the following additional faults:

5. **When car service light is activated**: The cars battery management system needs to be diagnosed.

6. **Car Accident**: This triggers the safety mechanism that opens the battery contact points protecting them, but then requires to be reset at the service center by a specialist.

7. **Battery cooling system**

Unfortunately, most of the degradation data for electric vehicle battery packs are confidential to electric vehicle OEMs. According to the industry expert mostly electric vehicles return back for battery remanufacturing in sixth, seventh, and eighth year during the warranty period. We are using triangular distribution (with mean value of 7 years) to calculate how long a remanufactured battery will stay in this state (remanufactured).
Figure 6: Triangular Distribution, f(x) vs Number of Years

\[ X = \frac{(a + b + c)}{3} = \frac{(6+7+8)}{3} = 7 \]

\[ F(x) = CDF = 1 - \frac{(c-x)^2}{(c-b)(c-a)} \]

\[ = 1 - \frac{(8-7)^2}{(8-7)(8-6)} \]

\[ = 0.5 \]

So, the probability that a remanufactured battery stays in remanufacturing state is 50%.

(\textit{Element)23 Remanufactured-Repurposed})

Casals et al. (2017) analyzed various situations regarding end-of-life EV batteries. They studied the possibility of different second-life applications for batteries with \( X \) amount of capacity left. What they found was as follows: if an EV battery has over 88\% capacity remaining after a state of health (SOH) test, then it could be reused in an EV by replacing non-functioning parts in first life batteries. If the battery’s capacity is between 88\% to 75\%, then it can either be used for stationary applications like renewable firming, self-consumption area regulation, transmission deferral, or for less demanding transportation applications like start and stop driving cycles in cities after traffic lights. Finally, if a battery has under 75\% capacity, it can be used for very low demanding vehicles like golf cars. By considering all the facts about battery state of health (SOH) and the industry expert’s information, we take the assumption that there is 45\% chance that a remanufactured battery will transit to the state (repurposed).
Remanufactured-Recycled

There is 5% chance that remanufactured batteries may lose all of its storing capacity and needed to be recycled. So, the probability of battery transiting to this state (recycled) is 5%

Category 3. Repurposed (or third row of the matrix, P)

Across the globe, countries are looking to improve their electricity distribution. Studies have also been conducted on the latest services to check for their feasibility, like peak shaving (Husain, 2010), load leveling (Linden and Reddy, 2002), area regulation, transmission deferral (Boulanger et al., 2011), renewable firming (Omar et al., 2014), distributed generation (Cready et al., 2003), smart grid implementation (Saxena et al., 2015). For these services, batteries have been observed to provide high results, especially LIBs which have many applications (Charles et al., 2019). That being said, LIBs are too costly to be mass produced and used solely in stationary applications, even with the expected drops in price in the future (General Motors, 2016). The idea of repurposing LIBs from EVs has been proposed. After LIBs reach 80% of their state of health (SOH), the automotive standard deems them inapplicable for the use in EVs (Buchmann, 2016). A study done by Foster et al. (2014), determines that 85% of LIBs that have been removed from EVs (at their EOL) can be repurposed for stationary applications with lower costs (Tesla Motors, 2010). By reusing LIBs like this, it is possible to regulate the frequencies at which energy is passed into the grid and to the consumer. This balance in demand and generation makes this solution to the electricity distribution problem highly attractive (Natural Resources Canada, 2015; Hadjipaschalis et al., 2009).
Casals et al. (2019) found how long second-life EV batteries would last through a battery testing simulation model. They looked at four applications for these second-life batteries: Fast EV Charge, Self-Consumption, Area Regulation, and Transmission Deferral. They considered their primary input for the model as the current load the batteries should go through for each application. Change in State of Health, Depth of Discharge, and current rates, at every instant was considered to calculate the aging of the batteries. The four applications are discussed as follows:

**Self-Consumption:** In this second-life battery application, it would run for 12 years.

**Transmission Deferral:** In this scenario, second-life batteries would run for 12 years.

**Fast Electric Vehicle Charge:** In this scenario, a repurposed battery would run for 30 years.

**Area Regulation:** In this second-life battery application, it would run for six years.

Walker et al. (2015) stated that a battery’s life can be extended by 10 years through repurposing.

This can be considered as conditional probability A and S₁, S₂, S₃, S₄ are the individual occurrences.

\[ A_{10\text{ years}} = \text{lifespan that a repurposed battery can be extended by 10 years} \]

\[ n = \text{number of repurposed battery applications} \]

**Self-consumption (s₁):** Repurposed battery life is 12-years

\[ p(S₁) = 1 \quad P(S₁|A_{10\text{ years}}) - \text{Bayes’ Rules} \]

**Transmission deferral (s₂):** Repurposed battery life is 12-years

\[ p(S₂) = 1 \quad P(S₂|A_{10\text{ years}}) \]

**Fast electric vehicle charge (s₃):** Repurposed battery life is 30-years

\[ p(S₃) = 1 \quad P(S₃|A_{10\text{ years}}) \]
\[ p(S_3) = 1 \quad P (S_3|A_{10 \text{ years}}) \]

**Area regulation (S4):** Repurposed battery life is 6-years

\[ p(S_4) = 0.6 \quad P (S_4|A_{10 \text{ years}}) \]

Because lack of experimental data, we assume a uniform distribution for equal occurrence in the four different applications as mentioned above.

\[ P(A) = (p(S_1) +p(S_2) +p(S_3) +p(S_4))/n = (1+1+1+0.6) =3.6/4 = 0.9 \]

So, there is a 90% chance that a repurposed battery will stay in this repurposed state,

(\textit{Element) }_{3,4} \textit{Repurposed-Recycled}

There is a 10% chance that battery will need recycling as it loses all of its storing capacity.

Category 4. Recycled (or last row of the matrix, P)

(\textit{Element) }_{4,4} \textit{Recycled-Recycled}

After a new battery has gone through both remanufacturing and repurposing, it can no longer hold a sufficient charge for other uses, and therefore must be recycled (Standrige and Corneal, 2014). Due to this state being the absorbing state, the probability of a battery staying in this state (recycled) is 100%.

### 4.5 Transition Probability Diagram

From the probability matrix, States 1 (New), 2 (remanufactured) and 3 (repurposed) are transient states, while State 4 (recycled) is the absorbing state. The states New, Remanufactured, and Repurposed are transient states because there are paths from these states to recycling, but no path returning from recycling back to the transient states, which makes recycling an absorbing state. The transitions between states displayed in Figure 8 are explained as follows: A new battery has an 92% probability to stay in State 1 (New condition), a 6% chance that the new battery will transition from State 1 to State 2 (needs
to be remanufactured) and 2% chance that the battery will transition from state 1 to state 3 (needs to be repurposed). A remanufactured battery has a 50% chance of staying in good condition (State 2), a 45% chance for the battery to require repurposing (State 2 to State 3), and a 5% chance for the battery to be taken for recycling (State 2 to State 4). When we consider a repurposed battery, there is 90% probability that it will remain in State 3 and a 10% probability of the battery shifting to State 4 for recycling (absorbing state). At State 4, there is a 100% chance that it will remain in State 4 (absorbing state).

Figure 7: Transition Probability Diagram

4.6 Use of LIBs in EV and Other Applications

Using the transition probability matrix, the matrices that are formed by Q and R are shown below:

\[
Q = \begin{bmatrix}
0.92 & 0.06 & 0.02 \\
0 & 0.50 & 0.45 \\
0 & 0 & 0.90
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
0 & 0.05 \\
0.10 & 0
\end{bmatrix}
\]

\[
I = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
(I-Q) = \begin{bmatrix}
0.08 & -0.06 & -0.02 \\
0 & 0.5 & -0.45 \\
0 & 0 & 0.10
\end{bmatrix}
\]

The inverse of this matrix is:

\[
E = (I - Q)^{-1} = \begin{bmatrix}
12.5 & 1.5 & 9.25 \\
0.00 & 2.00 & 9.00 \\
0.00 & 0.00 & 10.00
\end{bmatrix}
\]

4.6.1 Results

From matrix E above, it can be concluded that the expected time of LIBs will remain in good working condition in an EV is:
\[ E = (I - Q)^{-1}_{11} = 12.5 \text{ years} \]

Also, the expected lifetime of the remanufactured LIBs can be:
\[ E = (I - Q)^{-1}_{22} = 2 \text{ years} \]

Finally, the expected lifetime of repurposed LIBs will be:
\[ E = (I - Q)^{-1}_{33} = 10 \text{ years}. \]

<table>
<thead>
<tr>
<th>Lithium-Ion Batteries</th>
<th>Lifespan (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>12.5</td>
</tr>
<tr>
<td>Remanufactured</td>
<td>2</td>
</tr>
<tr>
<td>Repurposed</td>
<td>10</td>
</tr>
</tbody>
</table>

**4.7 Use of Batteries in EV Only**

If we consider LIBs being used solely for the purpose of powering EVs, our transition probability matrix now has values of \( Q \) and \( R \) as shown below:

\[
Q = \begin{bmatrix} 0.92 & 0.06 \\ 0 & 0.50 \end{bmatrix} \quad R = \begin{bmatrix} 0.02 & 0 \\ 0.45 & 0.05 \end{bmatrix} \quad I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

\[
(I - Q) = \begin{bmatrix} 0.08 & -0.06 \\ 0 & 0.50 \end{bmatrix}.
\]

The inverse of this matrix is:
\[
E = (I - Q)^{-1} = \begin{bmatrix} 12.5 & 1.5 \\ 0.00 & 2.00 \end{bmatrix}
\]

\[
A = (I - Q)^{-1} * R = \begin{bmatrix} 0.925 & 0.075 \\ 0.9 & 0.1 \end{bmatrix}
\]

**4.7.1 Results**

From matrix \( A \), the probability that a new and remanufactured battery will remain in good working condition at EV is 92.5% and 10% respectively.
Table 3: Lifespan Probabilities of LIBs in EVs.

<table>
<thead>
<tr>
<th>Lithium-Ion Batteries</th>
<th>Lifespan Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>92.5%</td>
</tr>
<tr>
<td>Remanufactured</td>
<td>10%</td>
</tr>
</tbody>
</table>

4.8 Environmental Benefits

To obtain a rational environmental impact assessment, the calculations are based on the result of this research work of 12.5-years battery lifespan instead of 8 years. Thus, four and half years of new battery production will be saved for every 12.5-years. This assumption will provide an average figure that can be calculated based on the Global EV outlook 2019 report as shown in Figure 8.

Ellingsen et al. (2013) explain that a cradle-to-gate global warming (GWP) of a Lithium-Ion battery of an EV at lower bound value is 4.6 tons of carbon dioxide equivalents (CO2-eq.), at the asymptotic value it is 6.4 tons of CO2-eq, and at the average value it is 13.0 tons of CO2-eq. For the calculations, we are using the average value (i.e., 13.0 tons of CO2-eq), as LIBs can vary in capacity depending on electric vehicle designs.

Based on Figure 8, about 15 million EVs are expected to be produced by 2020 for new policies scenario and 16 million for EV30@30. This takes into account Electric Vehicle Initiatives of the EV30@30 to reach a 30% market share for EVs in all modes except two-wheelers by 2030 IEA (2019). The environmental impact trade-off of the result of this research validation can be shown in the following:

New battery manufacturing will cost 13.0 tons of CO2-eq cradle-to-gate according to Ellingsen et al. (2013).
The potential saving of CO2 can be calculated as:

No. of EVs = No. of required LIBs

If the cradle-to-gate global warming (GWP) of LIBs cost 13.0 tons of CO2-eq and can be used for eight years, then the environmental impact will be \( \frac{13}{8} \) = 1.625 tons of CO2-eq per year. This research presumes that the life of LIBs can be extended up to 12.5 years, which then gives us an environmental impact of \( \frac{13}{12.5} \) = 1.04 tons of CO2-eq per year.

The environmental impact can be concluded as follows:

For the year 2020 (New Policies Scenario):

- **This research**
  
  15 million (No. of LIBs) \* 1.04 = 15.6 million tons of CO2-eq per year

- **Old presumption**
  
  15 million (No. of LIBs) \* 1.625 = 24.37 million tons of CO2-eq per year

**Saving of CO2-eq in the year 2020**
Old – New = 24.37 – 15.6 = 8.77 million tons of CO2-eq

For the year 2020 (EV30@30 scenario):

This research

16 million (No. of LIBs) x 1.04 = 16.64 million tons of CO2-eq per year

Old presumption

16 million (No. of LIBs) x 1.625 = 26 million tons of CO2-eq per year

Saving of CO2-eq in the year 2020

Old – New = 26 – 16.64 = 9.36 million tons of CO2-eq

For the year 2030 (New Policies Scenario):

This research

125 million (No. of LIBs) x 1.04 = 130 million tons of CO2-eq per year

Old presumption

125 million (No. of LIBs) x 1.625 = 203.12 million tons of CO2-eq per year

Saving of CO2-eq in the year 2030

Old – New = 203.12 – 130 = 73.12 million tons of CO2-eq

For the year 2030 (EV30@30 scenario):

This research

240 million (No. of LIBs) x 1.04 = 249.6 million tons of CO2-eq per year

Old presumption

240 million (No. of LIBs) x 1.625 = 390 million tons of CO2-eq per year

Saving of CO2-eq in the year 2030

Old – New = 390 – 249.6 = 140.4 million tons of CO2-eq
### Table 4: Environmental Benefits

<table>
<thead>
<tr>
<th></th>
<th>CO2-eq in 2020 NPS (million tons)</th>
<th>CO2-eq in 2020 EV30@30 (million tons)</th>
<th>CO2-eq in 2030 NPS (million tons)</th>
<th>CO2-eq in 2030 EV30@30 (million tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Presumption</td>
<td>24.37</td>
<td>26</td>
<td>203.12</td>
<td>390</td>
</tr>
<tr>
<td>New Presumption</td>
<td>15.6</td>
<td>16.64</td>
<td>125</td>
<td>249.6</td>
</tr>
<tr>
<td>Savings</td>
<td>8.77</td>
<td>9.36</td>
<td>73.12</td>
<td>140.4</td>
</tr>
</tbody>
</table>

### 4.9 Markov Chain Steady-State Census

The demand of electric vehicles is increasing every passing day, so for the long-term planning of LIBs in EVs, it is useful to predict the number of batteries that are required in the steady-state. A Markov chain steady-state census model is established to calculate the ratio composition of Lithium-Ion battery market in the future. Consider the LIBs having $S$ categories:

- Category 1: New
- Category 2: Remanufactured
- Category 3: Repurposed
- Category 4: Recycled

From the transition probability matrix, $P$, the states: new, remanufactured, and repurposed are transient because LIBs can either remain in the same state or shift to a different state over the passage of time. However, the batteries that have reached their end of life go to the absorbing state because when they enter this state they cannot leave or return to a transient state. We can represent the percentages of these probabilities by using $S \times (S+1)$ transition matrix.
\[
\begin{bmatrix}
\text{New} & \text{Remanufactured} & \text{Repurposed} & \text{Recycled} \\
0.92 & 0.06 & 0.02 & 0 \\
0 & 0.50 & 0.45 & 0.05 \\
0 & 0 & 0.90 & 0.10 \\
\end{bmatrix}
\]

Transition Probability Matrix

At the beginning of each time period:

\( H_i \) = Number of LIBs of electric vehicles entering the market in year \( i \).

\( N_i \) = Number of LIBs of electric vehicles in the category \( i \) during a steady-state.

\( N_i(t) \) = Number of LIBs of electric vehicles of category \( i \) at the beginning of period \( t \).

As \( t \) grows larger through the occurrence of several time periods, either each \( N_i \) will approach a limit, or all \( N \) reach the steady-state census. If each \( N_i \) approaches a limit, all \( N = N_1, N_2, N_3, \ldots, N_s \) is the steady-state census required to fulfill the demands of LIBs in the market.

Steady-state census of LIBs in EVs can be written as:

Number of LIBs in EVs entering the market in the year \( i \) = Number of LIBs in EVs leaving the market in the year \( i \).

In the mathematical form it can be expressed as it follows:

\[ H_i + \sum_{k \neq i} N_k p_{ki} = N_i \sum_{k \neq i} p_{lk} \] (Winston and Goldberg 2004)

\( H_i \) = Number of LIBs entering the market

\( N_i \) = Number of LIBs in category \( i \) during the steady-state.

\( p \) = Fraction of LIBs from one category to the other.

In order to solve the steady-state census, the following equation can be used:

\[ \sum_{k \neq i} p_{lk} = 1 - p_{ii} \]
In Figure 9:

$N_1$ = Number of batteries in category 1 (New) in the steady-state

$N_2$ = Number of batteries in category 2 (Remanufactured) in the steady-state

$N_3$ = Number of batteries in category 3 (Repurposed) in the steady-state

$N_4$ is not in the market, as it is the absorbing state (Recycled)

4.10 Additional Information

Based on the IEA 2019 study shown in Figure 8 above, 100 million EVs will be manufactured by around 2025 according to EV30 @ 30 scenario or 2029 according to new policy scenario. This value will be used for new battery ($H_1$) in order to calculate the steady-state census of the LIBs market. The EV stock projections show an exponential growth but are not considering the emerging technology of fuel cells. Fuel cell powered vehicles may become more popular and offer an alternative to Electric vehicles. Therefore, actual EV sales may be severely affected by the emergence of fuel cell technology in the near future.
4.11 Assumptions

1. From Ramoni et al., (2017), with laser technology to ablate solid electrolyte interface (SEI) from electrodes of an EV LIB new batteries may see a decrease in manufacturing as old batteries that have been affected by SEI can easily be repaired and reused.

2. Siekierska (2018) stated that in the future, Toyota plans to increase the production of their hydrogen fuel cell EV (Mirai) from 3,000 to 30,000 by 2020. Due to high demands and costs for EVs, using hydrogen fuel cells to power vehicles seems like a much more cost-effective and efficient option. In the future, the number of LIBs is expected to stabilize.

3. Charging infrastructure is quite developed in urban areas, but for long-distance travels, there is less infrastructure on highways and suburban to rural areas. This can affect the number of EVs sold and therefore the demand for LIBs.

4. From Standridge and Hasan (2015), it is found that if EOL LIBs are taken for remanufacturing instead of disposal, then in 2030, the demand for new LIBs can decrease by about 25%.

5. Foster et al. (2014) forecasted the demand for LIBs until the year 2049. They formed optimistic, pessimistic, and middle views for said demand. Their pessimistic view (presented by the Energy Information Agency) shows that after 2034, the demand for EVs will flatline (remain steady). This means that the LIB demand will also flatline at around the same time as EV.

For our calculations, the value $H_1$ represents the number of new LIBs that are entering the market each year. From the assumptions made above, we can estimate that the number of new batteries, $H_1$, entering the market each year at 100 million. The values $H_2$ and $H_3$
represent the number of remanufactured and repurposed LIBs entering the market, respectively. For steady-state census model, the calculation is based on the amount of new batteries $H_1$, where $H_2$ and $H_3 = 0$. So, in the long run, the following results are obtained:

\[
H_1 = (0.06+0.02) N_1
\]

\[
100 = (0.08) N_1
\]

$N_1 = 1250$ million

\[
H_2 + (0.06) N_1 = (0.45+0.05) N_2
\]

\[
0 + 0.06 \times 1250 = (0.50) N_2
\]

$N_2 = 150$ million

\[
H_3 + (0.45) N_2 = (0.10) N_3
\]

\[
0 + 0.45 \times 150 = (0.10) N_3
\]

$N_3 = 675$ million

<table>
<thead>
<tr>
<th>Table 5: Long Run Ratio Composition of LIBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>New ($N_1$)</td>
</tr>
<tr>
<td>Remanufactured ($N_2$)</td>
</tr>
<tr>
<td>Repurposed ($N_3$)</td>
</tr>
</tbody>
</table>

4.12 Consideration of Sustainability

As we constantly extract and use resources from the Earth, they cannot regenerate fast enough to meet demands many years from now. Due to this, the demands of materials (cobalt, nickel, copper, lithium, and aluminum) are drastically increasing, and it is becoming costly to buy them for different applications. In the automotive industry, there are many opportunities to reuse materials in different parts, with remanufacturing playing a big role. In Abdul-Kader and Haque (2011), they address the possibility to decrease the
number of tires needed to be produced by 25% by remanufacturing; thus, reducing material consumption. Furthermore, recycling products can reduce the amount of raw material required for manufacturing, as one can recover the materials by processing existing products and extracting them. As many EVs are entering the market, materials needed for LIBs are highly in demand, but that also entails wastage of materials. After using an LIB in both EVs and post-vehicle applications, through Reverse Logistics, we can bring LIBs to recycling facilities and recover valuable materials to assist in sustainable battery manufacturing. Through recycling LIBs, some materials that can be recovered are cobalt, nickel, copper, lithium, and aluminum as shown in Figure 10 below.

In this thesis, we are considering three key raw materials that can be extracted from LIBs during recycling processes: Cobalt, Nickel and Lithium. The importance of these materials and reason for considering them is presented below in detail.

![Diagram of Assets Recovery](image)

**Figure 10: Assets Recovery**

### 4.12.1 Cobalt

In the Lithium-Ion Batteries (LIB), Cobalt which forms a part of cathode is considered the most expensive and important part. It is the by-product of copper and Nickel production in various deposits around the globe. A 51% of the global cobalt production is mined in the
Democratic Republic of Congo (DRC). It is predicted that the demand for cobalt will reach at its peak by 2050 (Lebedeva et al., 2016). There are chances of supply risk of Cobalt due to its increasing demand and high concentration in the DRC.

4.12.2 Lithium

Demand of lithium carbonate which is used in Lithium-Ion batteries is expected to increase as the demand of EVs is anticipated to increase. In 2015, Lithium Carbonate Equivalent (LCE) production was used for Lithium-Ion batteries and its demand will triple the current value by 2025 (Roskill, 2017). Presently, the total global demand for lithium carbonate is 200,000 tons but is expected to reach this value only for EVs by 2025 (Lebedeva et al., 2016).

4.12.3 Nickel

Nickel is the key component in LIB, which is also used in manufacturing Cathode. NMC (Nickel-manganese-cobalt) 1:1:1 cathode are frequently used in the batteries of vehicles made by Tesla, but in the future, it is predicted that the amount of nickel needed in NMC cathodes will increase from 33% of the cathode to 80% of the cathode (giving a ratio of 8:1:1) (Drabik and Rizos (2018)). Nickel market is certainly going to be affected by this shift.

At present, annual sale of Nickel is 2 million tons worldwide. Canada, Russia, Philippines and Australia are among the major producers of Nickel. Assuming 10% increase in electric vehicle fleet globally, demand for Nickel is expected to reach 400,000 tons (Desjardins, 2017).
4.13 Recycling Efficiency

The percentage weight of material which can be recovered from spent Lithium-Ion batteries is called recycling efficiency. Pyrometallurgical and hydrometallurgical techniques are two processes that are very commonly used in the recycling of LIBs. Cobalt, nickel, copper and iron are recovered through pyrometallurgical process by using high temperature, but manganese and lithium cannot be recovered by this process. By the combination of pyrometallurgical and hydrometallurgical processes, lithium can also be recovered (Friedrich & Peters, 2017). Zheng et al. (2018) has calculated that more than 99.96% of cobalt and 99.90% of lithium could be recovered from LIBs by using hydrometallurgical processes (leaching). They mention in their research paper that several conditions needed to be satisfied for efficient leaching: a molar ratio of 10 parts formic acid for every 1-part LiCoO₂, a temperature of 60 degrees Celsius, 20g/L as the solid-to-liquid ratio, and a 20-minute reaction time. Moreover 95% of nickel can be recovered from LIBs (Lebedeva et al., 2016).

4.14 Volume of Raw Materials in EOL EV Batteries

Fickling (2017) provides an estimation, based on battery chemistry that 116, 400, and 73 g/KWh of cobalt, nickel and lithium, respectively can be recovered from spent LIBs.

4.15 Electric Vehicle and Battery Capacity

Recent releases of EVs show battery capacities 74, 64, 64, 60, and 60 KWh for the car brands Tesla, Kia, Hyundai, GM and Nissan respectively (Chevrolet Pressroom (2019), Lambert (2018), The Car Guide (2019), “New Kia Soul” (2019)). For our calculations, the modal value 64 KWh is used.
Based on Figure 8 above, it is expected that about 15 million EVs will be produced by 2020 for new policies scenario. According to this research the original lifespan of LIBs is 12.5 years in EVs, and after that, these LIBs can be used for stationary applications with its lifespan increasing by 10 years. Thus, LIBs should be taken for recycling after a maximum of 22.5 years (after both their use in EVs and second-use applications). This research indicates that the batteries in 2020 (15 million batteries) will be available for recycling in mid-2042 (twelve and half years in EVs and 10 years in post-vehicle applications). That being said, the old presumption of a total battery lifespan of 18 years says that the batteries produced in 2024 (48 million batteries new policies scenario) will be available in mid-2042 for recycling. This gives us a difference of 33 million batteries. Our calculations involving recycled materials will be on this basis.

A study done by Foster et al. (2014) assumed that 85% of LIBs that have been removed from EVs (at their EOL) can be repurposed for a stationary application. On this basis, we are making an assumption that 10% of batteries do not come to recycling facilities due to reasons such as batteries being damaged, landfilled, or improperly collected and transported. On the basis of this assumption, below are the calculations for the available batteries in recycling facilities.

- No. of LIBs that would be available in mid-2042 for recycling is 33 million LIBs – 3.3 million (subtracting 10%) = 29.7 million LIBs.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total No of LIBs (million)</th>
<th>Capacity (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mid-2042</td>
<td>29.7</td>
<td>1,900,800</td>
</tr>
</tbody>
</table>

Table 6: Capacity and Total Number of EOL LIBs in mid-2042 (IEA, 2019)
Table 7: Recovered Materials (Fickling, 2017; Zheng et al., 2018; Lebedeva et al., 2016)

<table>
<thead>
<tr>
<th>Recovered Materials</th>
<th>Year mid-2042 (Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>220,492.8</td>
</tr>
<tr>
<td>Lithium</td>
<td>138,758.4</td>
</tr>
<tr>
<td>Nickel</td>
<td>760,320</td>
</tr>
</tbody>
</table>

There exists an uncertainty of the price for the materials that makes up the EVs battery. Due to unpredictable changes in demand patterns, current prices have been used to calculate the value of raw material as follows: Price of cobalt, lithium and nickel are 35,000, 10,000, and 6,945 US dollars per ton, respectively (LME, 2019; LME, 2019; LME, 2019).

Table 8: Value of Recovered Materials

<table>
<thead>
<tr>
<th>Recovered Material</th>
<th>Value (million US dollar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>7,717.24</td>
</tr>
<tr>
<td>Lithium</td>
<td>1387.58</td>
</tr>
<tr>
<td>Nickel</td>
<td>5,280.42</td>
</tr>
<tr>
<td>Total</td>
<td>14,385.24</td>
</tr>
</tbody>
</table>

The calculations in Table 8 are especially important for the purpose of sustainable manufacturing, recycling and reverse logistics, as this data will help in optimizing manufacturing/recycling facilities’ capacities and locations as well as economic benefits.

4.16 Sensitivity Analysis

Most of the degradation data for EV battery packs are confidential to electric vehicle OEMs. Because of the limitation due to data availability in reasonable volume in order to validate this study, a sensitivity analysis is carried out by different scenario assumptions to
tackle wide possible results. The following scenarios are considered for the sensitivity analysis.

**Scenario 1:**

\[
P = \begin{bmatrix}
\text{New} & \text{Remanufactured} & \text{Repurposed} & \text{Recycled} \\
0.89 & 0.07 & 0.04 & 0 \\
0 & 0.60 & 0.35 & 0.05 \\
0 & 0 & 0.90 & 0.10 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

For each scenario, we change the entries in category 1, New battery (or first row of the matrix, P) and category 2, Remanufactured (or second row of the matrix, P). The entries in category 3, Repurposed, and category 4, Recycled remain unchanged as explained below:

**Category 1. New Battery (or first row of the matrix, P)**

(Element)\(_{11}\) New-New 0.89

(Element)\(_{12}\) New-Remanufactured 0.07

(Element)\(_{13}\) New-Repurposed 0.04

(Element)\(_{14}\) New-Recycled 0

**Category 2. Remanufactured (or second row of the matrix, P)**

(Element)\(_{22}\) Remanufactured-Remanufactured 0.60

(Element)\(_{23}\) Remanufactured-Repurposed 0.35

(Element)\(_{24}\) Remanufactured-Recycled 0.05

**Scenario 2:**

\[
P = \begin{bmatrix}
\text{New} & \text{Remanufactured} & \text{Repurposed} & \text{Recycled} \\
0.90 & 0.06 & 0.04 & 0 \\
0 & 0.65 & 0.30 & 0.05 \\
0 & 0 & 0.90 & 0.10 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
**Category 1. New Battery (or first row of the matrix, P)**

(Element)\textsubscript{11} New-New 0.90  
(Element)\textsubscript{12} New-Remanufactured 0.06  
(Element)\textsubscript{13} New-Repurposed 0.04  
(Element)\textsubscript{14} New-Recycled 0

**Category 2. Remanufactured (or second row of the matrix, P)**

(Element)\textsubscript{22} Remanufactured-Remanufactured 0.65  
(Element)\textsubscript{23} Remanufactured-Repurposed 0.30  
(Element)\textsubscript{24} Remanufactured-Recycled 0.05

**Scenario 3:**

\[
P = \begin{bmatrix}
\text{New} & \text{Remanufactured} & \text{Repurposed} & \text{Recycled} \\
0.91 & 0.07 & 0.02 & 0 \\
0 & 0.55 & 0.40 & 0.05 \\
0 & 0 & 0.90 & 0.10 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

**Category 1. New Battery (or first row of the matrix, P)**

(Element)\textsubscript{11} New-New 0.91  
(Element)\textsubscript{12} New-Remanufactured 0.07  
(Element)\textsubscript{13} New-Repurposed 0.02  
(Element)\textsubscript{14} New-Recycled 0

**Category 2. Remanufactured (or second row of the matrix, P)**

(Element)\textsubscript{22} Remanufactured-Remanufactured 0.55  
(Element)\textsubscript{23} Remanufactured-Repurposed 0.40  
(Element)\textsubscript{24} Remanufactured-Recycled 0.05
Scenario 4:

\[
P = \begin{bmatrix}
New & Remanufactured & Repurposed & Recycled \\
New & 0.93 & 0.05 & 0.02 & 0 \\
Remanufactured & 0 & 0.50 & 0.40 & 0.10 \\
Repurposed & 0 & 0 & 0.90 & 0.10 \\
Recycled & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

Category 1. New Battery (or first row of the matrix, P)

(Element)_{11} New-New 0.93

(Element)_{12} New-Remanufactured 0.05

(Element)_{13} New-Repurposed 0.02

(Element)_{14} New-Recycled 0

Category 2. Remanufactured (or second row of the matrix, P)

(Element)_{22} Remanufactured-Remanufactured 0.50

(Element)_{23} Remanufactured-Repurposed 0.40

(Element)_{24} Remanufactured-Recycled 0.10

Scenario 5:

\[
P = \begin{bmatrix}
New & Remanufactured & Repurposed & Recycled \\
New & 0.94 & 0.05 & 0.01 & 0 \\
Remanufactured & 0 & 0.50 & 0.45 & 0.05 \\
Repurposed & 0 & 0 & 0.90 & 0.10 \\
Recycled & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

Category 1. New Battery (or first row of the matrix, P)

(Element)_{11} New-New 0.94

(Element)_{12} New-Remanufactured 0.05

(Element)_{13} New-Repurposed 0.01

(Element)_{14} New-Recycled 0

Category 2. Remanufactured (or second row of the matrix, P)

(Element)_{22} Remanufactured-Remanufactured 0.50
(Element)$_{23}$ Remanufactured-Repurposed 0.45

(Element)$_{24}$ Remanufactured-Recycled 0.05

4.16.1 Results

Scenario 1: Lifespans of LIBs in EV and other applications

Using the transition probability matrix from scenario one, the matrices that are formed by $Q$ and $R$ are shown below:

$$Q = \begin{bmatrix} 0.89 & 0.07 & 0.04 \\ 0 & 0.60 & 0.35 \\ 0 & 0 & 0.90 \end{bmatrix} \quad R = \begin{bmatrix} 0 \\ 0.05 \\ 0.10 \end{bmatrix} \quad I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$(I-Q) = \begin{bmatrix} 0.11 & -0.07 & -0.04 \\ 0 & 0.40 & -0.35 \\ 0 & 0 & 0.10 \end{bmatrix}.$$ The inverse of this matrix is:

$$E = (I - Q)^{-1} = \begin{bmatrix} 9.09 & 1.59 & 9.20 \\ 0.00 & 2.50 & 8.75 \\ 0.00 & 0.00 & 10.00 \end{bmatrix}$$

From matrix $E$ above, it can be concluded that the expected time of LIBs will remain in good working condition in an EV is:

$$E = (I - Q)^{-1}_{11} = 9.09 \text{ years}$$

Also, the expected lifetime of the remanufactured LIBs can be:

$$E = (I - Q)^{-1}_{22} = 2.5 \text{ years}$$

Finally, the expected lifetime of repurposed LIBs will be:

$$E = (I - Q)^{-1}_{33} = 10 \text{ years}.$$

The lifespan of LIBs for scenario one is calculated above and the same procedure is applied for the calculations of the four other scenarios. The results are shown in Table 9 below.
Table 9: Lifespans of LIBs in EVs and Other Applications (sensitivity analysis)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lifespan (years)</th>
<th>Lifespan (years)</th>
<th>Lifespan (years)</th>
<th>Lifespan (years)</th>
<th>Lifespan (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>9.09</td>
<td>10</td>
<td>11.11</td>
<td>14.28</td>
<td>16.66</td>
</tr>
<tr>
<td>Remanufactured</td>
<td>2.5</td>
<td>2.86</td>
<td>2.22</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Repurposed</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

![Lifespans (in years) of LIBs in EVs and Other Applications](image)

Figure 11: Lifespans of LIBs in EV and Other Applications

Scenario 1: Lifespan Probabilities of LIBs in EVs

If we consider LIBs being used solely for the purpose of powering EVs, our transition probability matrix from scenario one now has values of $Q$ and $R$ as shown below:

$$Q = \begin{bmatrix} 0.89 & 0.07 \\ 0 & 0.60 \end{bmatrix}, \quad R = \begin{bmatrix} 0.04 & 0 \\ 0.35 & 0.05 \end{bmatrix}, \quad I = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$(I - Q)^{-1} = \begin{bmatrix} 0.11 & -0.07 \\ 0 & 0.40 \end{bmatrix}. \text{ The inverse of this matrix is:}$$

$$E = (I - Q)^{-1} = \begin{bmatrix} 9.09 \\ 0.00 \end{bmatrix}, \quad A = (I - Q)^{-1} * R = \begin{bmatrix} 0.920 \\ 0.875 \end{bmatrix}$$

From matrix $A$, the probability that a new and remanufactured battery will remain in good working condition at EV is 92% and 12.5% respectively, shown in Table 10.
Table 10: Lifespan Probabilities of LIBs in EVs (sensitivity analysis)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lifespan Probabilities</th>
<th>Scenario</th>
<th>Lifespan Probabilities</th>
<th>Scenario</th>
<th>Lifespan Probabilities</th>
<th>Scenario</th>
<th>Lifespan Probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>92%</td>
<td>Scenario 2</td>
<td>91.42%</td>
<td>Scenario 3</td>
<td>91.97%</td>
<td>Scenario 4</td>
<td>85.36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remanufactured</td>
<td>12.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scenario 1: Long run ratio composition of LIBs

Based on the IEA 2019 study shown in Figure 8, 100 million EVs will be manufactured by around 2025 according to EV30 @ 30 scenario or 2029 according to new policy scenario. This value will be used for new battery (H₁) in order to calculate the steady-state census of the LIBs market.

\[
H₁ = (0.07+0.04) N₁ \\
100 = (0.11) N₁ \\
N₁ = 909 \text{ million} \\
H₂ + (0.07) N₁ = (0.35+0.05) N₂ \\
0+ 0.07 \times 909 = (0.40) N₂ \\
N₂ = 159 \text{ million} \\
H₃ + (0.35) N₂ = (0.10) N₃ \\
0 + 0.35 \times 159 = (0.10) N₃ \\
N₃ = 556.5 \text{ million}
\]

The long run ratio composition of LIBs for scenario one is calculated above, and the same procedure is applied for the calculations of the four other scenarios. The results are shown in Table 11.
Table 11: Long Run Ratio Composition of LIBs (sensitivity analysis)

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1 LIBs (million)</th>
<th>Scenario 2 LIBs (million)</th>
<th>Scenario 3 LIBs (million)</th>
<th>Scenario 4 LIBs (million)</th>
<th>Scenario 5 LIBs (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New (N₁)</td>
<td>909</td>
<td>1000</td>
<td>1111</td>
<td>1428.57</td>
<td>1666.66</td>
</tr>
<tr>
<td>Remanufactured (N₂)</td>
<td>159</td>
<td>171.28</td>
<td>172.83</td>
<td>142.85</td>
<td>166.66</td>
</tr>
<tr>
<td>Repurposed (N₃)</td>
<td>556.5</td>
<td>513.84</td>
<td>691.35</td>
<td>571.4</td>
<td>750</td>
</tr>
</tbody>
</table>

Figure 12: Long Run Ratio Composition of LIBs

Scenario 1: Environmental Benefits

To obtain a rational environmental impact assessment, the calculations are based on the result of scenario one of 9.09-years battery lifespan instead of 8 years. Based on Figure 8, about 15 million EVs are expected to be produced by 2020 for new policies scenario and 16 million for EV30@30 scenario.

Ellingsen et al., (2013). States that new battery manufacturing will cost 13.0 tons of CO2-eq cradle-to-gate. The potential saving of CO2 can be calculated as:

No. of EVs = No. of required LIBs

If the cradle-to-gate global warming (GWP) of LIBs cost 13.0 tons of CO2-eq and can be used for eight years, then the environmental impact will be $13/8 = 1.625$ tons of CO2-eq
per year. From scenario one it is presuming that the life of LIBs can be extended up to 9.09 years, which then gives us an environmental impact of 13/9.09 = 1.43 tons of CO2-eq per year.

The environmental impact can be concluded as follows:

For the year 2020 (New Policies Scenario):

This research
15 million (No. of LIBs) x 1.43 = 21.45 million tons of CO2-eq per year

Old presumption
15 million (No. of LIBs) x 1.625 = 24.37 million tons of CO2-eq per year

Saving of CO2-eq in the year 2020
Old – New = 24.37 – 21.45 = 2.92 million tons of CO2-eq

For the year 2020 (EV30@30 scenario):

This research
16 million (No. of LIBs) x 1.43 = 22.88 million tons of CO2-eq per year

Old presumption
16 million (No. of LIBs) x 1.625 = 26 million tons of CO2-eq per year

Saving of CO2-eq in the year 2020
Old – New = 26 – 22.88 = 3.12 million tons of CO2-eq

For the year 2030 (New Policies Scenario):

This research
125 million (No. of LIBs) x 1.43 = 178.75 million tons of CO2-eq per year

Old presumption
125 million (No. of LIBs) x 1.625 = 203.12 million tons of CO2-eq per year
Saving of CO2-eq in the year 2030

Old – New = 203.12 – 178.75 = 24.37 million tons of CO2-eq

For the year 2030 (EV30@30 scenario):

This research

240 million (No. of LIBs) x 1.43 = 343.2 million tons of CO2-eq per year

Old presumption

240 million (No. of LIBs) x 1.625 = 390 million tons of CO2-eq per year

Saving of CO2-eq in the year 2030

Old – New = 390 – 343.2 = 46.8 million tons of CO2-eq

The environmental benefit for scenario one is calculated above and the same procedure is applied for the calculations of the four other scenarios. The results are shown in Table 12 below.

Table 12: Environmental Benefits (sensitivity analysis)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2020 (NPS)</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saving CO2-eq (million tons)</td>
<td>Saving CO2-eq (million tons)</td>
<td>Saving CO2-eq (million tons)</td>
<td>Saving CO2-eq (million tons)</td>
<td>Saving CO2-eq (million tons)</td>
<td></td>
</tr>
<tr>
<td>2020 NPS</td>
<td>2.92</td>
<td>4.87</td>
<td>6.82</td>
<td>10.72</td>
<td>12.67</td>
</tr>
<tr>
<td>2020 EV30@30</td>
<td>3.12</td>
<td>5.2</td>
<td>7.28</td>
<td>11.44</td>
<td>13.52</td>
</tr>
<tr>
<td>2030 NPS</td>
<td>24.37</td>
<td>40.62</td>
<td>56.87</td>
<td>89.37</td>
<td>105.62</td>
</tr>
<tr>
<td>2030 EV30@30</td>
<td>46.8</td>
<td>78</td>
<td>109.2</td>
<td>171.6</td>
<td>202.8</td>
</tr>
</tbody>
</table>
As mentioned previously, we are using the model value of 64 kWh as the battery capacity for our calculations. Based on Figure 8 it is expected that about 15 million EVs will be produced by 2020 for new policies scenario. According to scenario one the original lifespan of LIBs is 9.09 years in EVs, and after that, these LIBs can be used for stationary applications with its lifespan increasing by 10 years. Thus, LIBs should be taken for recycling after a maximum of 19 years (after both their use in EVs and second-use applications). Scenario one indicates that the batteries in 2020 (15 million batteries) will be available for recycling in 2039 (9 years in EVs and 10 years in post-vehicle applications). That being said, the old presumption of a total battery lifespan of 18 years says that the batteries produced in 2021 (16 million batteries new policies scenario) will be available in 2039 for recycling. This gives us a difference of 1 million batteries. Our calculations involving recycled materials will be on this basis.

- No. of LIBs that would be available in 2039 for recycling is 1 million LIBs – 0.1 million (subtracting 10%) = 0.9 million LIBs. This will give a capacity of 57,600 (MWh).
Total number of EOL LIBs and capacity (MWh) for scenario one is calculated, and the same procedure is applied for the four other scenarios.

Table 13: Capacity and Total Number of EOL LIBs (sensitivity analysis)

<table>
<thead>
<tr>
<th>Year</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2039</td>
<td>2040</td>
<td>2041</td>
<td>2044</td>
<td>2047</td>
</tr>
<tr>
<td>Total no of LIBs (million)</td>
<td>0.9</td>
<td>1.8</td>
<td>27</td>
<td>38.7</td>
<td>76.5</td>
</tr>
<tr>
<td>Capacity (MWh)</td>
<td>57,600</td>
<td>115,200</td>
<td>1,728,000</td>
<td>2,476,800</td>
<td>4,896,000</td>
</tr>
</tbody>
</table>

Figure 14: Total Number of EOL LIB and Capacity

Scenario 1: Recovered Materials

As previously indicated by Fickling (2017), Zheng et al. (2018), and Lebedeva et al. (2016), the recovered materials cobalt, lithium and nickel is calculated for scenario one and for the four other scenarios same procedure is applied.
Table 14: Recovered Materials (sensitivity analysis)

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1 Recovered Materials (tons)</th>
<th>Scenario 2 Recovered Materials (tons)</th>
<th>Scenario 3 Recovered Materials (tons)</th>
<th>Scenario 4 Recovered Materials (tons)</th>
<th>Scenario 5 Recovered Materials (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>6,681.6</td>
<td>13,363</td>
<td>200,448</td>
<td>287,308.8</td>
<td>567,936</td>
</tr>
<tr>
<td>Lithium</td>
<td>4,204.8</td>
<td>8,409</td>
<td>126,144</td>
<td>180,806.4</td>
<td>357,408</td>
</tr>
<tr>
<td>Nickel</td>
<td>23,040</td>
<td>46,080</td>
<td>691,200</td>
<td>990,720</td>
<td>1,958,400</td>
</tr>
</tbody>
</table>

Scenario 1: Value of Recovered Materials

As stated earlier, the price of cobalt, lithium and nickel are 35,000, 10,000, and 6,945 US dollars per ton, respectively (LME, 2019; LME, 2019; LME, 2019). The value of recovered material for scenario one is calculated and the same procedure is applied for the four other scenarios. The results are shown in Table 15 below.

Table 15: Value of Recovered Materials (sensitivity analysis)

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1 Value (million US dollar)</th>
<th>Scenario 2 Value (million US dollar)</th>
<th>Scenario 3 Value (million US dollar)</th>
<th>Scenario 4 Value (million US dollar)</th>
<th>Scenario 5 Value (million US dollar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>233.85</td>
<td>468</td>
<td>7,015.68</td>
<td>10,630.42</td>
<td>19,877.76</td>
</tr>
<tr>
<td>Lithium</td>
<td>42.04</td>
<td>84</td>
<td>1,261.44</td>
<td>1,808</td>
<td>3,574</td>
</tr>
<tr>
<td>Nickel</td>
<td>160</td>
<td>781</td>
<td>4800.38</td>
<td>6,880.55</td>
<td>13,601</td>
</tr>
<tr>
<td>Total</td>
<td>435.9</td>
<td>1,333</td>
<td>13,077.5</td>
<td>19,318.97</td>
<td>37052.76</td>
</tr>
</tbody>
</table>

Figure 15: Value of Recovered Materials (million US dollar)
CHAPTER 5

CONCLUSION

The goal of this research was to analyze the lifespan and long-term ratio composition of Lithium-Ion Batteries in electric vehicles by developing two models: An Absorbing Markov Chain model, and a Markov Chain Steady-State Census model. Both models utilized a probability matrix that was formed based on available information from the published literature and interviews. The absorbing Markov chain model was used to calculate the lifespan of new, remanufactured and repurposed LIBs; and the probabilities of how long new and remanufactured batteries will stay in good working conditions. The steady-state census model was used to investigate how the EV LIB market composition would look in the future.

The first model considered batteries being new, remanufactured, and repurposed as transient states, and batteries being recycled as the absorbing state. The results from this model were that the lifespan of new, remanufactured and repurposed batteries are 12.5, 2, and 10 years, respectively. Furthermore, the probability of new and remanufactured batteries staying in good working condition are 92.5% and 10% respectively. The second model takes the number of batteries entering and exiting the market. When forecasting events and amounts of certain products in the future, there are often flaws that come with forecasting methods. Due to this, steady-state census models are an important part for predictions, as they strengthen the reliability of the forecast. The outcome was that we will have 1250 million new batteries, 150 million remanufactured batteries, and 675 million repurposed batteries globally. Sensitivity analysis has been carried to alleviate for the lack of input data in this new area of research.
Battery manufacturers, remanufacturers, and government concerned organizations may utilize these outcomes to aid in decision-making that regards their respective fields. Using the results above, due to the rapidly increasing number of EVs on the road, the next generation’s automotive industry can optimize sustainable manufacturing, improve lifecycle efficiencies and reduce the environmental impact of LIBs used in EVs. The lifespan of LIBs in old presumptions was 8 years, but with this new findings, a 12.5-year lifespan is possible. This 4.5-year difference can reduce the battery production required in the future, which can drastically cut down on raw material extraction, use, and CO2-equivalent emissions that are associated with LIB production.

The increasing demand for EVs globally has created a necessity for more batteries to power them, and these batteries require materials to be made. By considering reverse logistics processes, it is possible to recycle batteries in exchange for the aforementioned valuable materials. Not only does this benefit the environment, but due to the rising demands and decreasing supplies of the materials used in battery production, there is also an equally beneficial economic impact, as fewer materials are needed to manufacture batteries. From this research, the material cobalt, lithium, and nickel that can be recovered in the example year of mid-2042 is 220,492.8 tons, 138,758.4 tons, 760,320 tons less than the originally expected amount based on the old calculations with a total estimated value of 14,385.24 million US dollars in current prices. These calculations are mainly important for the purpose of sustainable manufacturing, and recycling as this data will help in optimizing manufacturing/recycling facilities’ capacities and locations as well as economic calculations.
Our steady-state census model viewed the battery market at a world level, but it is entirely feasible for a specific country or region to find the long-term ratio composition of any market using similar steps. Since this research tackles a topic that is fairly new, limited market data is available for study. This study relied on a probability matrix that was formulated using information from the literature and through interviews, but the models utilized in this research can also be applied with more concrete data such as information for degradation of LIBs which is currently kept confidential by OEMs. Furthermore, because our research focused on the benefits in terms of environmental impacts, there is still room to look into the consequences that exist when transporting batteries to recycling facilities through Reverse Logistics.
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Vita Auctoris

<table>
<thead>
<tr>
<th>NAME:</th>
<th>Muhammad Nadeem Akram</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLACE OF BIRTH:</td>
<td>Sheikhupura, Pakistan</td>
</tr>
<tr>
<td>YEAR OF BIRTH:</td>
<td>1970</td>
</tr>
<tr>
<td>EDUCATION:</td>
<td>University of Punjab, B.Sc., Mathematic &amp; Physics Lahore, 1992</td>
</tr>
<tr>
<td></td>
<td>University of Engineering and Technology, B.Sc., Electrical engineering Lahore, 1998</td>
</tr>
<tr>
<td></td>
<td>University of Windsor, MEng., Industrial Engineering Windsor, ON, Canada, 2017</td>
</tr>
<tr>
<td></td>
<td>University of Windsor, MASc Industrial Engineering Windsor, ON, Canada, 2020</td>
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