LITHIUM-BASED BATTERY FIRES IN CALIFORNIA:

A POLICY ANALYSIS

A Thesis

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by

Monia Akter Holleman

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Edward Lascher, Ph.D. Date

Department of Public Policy and Administration

Abstract

of

LITHIUM-BASED BATTERY FIRES IN CALIFORNIA:

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Monia Akter Holleman

One of the leading energy sources used in our modern consumer society is lithium batteries. Lithium batteries are expected to become the new source of fuel as demand grows for smaller, longer-lasting devices. Lithium-based batteries are in smartphones, digital cameras, laptops, and even electric cars. However, the nature of lithium-based batteries makes it highly volatile. These batteries can catch on fire due to internal and external factors; the battery may short circuit or catch on fire due to extreme heat or physical damage. The number of fires and the cost of these fires are growing. In California, there are currently no major standards for disposing or recycling lithium-ion batteries beyond categorizing them as a hazardous waste. The laws regarding rechargeable batteries are outdated in terms of technology. Furthermore, the low recycling rate and improper dispose of these batteries are leading to these fires. Therefore, lithium battery fires are an urgent public policy issue that California's policymakers need to address. For this reason, the thesis topic I studied is, "In the State of California, the current management of Lithium batteries throughout the disposal process is causing too many costly fires." The purpose of my thesis is to suggest a possible policy solution at the state-level for the increasing occurrence of Lithium-ion battery fires in California. To solve this policy problem, I followed Bardach's (2009) "Eightfold Path for Policy Analysis" and used the Alternative Matrix (CAM) analysis to evaluate the policy alternatives for consideration. I concluded my study by suggesting a hybrid solution, which includes: (1) consumer education, (2) governmental oversight program, and (3) a fire suppression system in facilities.

_______________________, Committee Chair
Robert Wassmer, Ph.D.

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Date

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Bismillahir-Rahmanir-Rahim, Alhumdurilla.
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Chapter One

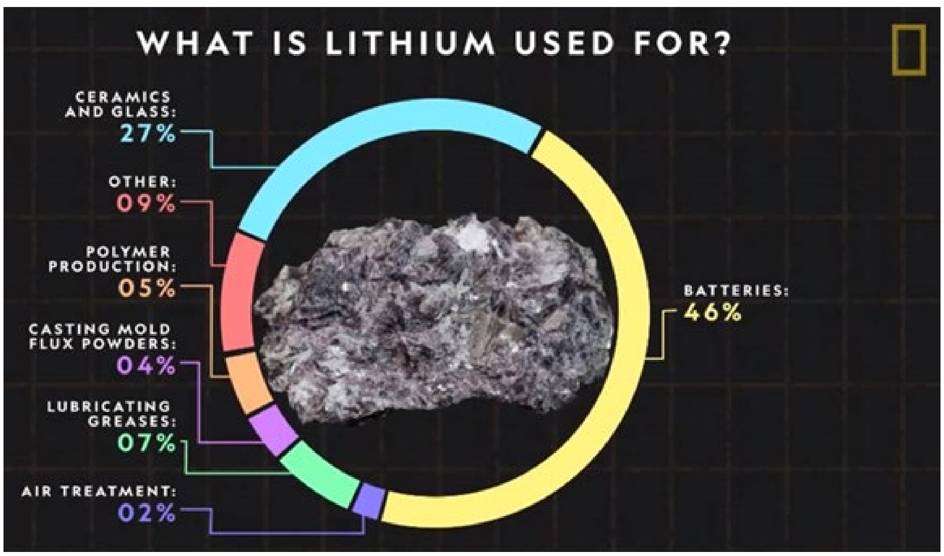
INTRODUCTION

One of the driving factors of human advancement is the need for reliable and relatively inexpensive energy. Currently, one of the leading energy sources used in our modern consumer society is a highly volatile element known as lithium (symbol Li). All sorts of products contain Li from smartphones, digital cameras, and laptops to electric cars. These products contain Li batteries within them. The nature of lithium-ion battery makes it highly volatile; this is one of the reasons why California's current disposal process led to many dangerous fires (CalRecycle, 2018). Thus, the purpose of my master's thesis is to explore the public policy problem that the current method(s) of recycling Lithium batteries in the State of California is causing too many costly fires. In this chapter, I will write about the background information needed to fully comprehend why this is a public policy concern warranting a thesis examination. I do this in the following sections that cover: what is lithium, the lithium battery boom, the cause of fires, the frequency of fires, examples of fires, cost of these fires, and laws on Battery Recycling. In the concluding section, I offer an overview of the remaining chapters in this thesis.

What is Lithium?

Lithium is a soft, grey element making up only 0.002% of the earth's crust. Discovered in 1817, this rare element is the lightest and least dense metal on earth. It is the first metal in the Periodic Table of Elements and Chemistry, with an atomic number of three, after Hydrogen and Helium. Lithium has the highest electrochemical potential (amount of work needed to move a unit of positive charge) and provides the largest specific energy per weight of any metal. Because lithium is the third-smallest element molecule, it can carry a positive charge in a tiny space. Lithium is incredibly versatile, and its uses include strengthening glass and refining metal alloys. However, the most popular use is in lithium batteries, amounting to about 46 percent of lithium's total consumer use, as shown in Figure 1.1 (National Geographic).

Figure 1.1: What is Lithium Used for? Source: National Geographic



A lithium-ion battery or Li-ion battery (LiB) is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Lithium-based batteries are in laptops, cell phones, tablets, iPods, electric cars, and more. Lithium-based batteries are popular because they can store more power than other battery technologies. Furthermore, as technology improves, LiB is becoming lighter, thinner, generally more mobile, and capable of delivering performance for more extended periods. Compared to 2010, today's Lithium batteries are 60% more powerful, 55% lighter and 40% cheaper. As a result, they have experienced high growth and consumption, with an approximate annual usage increase rate of 1.75 battery per person per year (Resource Recycling Systems, 2018). Lithium batteries are great for storing green energy like solar and wind. In addition, lithium-ion batteries have become the backbone of the mobile electronic revolution because of their compact, lightweight, yet powerful energy storage capabilities.

The lithium-based battery has brought about an evolution in convenience because of its advancing properties. The reasons for its rapidly increasing popularity are numerous. The batteries are lighter because lithium is a lightweight metal. Lithium has a very high energy density because it is highly reactive, which means in its atomic bonds, there is a great deal of energy stored. Compared to nickel-metal hydride battery and lead-acid battery LiB has higher energy density and energy storage ability. A typical lithium-ion battery can store 150 watt-hours of electricity in 1 kilogram of battery. A NiMH (nickel-metal hydride) battery pack can store about 60 to 100 watt-hours per kilogram. A lead-acid battery can store only 25 watt-hours per kilogram. It takes lead-acid technology 6-kilograms to store the same amount of energy that a 1-kilogram lithium-ion battery can handle. Another valuable attribute of lithium-based batteries is that they have the slowest self-discharge when not in use. A lithium-ion battery pack loses only about 5 percent of its charge per month, compared to a 20 percent loss per month for NiMH batteries. After 20 weeks, lithium-based batteries still maintain 80 percent of their charge, while, generally, other recharging batteries can lose approximately 80 percent of their charge over the same time. Additionally, lithium-ion batteries can go through the charge and discharge cycles hundreds of times, which makes them ideal as rechargeable batteries. Unlike some other batteries, LiB has no memory effect, which means the complete discharge of the batteries is not necessary before recharging them (Brain, 2006). For these reasons, Lithium-based batteries have become one of the most critical technologies of the 21st century.

Battery Boom

Improvements in energy storage are revolutionizing the use of electricity. As a new source of fuel, the expectation is, lithium batteries will make up the bulk of the energy storage in America's power grids through the coming years. LiBs are in all types of devices ranging from handheld devices to electric cars. One of the reasons lithium-ion batteries are becoming more popular and higher in demand is because of electric vehicles (EV); the highest expense in EV are the batteries. From 2010 to 2016, there was an increase in demand for EV due to oversupply and competition, which led to the lowering of prices on lithium-ion batteries, shown in Figure 1.2. The improvement in technology is reducing the production costs of the batteries.

According to Bloomberg New Energy Finance (BNEF), LiBs in Korean manufacturing plants in 2017 cost $162/kWh (kilowatt-hour) but are expected to drop to $74/kWh in 2030, as shown in Figure 1.3.

Figure 1.2: Bloomberg New Energy Finance Lithium-Ion Battery Prices from 2010-2016

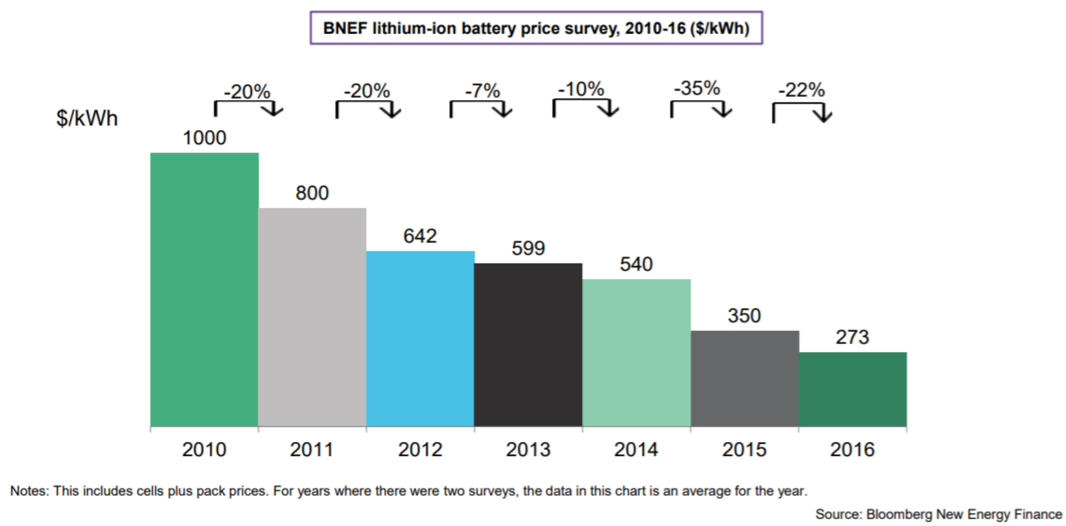
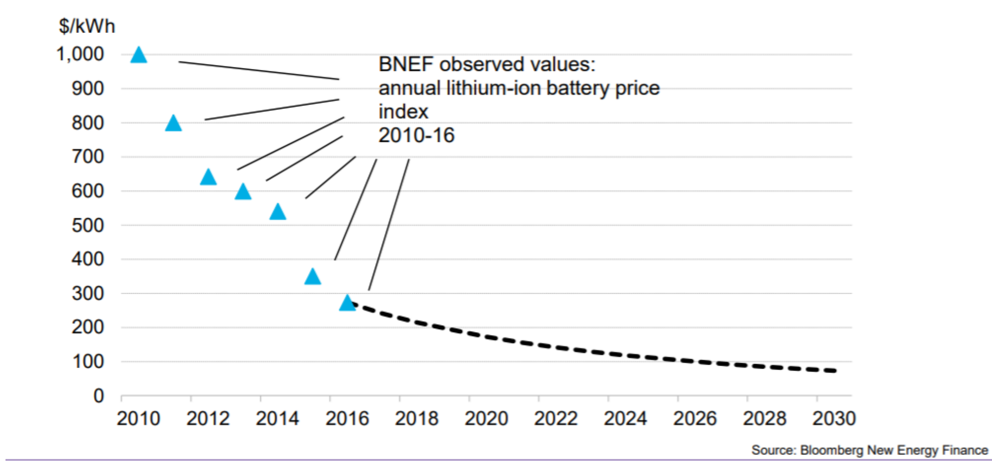


Figure 1.3: Bloomberg New Energy Finance Lithium-ion Battery Price Index



As of early October 2018, approximately 3 million electric vehicles were operating throughout the world. Volkswagen AG has estimated that by 2025, the number of electric vehicles that they will produce alone will be within 3 million electric vehicles annually (Bloomberg Commodities, 2018). Figure 1.4 shows the global forecasted demand for lithium-ion batteries for EV. BNEF predicts that the annual demand for lithium-ion batteries from EV sales will jump from 123 Gigawatt hours (GWh) in the year 2020 to 1,293 in the year 2030. Most of the demand coming from China and U.S. Figure 1.5 shows the increase in U.S. energy storage capacity.

Figure 1.4: Global Forecasted Demand for Lithium-Ion Batteries

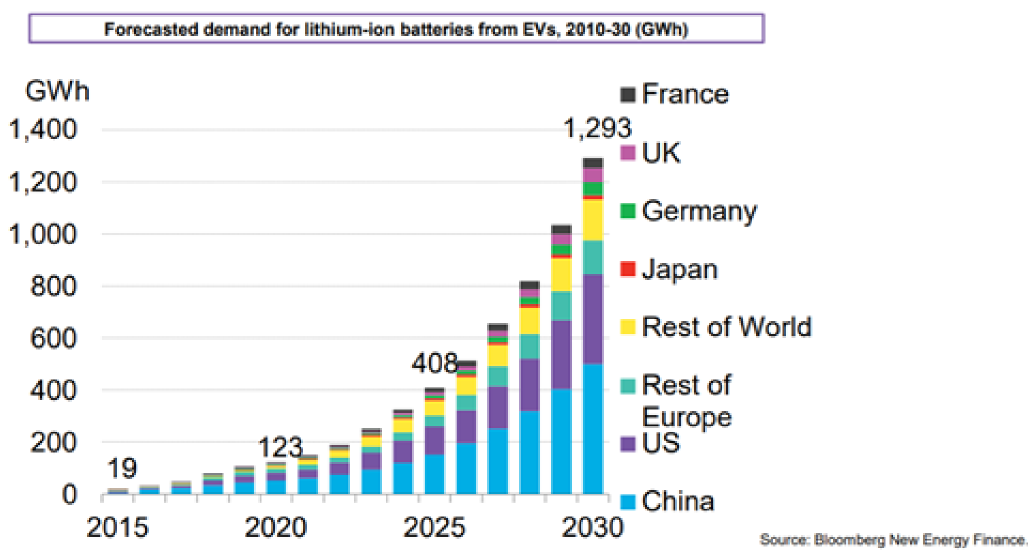
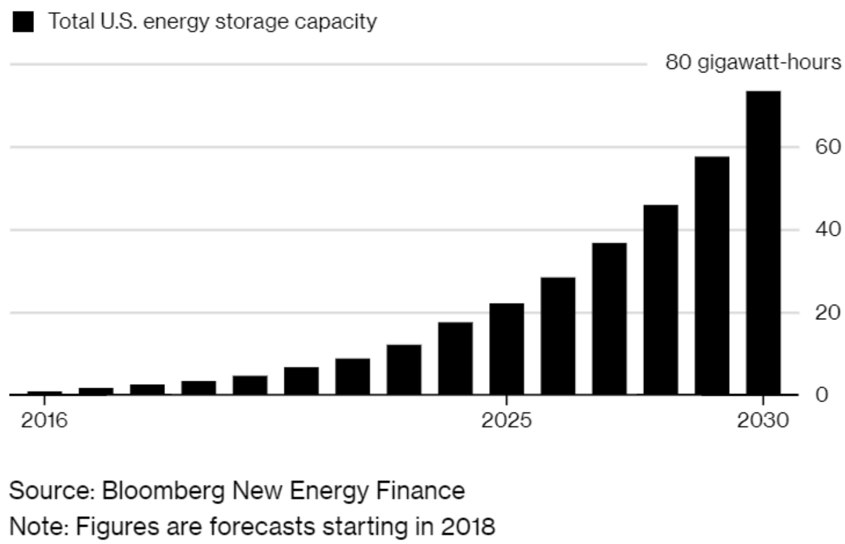


Figure 1.5: Total U.S. Energy Storage Capacity



Lithium-ion Batteries and Fires

<u>What Causes Fires</u>

The very thing that makes lithium-ion batteries so useful is what also gives them the capacity to catch fire or explode. Lithium excels at storing energy. LiB slowly releases energy to power technology. However, an instantaneous discharge can lead to an explosion.

Inside every lithium-ion battery, there are two electrodes, the positively charged cathode, and the negatively charged anode. Separating the positive and negative charge is a thin sheet of micro-perforated plastic that keeps the two electrodes from touching. When charging the LiB, the transfer of lithium ions occurs by electricity from the cathode moving through the micro-perforated plastic in the separator via an electrically conductive fluid to the anode. When the battery discharges, the reverse happens, the lithium ions flow from the anode toward the cathode, this reaction charges and powers cell phones, laptops, etc. Smartphones have small batteries, usually, have only a single lithium-ion cell. Laptops have larger batteries, typically between 6 and 12 lithium-ion cells. The batteries in electric cars and airplanes can have hundreds of cells (Guinness, 2018).

Most lithium-ion battery fires and explosions come down to a problem of short-circuiting. Short-circuiting happens when the plastic separator fails and lets the anode and cathode touch. Once those two connect, the battery starts to overheat. A bad design or manufacturing defect can lead to this problem, as it did for the Samsung Galaxy Note 7 cell phones. Samsung recalled their Galaxy Note 7 cell phones due to a high number of battery explosions. When the battery expanded a little as it charged, the electrodes bent and caused a short circuit. There was not enough space for the electrodes and separator in the battery (Guinness, 2018).

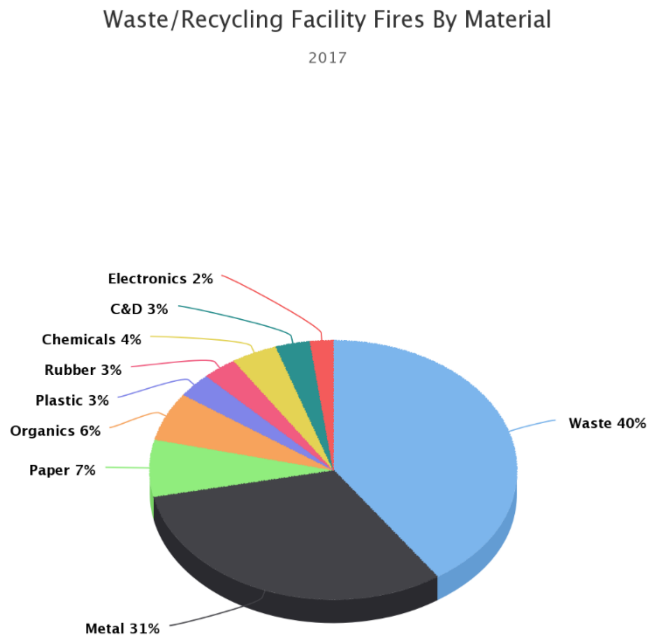
External factors such as extreme heat and physical damage can also lead to fires; this is an issue during the recycling system. Call2Recycle reports that during the collection and the material recovery operations process, the batteries can be dropped, scarped, crushed (the compression can be more than 1,800 PSI), punctured by shape objects such as glass, metal or during unloading the batteries can be run over with tires.

Resource Recycling System, a recycling consulting firm, states, in the recycling trucks, the batteries can be compacted or crushed in a truck compactor or underneath the wheels of front-wheeled loaders. In the facility, any jostling or damage to the batteries are potential fires waiting to happen. The batteries are thrown into a bucket, transferred into a larger storage container, or dropped underneath elevated sort lines for further storage or punctures from external sources (metals and glass). Other factors that can result in battery fires are things such as improper disposal with caustic agents (e.x. bleach, ammonia, acid, and other reactive compounds), if not captured separately in plastic bags at the curb.

Frequency of Fires

Fires have been a dangerous hazard in waste and recycling facilities for decades, these fires are dangerous for workers, and they can cause shutdowns of facilities leading to financial loss. A variety of reasons can cause waste and recycling facility fires. According to the report submitted by Ryan Fogelman, Vice President of Business Development at Fire Rover, in the U.S. and Canada, waste and metal comprise most of the reported fires, with waste accounting for 41 percent of fires and metal accounting for 31 percent (Kuffel, 2018).

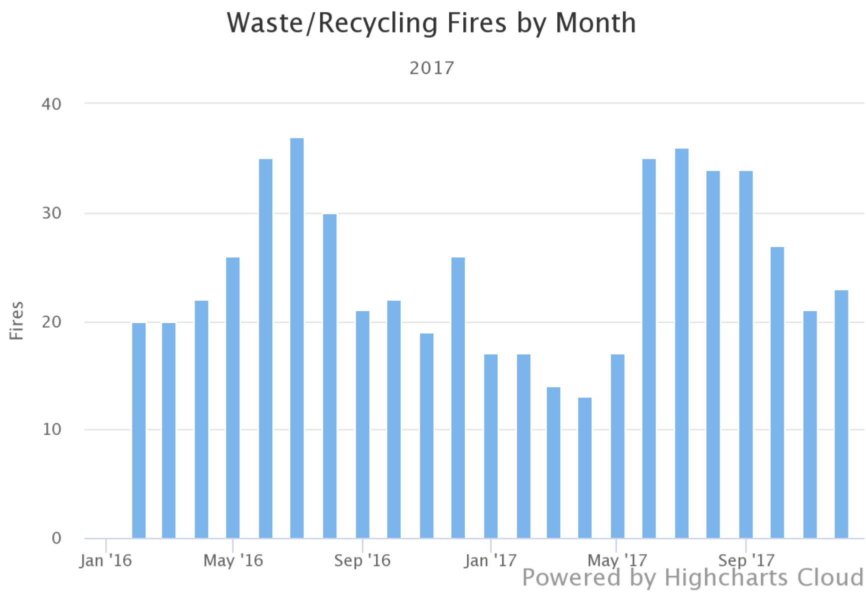
Figure 1.6: Percentage of Waste/Recycling Facility Fires by Material



Fogelman collected fire reports for 2016 and 2017 in the U.S. and Canada. He found in 2016, there were 272 reported fires and 287 fires in 2017. However, Fogelman, along with many others in the industry, believes that the numbers are too low to be accurate because these figures represent only the reported fires. They believe there are 'non-reported' fires that occur regularly in recycling operations.

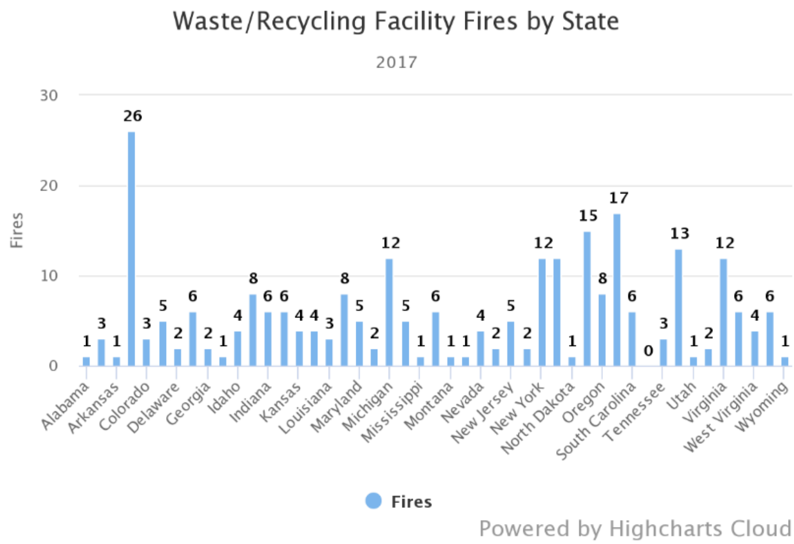
In the summer months, there is a higher trend of fires, due to the amount of dry material and abundance of fireworks during those months. There was also an increase in fire from 2016 to 2017. As indicated in Figure 1.7, from June 2017 through October 2017, 167 fires occurred; this is an increase in fires compared to the 145 fires documented in the same period in 2016.

Figure 1.7: Waste/Recycling Facility Fires in 2017 by Month



The highest number of fires reported in 2016 was in California at 34, and in 2017 California still had the most reported fires at 26, as shown in Figure 1.8. Pennsylvania had 17, Ohio had 15, and Texas had 13. South Dakota was the only state in 2017 to have no fires reported, although nine different states had only one reported (Kuffel, 2018).

Figure 1.8: Waste/Recycling Facility Fires by State in 2017



Examples of Fires

The increased regularity of fires in the North American solid waste and recycling systems has been due to the increased number of Li-based batteries entering the recycling and municipal solid waste/recycling streams. As mentioned earlier, it is difficult to account for the exact number of fires due to lithium-based batteries because of the nature of fires, and due to under-reporting. According to the Material Recovery Facility (MRF) operators, the leading causes are Lithium-based batteries and pressurized propane cylinders.

In 2017, 65% of waste facility fires in California began with lithium-ion batteries. In March 2017, an improperly tossed lithium-ion battery caused a five-alarm fire at a recycling facility in Queens in New York City. It burned for two days and shut down four branches of the Long Island Rail Road for several hours because of the thick smoke blowing onto the tracks. In that same month, an Indianapolis recycling plant also shut down after a fire blamed on batteries (Weise, 2018). In June 2017, in Ohio, a FedEx truck carrying old lithium batteries on their way to be recycled caught fire in the freeway. Fire marshal suspected one of the batteries leaked acid, which set the rest of them on fire (O'Hara, 2017).

Figure 1.9 below gives a list of MRF fires theoretically caused by lithium batteries. Unfortunately, I could not find the cost associated with these fires.

Figure 1.9: Major Material Recovery Facility Fires Suspected of Lithium Batteries
Source: Resource Recycling Systems

NUMBER OF MAJOR MRF FIRES EXPLODE AND SUSPECT LITHIUM BATTERIES

HEADLINE	SOURCE	COMPANY	DATE
BATTERY LIKELY CAUSE OF ECOMAINE RECYCLING CENTER FIRE	Ecomaine.com	Ecomaine	December 17, 2017
LITHIUM BATTERY CAUSED 5-ALARM FIRE THAT DISRUPTED LIRR SERVICE	Newsday	Royal Waste Services, Queens	March 17, 2018
RECYCLING FACILITY FIRE SPARKS WARNINGS ABOUT IMPROPERLY DISCARDED BATTERIES	Fox News 59 Indianapolis	Republic	March 27, 2018
MALL LITHIUM ION BATTERY PACK CAUSED A FIRE AT THE COMPANY'S CINCINNATI RECYCLING FACILITY	KFVE Cincinnati	Rumpke	March 29, 2018
FIRE AT RECYCLING CENTER DISRUPTS CLEARWATER'S PROGRAM	Tampa Bay Times	Waste Management	April 12, 2018
ELECTRONICS BATTERY MAY BE TO BLAME FOR RECYCLING FIRE LITHIUM ION BATTERY SUSPECTED	KGUN Channel 9 Tucson, AZ	Friedman	May 21, 2018
FIRE BURNS FOR HOURS AT SUBURBAN RECYCLING PLANT	Channel 5- Channel 5 NBC	Lakeshore, Disposal	May 2, 2018
FIRE HEAVILY DAMAGES WASTE MANAGEMENT FACILITY AS CREWS WORK WITH 'LIMITED' HYDRANTS	Chicago Tribune	WM	June 1, 2018
CREWS RESPOND TO STRUCTURE FIRE IN BLAINE	KSTP-Channel 5 ABC	Dem-Con	June 30, 2018
MASSIVE FIRE AT RECYCLING FACILITY MAY HAVE BEEN SPARKED BY LITHIUM BATTERY IN A BALE	Fox 6 news.com	Jones Disposal	July 1, 2018

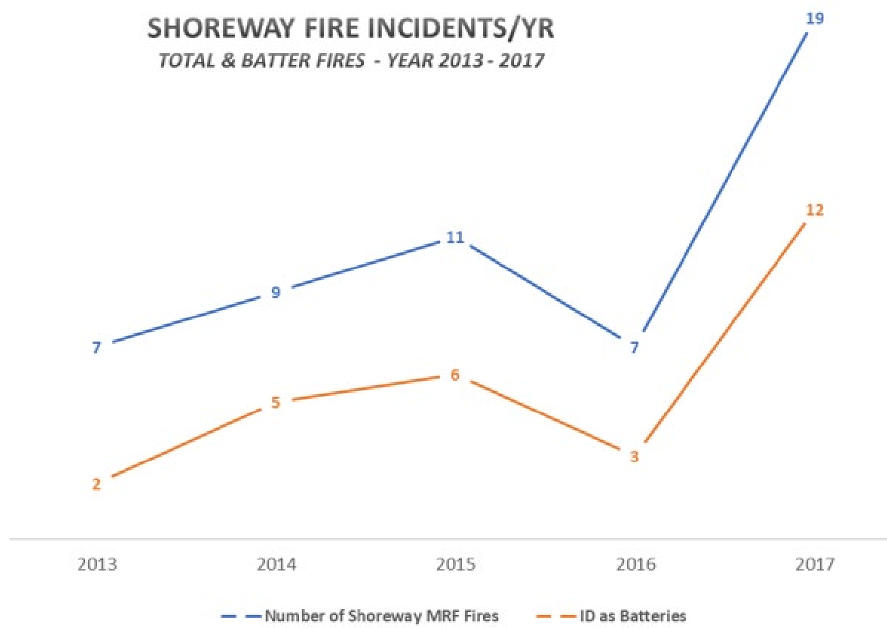
As technology increases to make lithium-ion batteries cheaper and more powerful, the LiB only increases the waste stream. According to Cameron Perks, a consultant for Industrial Minerals, the forecast for lithium-ion batteries is expected to increase up to seven-fold by 2024 (Fogelman, 2018). Apple is planning to add an estimate of three billion mini lithium-ion batteries to the market along with its new AirPod wireless headphones over the next ten years. The tiny lithium-ion batteries in the AirPods are glued-in, which would make it difficult to take apart and recycle. Usually, recyclers would shred wired headphones and send them to a smelter, which will melt them down for the copper inside. However, deceives like AirPods (with embedded LiBs) can catch on fire during the shredding process (Reuters, 2016). Therefore, present conditions in MRFs understate the future risk where battery fires are now increasing rapidly.

What is the Projected Annual Cost of These Fires?

In the United Kingdom, the Environmental Agency (EA) reported an average of 332 waste facility fires between 2001 and 2014 and 250 fires in 2015. The figures show that the overall trend of waste fires over the last ten years has remained consistent at around 250 incidents per year. The cost of fire and rescue services is estimated to be in the region of £16 million a year" (Eminton, 2016).

The exact cost of lithium-ion batteries fires in the U.S. is unknown due to a few factors. Facility owners do not always report fires, and sometimes, the exact cause of the fire can be challenging to determine. MRF operators believe that about 1 percent of all their major fires every year (over $1M in losses) are due to Li-based batteries and that this is likely a conservative estimate (Resource Recycling Systems, 2018). In 2013, the South Bayside Waste Management Authority (SBWMA), started to track the fires in their facilities. They found the number of fires has been increasing, and most of them are from lithium-ion batteries, as shown in Figure 1.10.

Figure 1.10: Shoreway Fire Incidents from 2013-2017



The drop in the number of fires in 2016 at SBWMA facilities (ironically) was due to an operation shutdown that lasted for about three months. The facility shut down was due to a lithium-ion battery fire in September 2016. It cost the facility $8.5 million in building and equipment restoration; it took them a year to make the site fully functional. The direct cost of that fire was $8.5 million, but the unaccounted cost includes: loss of business during the three-month facility shutdown, loss of insurance, and difficulty of finding new insurance that included six different insure with a much higher premium and deductible. One of the main negative externalities of these fires is the difficulty of acquiring insurance for the recycling facilities. One of the reasons recycling facilities are hesitant to report fires is the fear of an increase in insurance prices or loss of insurance (CalRecycle, 2018).

California Product Stewardship Council (CPSC) surveyed waste facilities operators across California (northern, southern, rural, and urban) to learn about the fires that happened in their facilities. The survey released on March 9, 2018, 26 personnel responded from 22 respective waste facilities, reported the following: 56 percent of the reported fires were due to batteries, while the remaining 44 percent were related to other items such as propane tanks, combustibles (butane lighters/aerosols, etc.), ashes and even greeting cards.

Battery Recycling Laws

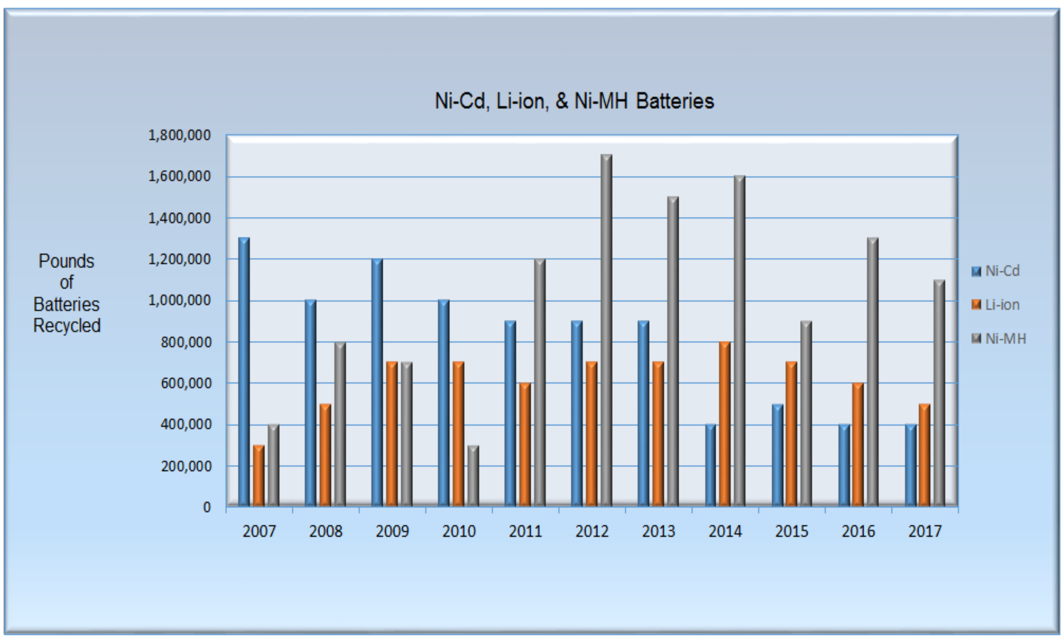
Batteries are a hazardous waste as described in chapter 11 of title 22, division 4.5, California Code of Regulations. They are hazardous products mainly because of the metals and other toxic or corrosive materials contained within. It is subject to regulation under articles 10.6 and 10.8 of California Health and Safety Code and California Code of Regulations, title 22, chapters 11, 12, 16 and 23 by the Department of Toxic Substances Control (DTSC) and the Certified Unified Program Agencies (CUPAs). By law, Californians cannot throw household hazardous waste (like batteries) into the trash or recycling bin (CalRecycle, 2019). The Rechargeable Battery Recycling Act (AB 1125) prohibits many retailers from selling rechargeable batteries in California unless they have a system in place for collecting used rechargeable batteries from consumers. This law provides a convenient, cost-free opportunity for consumers to return, recycle, and ensure the safe and environmentally sound management of used rechargeable batteries (Department of Toxic Substances Control, 2007).

According to the Official California Code of Regulations (CCR), Title 22, Division 4.5 chapters 10 through 12, 16, and 23, certain permitted facilities can accept hazardous waste batteries, universal wastes, or spent lead-acid batteries (Department of Toxic Substances Control, 2007). Only those facilities that have a DTSC permit or other type of authorization to treat, store, or dispose of hazardous wastes may accept hazardous waste batteries. According to the California Code, Public Resources Code (PRC) § 15013, the rechargeable battery must contain labels in a conspicuous manner that is visible to consumers and has proper recycling or disposal information on it. It is important to note that PRC § 15013 started in effect in 1995 before lithium-ion reusable batteries were on the market. Thus, the language only pertains to Nickel-Cadmium batteries.

Issues to Explore

In the United States and consequently California, there are currently no major standards for disposing or recycling lithium-ion batteries beyond categorizing them as a hazardous waste. The laws regarding rechargeable batteries are outdated in terms of technology. The AB 1125, which is more recent (effective since July 1, 2006), does address the way to properly dispose of batteries by providing a place for consumers to recycle their rechargeable batteries. Even with AB 1125, recycle battery collection is still low. The Department of Resources Recycling and Recovery (CalRecycle), submitted a report entitled, Household Universal Waste Generation in California, in August 2002; the report stated that there were 507,259,000 batteries sold in California in the year 2001, but only 0.55 percent of these batteries were correctly recycled. In 2017, DTSC surveyed battery handling and recycling facilities in California; they found that Californians only recycled 500,000 pounds of lithium-ion batteries. Figure 1.11 includes recycling data from 2007 to 2017.

Figure 1.11: Pounds of Batteries Recycled in CA from 2007-2017 Source: DTSC



If Lithium-based batteries are not properly recycled, they end up in the landfill. The landfill is very dangerous because it can cause massive fires due to the higher concentration of methane in the landfill.

Conclusion

In this chapter, I explained the lithium element, the devices containing lithium, the lithium battery boom, the cause of fires, the frequency and examples of these fires, the cost of these fires, and laws on battery recycling. To explore possible public policy solutions of lithium-ion battery fires and choose a policy alternative, in the following chapters, I will review academic articles on the subject and interview stakeholders. In chapter two, I will review the academic articles on lithium-ion battery fires. Furthermore, I will also address any gap in academic studies on this topic. In chapter three, I will explain my qualitative and quantitative CAM method and interview method and questions. The alternatives and questions I develop will be a result of my better understanding of the literature on this topic. In chapter four, I will include the results from those methods, and in chapter five, I will conclude with my final analysis and policy suggestion(s).

Chapter Two

LITERATURE REVIEW

The fires caused by lithium-ion batteries are not a recent phenomenon, but there is a gap in research needed to address this issue from a policy perspective; there is almost no academic research done on this topic. The lack of academic research means there are no "best practices" I could rely on or similar research I could use for background information on this topic. However, there are many academic studies relating to lithium-ion batteries. In this chapter, I will discuss the three themes I found relating to the recycling of lithium-ion batteries. The three themes are (a) battery extended producer responsibility (b) recycling processes of lithium-ion batteries (c) the technology of lithium-ion batteries. Although these are not California specific studies, I think these three themes are beneficial to understand moving forward. This literature review will allow me to build a better foundational knowledge to understand the recycling of lithium-ion batteries. The literature review will help shape the method I used to answer my thesis question by tailoring the questions that I will ask during my interviews with stakeholders.

Battery Extended Producer Responsibility

The cost of a product refers to the amount of money it takes to create the product. The cost may include materials, labor, employee expense, and more. These costs reflect on the market pricing of the product to ensure economic feasibility. In the case of batteries, the market price does not include the cost of proper end-of-life disposal. The current burden of society (or local government) is paying for the end-of-life disposal of batteries. When the market does not reflect the cost of diverting batteries from landfills and the cost of proper disposal, economists define this problem as a negative externality. According to economists, externalities are any benefit or cost placed on a third party without compensation. A negative externality is a signal to policymakers that the market is not including the true cost of batteries. Thus, addressing this inefficiency by policymakers is a priority. Extended producer responsibility (EPR), is one contemporary way that market economists propose addressing these negative externalities. EPR is a policy strategy that places a shared responsibility for end-of-life product management on the producers, and all entities involved in the product chain. EPR places primary responsibility on the producer, or brand owner, who makes design and marketing decisions. From the perspective of economics, EPR legislation ensures that a market that reflects the environmental impacts of a product by incorporating the costs of treatment and recycle/disposal into the total cost of a product (Calrecycle, 2019). Furthermore, EPR is an important vehicle for green innovation allocating for a smaller environmental footprint. The EPR is a popular strategy in the European Union (EU), Canada, the United States, for addressing the challenges of waste management and recovery.

Stakeholders

The public and private stakeholders in EPR include producers, retailers, regulatory authorities, municipalities, consumers, and recyclers. The following section covers the roles and responsibilities briefly by the stakeholder under an EPR regulatory regime.

Producers are the entities charged with the primary, if not sole, responsibility for financing the collection, transportation, and recycling of discarded products. Individual companies may fulfill these tasks by participation in a producer responsibility organization like stewardship organizations. The regulatory mechanism allows producers to take either individual responsibility or collective responsibility.

Retailers may serve as collection entities for discarded products in the EPR program. Depending on the EPR program, retailers may join voluntary or by regulatory requirements. For example, for the European Union's WEEE Directive or Japan's home appliances, it is required for a retailer to participate. Retailers may also be required to provide information to customers about the available collection opportunities for certain products (Hickle, 2014).

The regulatory authority, at the national or sub-national level, is charged with providing overall oversight of the program, including registration of participating producers, review and approval of a program plan, ensure compliance, and, if necessary, enforcement actions (Hickle, 2014). For example, the Connecticut Department of Environmental Protection approves the eligibility of recyclers.

Municipalities have traditionally organized, managed, and often directly provided recycling services. There are some conflicting opinions on whether the municipalities retain any physical or some degree of financial responsibility for products. The municipal role depends on the jurisdiction and the product. In Spain, the collection of Waste Electrical and Electronic Equipment (WEEE) in cities with 5000 or higher residents is the responsibility of the local authorities (Hickle, 2014). In France, implementing the EU Directive on Packaging and Packaging Waste, the designated authorities are the providers of collection services for waste packaging. In Quebec, the producers compensate the municipalities for their collection (Hickle, 2014). The State of Maine assigns municipalities with the responsibility to provide for waste collection and transport material to consolidation points (Hickle, 2014). In other circumstances, municipalities may choose to participate voluntarily as well as provide information to residents regarding available collection opportunities. The State of Washington specifies that municipalities provide that education.

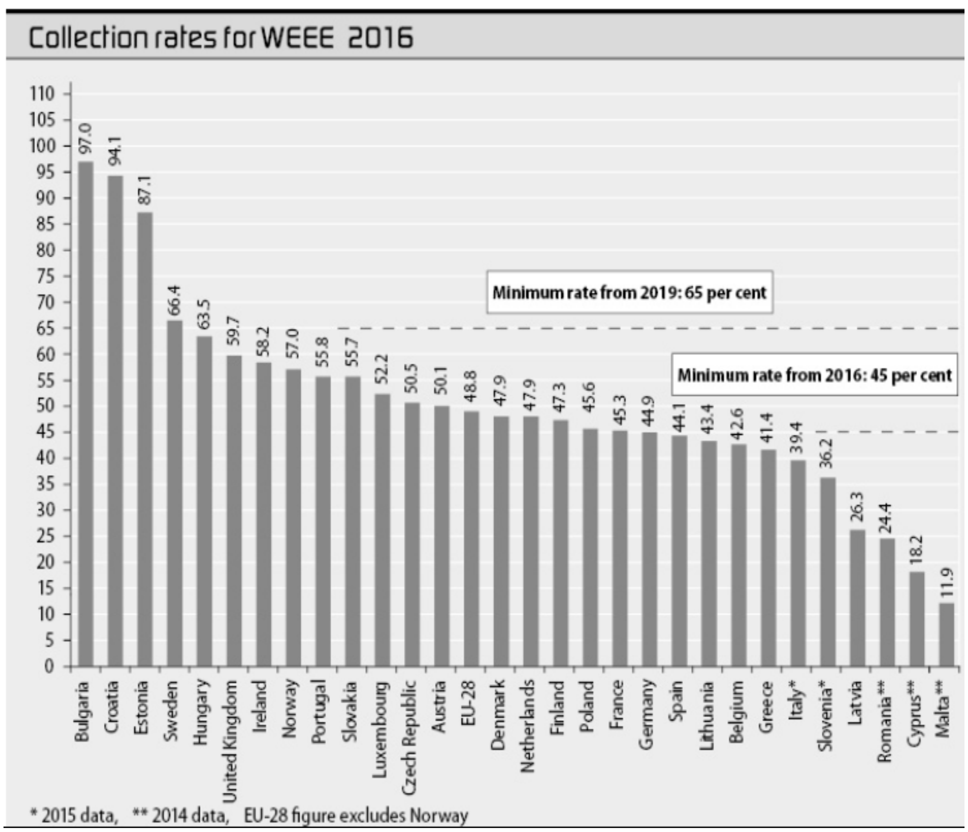
Although consumers typically do not have specific legal requirements, they are still crucial to the effectiveness of the program. If the legislature bans certain product disposal from the landfill or has a specific disposal requirement, consumers are responsible for disposing of it properly. In some instances, consumers may pay an extra fee for recycling a product either at the time of purchase or during disposal. In Japan, consumers pay a fee for specified kinds of home appliances during disposal (Hickle, 2014).

In terms of electronic waste (E-Waste), recyclers are responsible for properly de-manufacturing, recycling, and refurbishing electronic devices in an environmentally responsible manner. Depending on the jurisdiction, recyclers usually have certain laws about properly dismantling and disposing of hazardous materials in E-Waste. However, regarding EPR, they usually are not involved in the legal requirements.

Benefits of E-Waste EPR

From an international level, the implementation of EPR has been a success; it is essential for their environments and their economic wellbeing. An implemented EPR is often for electronic waste, and in doing so it increases the productivity and usage of recyclable materials. On January 27, 2003, the European Union (EU) signed the (WEEE) Directive, which requires members of the EU to hold electronics producers responsible for the collection, treatment, recovery, and environmental disposal of e-waste (Fehm, 2011). In 2016, the EU WEEE Directive had overwhelming success as many of the EU countries fulfilled the collection requirement. As shown in figure 2.1 below, 17 member states (and Norway) achieved the minimum collection rate of 45 percent for 2016 (EUWID, 2018). Some countries like Bulgaria, Croatia, Estonia, and Sweden, even passed the minimum rate for 2019 (which is 65 percent) in 2016 (EUWID, 2018). Bulgaria had the highest collection rates at 97 percent. Sweden collected 66.4 percent of WEEE, which is at 16.5 kg per inhabitant (Fehm, 2011). The United Kingdom averted 59.7 percent of its e-waste from landfills because of the program (EUWID, 2018). Belgium has a state-of-the-art recycling facility. Its advanced technology allows them to recycle ninety-five percent of the items into new items, preventing the need to expend resources to mine for new materials (Fehm, 2011). South Korea recycled six million tons of waste and has a financial benefit of over $1.6 billion. At the same time, mandatory EPR laws in South Korea have created new jobs and income (Fehm, 2011).

Figure 2.1: Collection Rate for EU Waste Electrical and Electronic Equipment in 2016 Source: EUWID 2018



<u>Criticism of EPR</u>

Electronic producers are critical of EPR for a few reasons. The main reason is that EPR puts extraordinary pressure on the producer to manage its product at end-of-life is because of the cost. EPR requirements forces producers who cannot afford to pay for end-of-life treatment out of the market, thus decreasing overall competition is a genuine concern (Hickle, 2014). Less competition is unfortunate for the consumers because they will have fewer choices among producers, and most of the end-of-life cost will likely be passed down to them through increased prices (Hickle, 2014). Some producers believe consumers should bear some responsibility for pollution because they purchase and use the product.

On the other hand, Turner and Nugent (2016) criticize EPR for not requesting enough from producers. EPR has been successful in shifting the cost of product collection and recycling to producers and third-party stewardship organization from municipalities. However, Turner and Nugent (2016) state that EPR has not always changed product design to minimize environmental impact. They argue that EPR policy should require to consider the environmental consequences of the end of life management regarding the collection and recycling of products.

Below are some historical backgrounds on the use of EPR in the European Union, Canada, and the United States. It is important to note that although EPR is becoming more popular throughout the other parts of the world, battery EPR is still new to most of the countries. I chose to look at these three countries because they already had an established battery EPR programs.

Battery EPR in the U.S.

In the United States, from 1991 to 2011, there were more than 70 EPR laws enacted at the state level in the United States covering products such as paint, thermostats, mattresses, and batteries (Turner & Nugent, 2016). Since the 1980s, removing batteries from the waste stream has been a concern for Europe and North America because batteries were a significant source of heavy metals in the waste stream (Turner & Nugent, 2016). The 1991 European Battery Directive and the 1996 U.S. Mercury-Containing and Rechargeable Battery Management Act both established uniform labeling requirements, encouraged collection and recycling of batteries containing heavy metals like lead and cadmium (U.S. EPA, 1996). In the mid-1990s, when industry removed mercury from most batteries, policies shifted from toxic reduction to focus on recycling. Since 1990, California classified single-use batteries as hazardous waste because of its corrosive nature, which can lead to leaching in landfills. In 2006, California designated batteries under hazardous waste law as a form of universal waste (CalRecycle, 2018). As a result, consumers could not put batteries into household trash; this led to the state creating an EPR program for single-use batteries.

European Union

In the European Union (EU), the 1991 Battery Directive policy focused on reducing toxins while the 2006 Battery Directive established EPR requirements for all batteries. The EU Battery Directive defines recycling batteries as the "processing of waste batteries and accumulators for the generation of products that can be directly reused in battery production or other applications or processes" (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012 p. 2). The definition, however, excludes the possibilities of disposal or energy recovery. Even though the directive does not focus on energy recovery, they included strict guidelines to focus on recycling and resource recovery. There was a requirement for recovering at least 50% of materials by average weight from the recycled batteries (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012). Unfortunately, the EU fell short in meeting its target goals, only collecting 25% of used batteries by 2012 and 45% by 2016 (Turner & Nugent, 2016).

The policy in the EU focused mainly on collection rates and using the best available techniques (BATs) to treat used batteries. BAT encourages increasing recycling and recovery rates, reducing waste and energy emissions, decreasing the use of raw materials and hazardous substances, and evaluating the net environmental impact (Turner & Nugent, 2016). Even though BAT encourages environmental and energy-efficient recycling technology due to the lack of guidelines (thus enforcement), BAT remains ineffective in practice.

Canada: British Columbia and Ontario

Compared to the EU, Canadian's EPR policy took a different approach by using product stewardship and waste management framework policies. This allows for more flexibility that applies to a range of consumer products, instead of product-specific legislation. Each province (British Columbia, Ontario, Manitoba, and Quebec) has applied battery policies differently.

In 2010, British Columbia accepted a product stewardship plan from Call2Recycle, a private, nonprofit stewardship organization who represented major battery producers (Turner & Nugent, 2016). Call2Recycle specializes in managing EOL cell phones and batteries; thus, under the product stewardship plan, they took responsibility for developing a collection system, public outreach, handling transport and recycling, and meeting reporting standards. Call2Recycle also selected certified recyclers based on a competitive bidding process (Turner & Nugent, 2016).

Call2Recycle had ambitious recycling targets; for single-use batteries, they wanted to increase the recycling rate from 12% in 2010 to 40% in 2014 (Call2Recycle, 2010). Furthermore, the program wanted to have an efficient resource recovery rate of 50% for single-use alkaline batteries. However, in 2013, Call2Recycle collected only 16 %, well below their target of 32% for that year (Turner & Nugent, 2016).

Ontario's Waste Diversion Act of 2002 is Ontario's battery recycling program. Ontario has a similar private stewardship organization as British Columbia called Stewardship Ontario (Turner & Nugent, 2016). They have similar responsibilities as Call2Recycle, to oversee the planning, implementation, and operation of stewardship programs for municipal hazardous and special wastes targeted by the provincial government, including batteries. For single-use batteries, Stewardship Ontario also established ambitious target collection rates from 20% in 2011 to 45% in 2016 (Turner & Nugent, 2016). Even more challenging, their target recycling efficiency standard rate was 80%. In 2013, like Call2Recycle, Stewardship Ontario also fell short of their collection target, hitting only 17%, when their target was 30% for that year (Turner & Nugent, 2016).

The implementation of these EPR programs raises important questions about the performance, reporting, and accountability of these programs. Both product stewardship plan results were far below their stated targets but did not receive a penalty for it., it is unclear if the enforcing of penalties would ever happen for continued failure in the future under the current framework. Turner and Nugent (2016) argue that without better reporting requirements and more carefully defined metrics, it is unclear to the net environmental benefits of these programs.

United States

The signing of The Battery Act into law on May 13, 1996, to phase out the use of mercury in batteries. The law also required for efficient and cost-effective collection and recycling or proper disposal of regulated batteries (Espinosa, Bernardes, & Tenório, 2004). Over time, as the Canadian provinces, California, and other states began to explore EPR legislation for single-use batteries in the 2000s, U.S. industry stakeholders changed their position. The U.S. adopted EPR policy on a state-by-state basis; California, Connecticut, Minnesota, and Vermont have considered EPR legislation that applies to single-use batteries (Turner & Nugent, 2016).

Vermont enacted the first EPR bill in May 2014 with an industry-proposed stewardship plan, but it did not include any statutory performance-based requirements regarding collection rates or recycling efficiency (Turner & Nugent, 2016). Soon after, four leading battery interest groups (the Corporation for Battery Recycling (CBR), the leading battery manufacturers from the National Electrical Manufacturers Association (NEMA), The Rechargeable Battery Association (PRBA) and Call2Recycle) all came together to propose a model all battery EPR legislation, known as the Model Consumer Battery Stewardship Act, in hopes of harmonizing policies across states (Turner & Nugent, 2016).

The model bill includes detailed requirements regarding stewardship plans, financing, and enforcement. The bill states producers must participate in a battery stewardship plan if they sell batteries in the state; stewardship plans must detail the collection points, educational efforts, recycling processes, and financial model; and stewardship organizations must report annually on plan performance (Turner & Nugent, 2016). The model bill also allows a producer or stewardship organization to bring a civil action against a producer who has failed to participate in a stewardship plan. Unlike the EU and Canadian bills, the bill does include novel reimbursement incentives and enforcement provisions (Turner & Nugent, 2016).

Although the bill does discourage free riders, it misses some essential elements. The bill's primary focus is on battery collection but pays little attention to recycling performance or environmental benefits (Turner & Nugent, 2016). The bill does not even necessarily require battery recycling; instead, it requires producers to recycle covered batteries in an economically and technically feasible way (Turner & Nugent, 2016). The term "recycling" is defined based upon existing state laws and includes no specific targets for recycling efficiency or provisions for ensuring recycling efficiencies are reported consistently (Turner & Nugent, 2016). Furthermore, the model bill intends to ensure a consistent approach to battery management across the U.S. states, but it cannot happen without a standard methodology to assess recycling efficiency and other performance metrics. Without more explicit standards for recycling efficiency and reporting, stewardship organizations have little incentive to focus on net environmental benefits. Although the model bill is positioned well to ensure producer responsibility for the collection of single-use batteries, it is poorly arranged to ensure a harmonious approach to how waste batteries are recycled, how those activities are reported and lack the assessment of the environmental consequences of such activities (Turner & Nugent, 2016).

Takeaway

Each of the EPR programs has its strengths; the EU has progressive standards for recycling efficiency, collection rates, and best-available technology. Ontario does not consider down cycling as a form of recycling. The U.S. model bill has a collection of incentives and private action enforcement measures. Nevertheless, each EPR has its challenges; the EU and Ontario lack enforcement and accountability measures. British Columbia's recycling regulation and the U.S. model bill do not directly define recycling at all. All these programs need to ensure the quality of recycling and address the net environmental benefit. For example, curbside recycling can have high GHG emissions.

Even the collection rates focus only on how many batteries are collected, not how they are collected; there is no agreement on a calculation method for recycling efficiencies regarding battery recycling processes (Turner & Nugent, 2016). Depending on the method, it can cause environmental burdens. Transporting batteries from collection points to recycling facilities can also have environmental consequences. Call2Recycle ships batteries approximately 4,000 kilometers from British Columbia to Pennsylvania for processing, although long-distance transport is often necessary, given that there are only few battery recyclers, this process still adds 3MJ and 0.2 kg CO2 per kilogram batteries processed to the environmental burden (Turner & Nugent, 2016).

To make EPR policies more effective, the literature suggest that two requirements be included: (1) policies should adopt reporting requirements that address the net environmental benefits and (2) set recycling standards that encourage the recovery of high-grade secondary materials, which can be suitable for reuse in new batteries or other products (Turner & Nugent, 2016). Both changes will yield net environmental benefits. There should also be audits of the stewardship plans, requiring that the scope of such audits include the environmental consequences of the plan (Turner & Nugent, 2016). Such reporting requirements will provide incentives for product stewardship organizations and recyclers to ensure that programs yield a net environmental benefit, rather than just achieving collection rates or recycling efficiencies. With these changes in existing and proposed EPR policy, product stewardship programs that include single-use batteries in North America will result in a lesser environmental impact on energy demands, resource damage, and global warming potential.

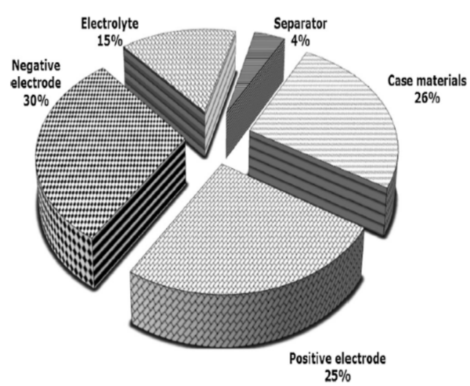
Recycling Processes of Lithium-ion Batteries

Introduction to Lithium-ion recycling

In the early 1990s, lithium-ion batteries (LiBs) were becoming popular as a new promising energy source for portable electronic devices. As a result, LiBs started replacing NiCd batteries as well as NiMH batteries in mobile phones. LiBs have many advantages compared to other rechargeable battery systems because of their high operating voltage, high specific energy, and long lifetime (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012).

Ordinarily, a LiB contains a positive and negative electrode, an electrolyte, a separator, and a stainless-steel shell. Figure 2.2 shows the percentage of each component. The electrolyte is commonly Lithium hexafluorophosphate -LiPF6, salt dissolved in organic carbonates such as ethylene carbonate (EC) with dimethyl carbonate - DMC, the separator in most cases micro porous polypropylene - PE, and a stainless-steel shell (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). The general design uses a positive electrode made of graphite coated on copper foil while contrastingly, the negative electrode consists of a lithium mixed oxide (LiCo O2, LiMn 2O2, and LiNi O2) coating aluminum foil (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). The graphite and lithium mixed oxide powder attaches to a sustaining substrate via a polymer binder, frequently polyvinylidene fluoride (PVDF), butadiene-styrene copolymer, or modified cellulose (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

Figure 2.2: LiBs Major Components Source: Al-Thyabat, Nakamura, Shibata, & Iizuka (2013)



The primary metals in LiBs scrap are cobalt, aluminum, nickel, lithium, copper, manganese, and iron/steel (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012). The most valuable metal inLiB is cobalt, which is in the battery electrode material. Thus, cobalt recovery has a strong influence on the economic efficiency of a battery recycling process. Ideally, a closed-loop recycling process should allow for the returning of recycling products to the production of new batteries. The challenge is how to recover all the valuable metals without sacrificing the economics of the recycling process (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

Generally, the definition of recycling efficiency is the weight ratio of acceptable recycling products and considered battery scrap mass (Fehm, 2011). The recycling process's efficiency is calculated on very conservative assumptions regarding estimated metal yields for further processed metal containing material fractions.

Recycling potential

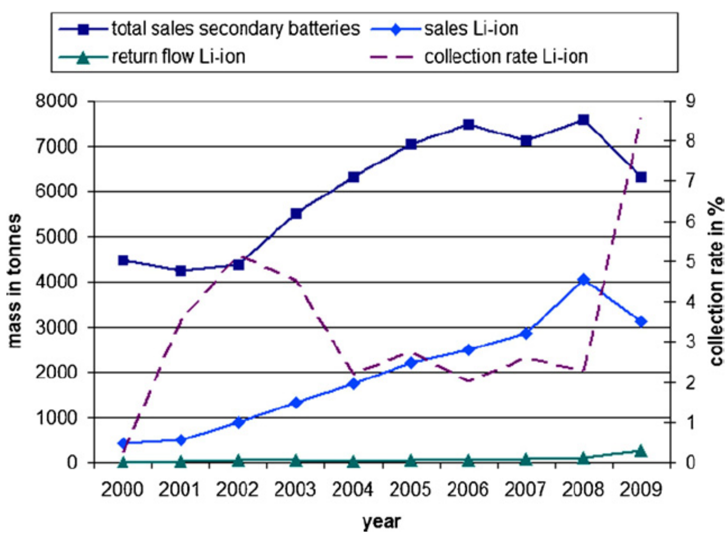
Compared to the rest of the world, in 2006, the United States had the highest usage of Li-ion batteries at 28.4 percent. Europe came a close second at 27.2 percent. However, the U.S. only produced 0.4 percent (Europe 2 percent) of Li-ion batteries (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012). Japan is the highest Li-ion battery cell producer at 40 percent; 50 percent of LIB came from China and South Korea combined. Despite the high production and usage of LIBs, the recycling of LiBs is still very low (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012). The collection rate in 2007 was only about 3 percent of the EU. Table 2.1 below shows sales of Li-ion batteries in the EU from the year 2002-2007 and the percentage of the collection (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012).

Table 2.1: EU sales figures return flow and collection rate of LiBs from 2002-2007
Source: Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz (2012).

	2002	2003	2004	2005	2006	2007
Sales in tonnes	3771	4977	6712	8210	9138	13,181
Return in tonnes	17	54	170	175	418	354
Collection in %	0.5	1.1	2.5	2.1	4.6	2.7

In Germany, Li-ion batteries had a market share of more than 50 percent for the first time in 2008, but the collection rate of approximately only 9 percent (Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz, 2012). Table 2.2 below shows the sales of Li-ion batteries in Germany and the collection rate from 2000-2009.

Table 2.2: Germany sales return flow and collection rate of LiBs from 2000-2009
Source: Georgi-Maschler, Friedrich, Weyhe, Heegn, & Rutz (2012).



In California, CalRecycle states in its Household Universal Waste report that there were 507,259,000 batteries sold in California in the year 2001 (Call2Recycle, 2010). According to their report, Californians only recycled 0.55% of those batteries. Department of Toxic Substances Control (DTSC) voluntarily surveys the major battery recyclers in California. According to DTSC's report in 2017, approximate 500,000 pounds of lithium-ion batteries (LiBs), the collection of rechargeable batteries for recycling in California (DTSC, 2019). More detail on this shown previously in Figure 1.11 from chapter one. These figures show that many Li-ion batteries are not recycled, which could be due to three reasons. One, consumers are not correctly recycling the batteries and may dispose of them with regular household garbage, two consumers have unused LiBs in their homes, or three, the LiBs are still in use. These batteries last many years, most likely the batteries recently bought are probably still in-use. The recyclability of LiBs is very high because there are potentially many LiB available for recycling. Also, the recent increase in mineral price makes these batteries a cheaper source of valuable metals (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

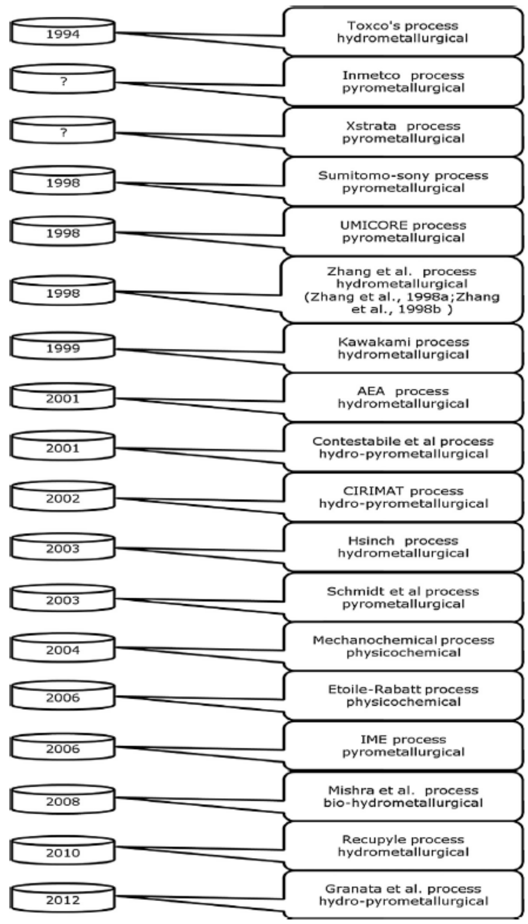
Current Recycling Processes

There are two broad categories for LiBs recycling process: physical-based technologies and chemical-based technologies. The main subcategories of physical separation technologies are gravity, magnetic, and electrostatic based separations. Chemical-based technologies include leaching, bioleaching, solvent extraction, precipitation, and electrolysis-based separations (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

Hydrometallurgical processes are one of the main chemical-based technologies. It requires dissolving metals from spent batteries scraps and then selectively separating them from the leach liquor (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). Toxco's process was one of the first hydrometallurgical processes developed in 1994. It includes putting the used batteries in liquid nitrogen to deactivate them, then, the batteries were crushed and placed in a high pH solution using lithium hydroxide (LiOH) (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). During this process, lithium salts (LiCl, Li2CO3, and LiSO 3) were precipitated, filtered, and then washed with mild sulfuric acid (H2SO4). Lastly, after putting in CO2 in the solution, lithium carbonate (Li2CO3) was formed (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

In 1998, Zhaolei Zhang developed a hydrometallurgical technology to recover cobalt and lithium from used LiBs (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). After manual shredding, the separation of the anode materials was possible. Then, to leach the anode materials, hot hydrochloric acid assisted in extracting the cobalt from a solution (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). The development of The Kawakami hydrometallurgical processes in 1999 for lithium metallic containing batteries was another turning point for battery recycling. The Hsinch process used membrane hydrolysis in LiBs recycling. In 2008, Mishra developed a bio-hydrometallurgical process to recycle spent LiBs. They used Acidithiobacillus Ferrooxidans (ATCC19859) bacteria, to leach cathode waste powder (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). In 2003, Schmidt developed a process to recycle electrodal materials (positive and negative electrode, electrolyte, and the separator) from spent LiBs to reuse them for manufacturing new batteries (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). In 2012, Granata developed a hydro-pyrometallurgical process, this process crushed the batteries first then separated ferrous, nonferrous, and nonmetals, then leached by a mixture of sulfuric and hydrochloric acid (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). Afterward, precipitation process removed iron and aluminum while solvent extraction separated cobalt and nickel. Table 2.3 below shows the timeline of these developments.

Table 2.3: Timeline of the development of LiB recycling processes. Source: Al-Thyabat, Nakamura, Shibata, & Iizuka (2013)



Drawbacks

These processes help recycle LiBs but are not without their drawbacks. The main concerns about the current recycling technology are cost and safety. At least one-third of the production costs for portable LiBs are related to the materials because they contain a high amount of valuable metals, which are present in their metallic forms as well as in the form of inorganic metallic compounds (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). Due to the nature of Li-ion batteries, during the recycling processes, the batteries may explode or catch fire due to their high-energy storage and rapid oxidation of lithium metallic substances, deposits formed due to battery overcharging. Environmental safety is also a concern. The hydrometallurgy processes use sulfuric acid to extract materials. Although sulfuric acid is more environmental-friendly compared to hydrochloric acid and nitric acid, the use of acid has negative environmental impacts (Fehm, 2011). Another issue is that these processes may not work in actual recycling facilities. Developing these processes on a laboratory scale where manual sorting and dismantling took place before the recycling process gave little in the way of its long-term effects, but theoretically leads to fewer incidents in the future. In reality, battery streams may contain mixtures of batteries, including primary lithium batteries that contain metallic lithium and manganese. Processing these differently is necessary, but designing a recycling process for each type of cathode active material is not practical in terms of a commercial point of view (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). Furthermore, there may be impurities in the recycling facility or batteries that can make hydro-metallurgical and pyrometallurgical processes inefficient (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). The contaminants can make the final product not desirable, which is not economically viable.

Another reason the processes can be economically questionable is that some recycling process (like leaching) is inefficient because it cannot recover all the valuable elements. For example, lithium cobalt oxide does not leach easily due to the strong bond between oxygen and cobalt, and thus the Inmetco and Kayser–Umicore recycling processes do not capture the lithium (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013). A significant disadvantage of all pyrometallurgical recycling processes is the fact that the recovery of lithium is not possible. Most of the losses occurred in pyrometallurgical process where plastics, electrolyte, and lithium were evaporated (Al-Thyabat, Nakamura, Shibata, & Iizuka, 2013).

Due to the loss of lithium, the pyrometallurgical process mostly will be used less in the future LiB recycling because of the loss of lithium (Fehm, 2011). It is economical to recover cobalt and nickel because of their market values. However, due to the demand for electric vehicles, a 90% lithium recovering rate is more desirable soon (Fehm, 2011). Furthermore, during the manufacturing of LIBs, the production of lithium and its compounds contribute many carbon footprints (Fehm, 2011). Therefore, it is essential to recover as much of the used lithium as possible. Other materials that should be a focus in the recovery process are iron and manganese.

It is economically and environmentally beneficial to recycle LiB. There is an increasing demand for minerals and metals found in LIB in the market. It is cheaper to recycle these materials than to obtain virgin materials. In addition, recycling these materials has less of a carbon footprint. If these batteries end up in the landfill mixed with other municipal waste, they may pollute the soil, underground water; the chemicals may leach into the soil, and if incinerated, contaminate the air by releasing toxic gases (Al-Thyabat, Nakamura, Shibata, & Iizuka 2013. If one of those batteries catches fire for any reason (crushed, punctured, short circuit), they can enable other batteries near them to also catch fire. Fires in landfills are especially dangerous because of the abundant presence of methane gas, which is a highly flammable gas greenhouse gas. Hence, the safe disposal of these batteries is an environmental necessity. Moreover, the recent surge in mineral prices turned these types of secondary batteries into a cheaper source of valuable metals.

The Technology of Lithium-ion Batteries

The following section discusses the current technology advancement for lithium-ion batteries. I reviewed what I found in the literature review regarding the thermal runaway process and mitigation methods. I also discussed a new in-development lithium-ion battery that may not catch on fire.

<u>Thermal Runaway Process</u>

A thermal runaway is when a lithium-ion battery's temperature rises rapidly within milliseconds, and a release of the energy stored in the battery is sudden

(GmbH, 2018). At temperatures exceeding 400 degrees Celsius, the lithium becomes gaseous and can immolate. Unfortunately, while batteries can become critical at 100 degrees Celsius, the batteries can become unstable in temperatures as low as 60 degrees Celsius (GmbH, 2018).

A battery's voltage, temperature, and pressure affect the thermal runaway process. Due to an internal short circuit, there is a separation of the battery's electrodes, which leads the battery voltage to drop sharply (Kong, Li, Jiang, & Pecht, 2018). The sharp voltage drops occurred around the separator melting point due to an uncontrolled temperature increase. The battery's open-circuit voltage and the type of battery cathode material influence the increase in temperature. The battery temperature increases because the heat generation rate overwhelms the heat dissipation rate. Thermal runaway can happen when the battery temperature reaches 104-144 degrees Celsius (Kong, Li, Jiang, & Pecht, 2018). Furthermore, the initial spot for the thermal runaway can be as high as 800 degrees Celsius and spread throughout the battery (Kong, Li, Jiang, & Pecht, 2018). The high temperature is why often thermal runaway leads to the unequal temperature distribution. In one example, there was a 520 degrees Celsius difference in temperature between the battery case and the core. Lastly, the battery pressure is the reactions among active battery materials, organic electrolyte evaporation, and gas accumulation (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). Gas generation can happen during regular operation. However, the thermal runaway process creates flammable gases (Kong, Li, Jiang, & Pecht, 2018). During regular operation and/or aging batteries, gases like CO_2, CO, CH_4, and O_2 occur. During thermal runaway, the electrolyte can release flammable hydrocarbons like H_2, C_2H_6, and C_2H_4. Under all these conditions, the battery catches fires or explodes (Kong, Li, Jiang, & Pecht, 2018).

There are three measures to mitigate thermal runaway: preventive measures, fail-safe measures, and extinguishing measures. Each of these categories takes effect at various stages of the thermal runaway process. The first category is preventive measures, which is adding flame retardants for battery thermal stability. One way to improve the thermal stability of electrolyte is to add flame retardants to the electrolyte (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). For the flame retardant to be efficient, it must have a high melting point, but with a low viscosity so the battery's performance can also be efficient. Xu synthesized three flame retardants: tris-(2,2,2-trifluoroethyl) phosphate (TFP), bis(2,2,2-trifluoroethyl)-methylphosphate (BMP), and (2,2,2-trifluoroethyl) diethyl phosphate (TDP) (Kong, Li, Jiang, & Pecht, 2018). These three additives have great electrochemical properties while maintaining the electrolyte conductivity needed for battery operation. Out of these three, Xu found that TFP has the best overall battery performance compared to BMP and TDP (Kong, Li, Jiang, & Pecht, 2018).

As stated previously, there are five key parts to a LiB: anode, separator, cathode, current collectors, and electrolyte. Since the separator is sensitive to increasing temperature, one of the ways to incorporate a flame retardant is to add the flame retardant into the battery with the separator. The separator is a specially designed core-shell structure. The shell is made of poly-vinylidene fluoride-hexafluoropropylene (PVDF-HFP), and it can protect the core because it is insoluble in the electrolyte. The core is made of the flame retardant, triphenyl phosphate (TPP), which has a melting point around 160 degrees Celsius (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). Thus, during the early stage of combustion, when the battery temperature increases to the melting point of PVDF-HFP (160 degrees Celsius), the encapsulated TPP flame retardant is released into the electrolyte (Kong, Li, Jiang, & Pecht, 2018). Meanwhile, the PVDF-HFP will not influence the battery electrochemical reactions; thus, the flame retardant can deter fire without hindering the battery's performance.

The second category is a fail-safe measure, which stops or decreases the damage caused by thermal runaway. There are three types of fail-safe mechanisms, including safety vents, thermal fuses, and shutdown separators. When flammable gases accumulate inside the battery, safety vents can activate and release extra internal pressure, which can prevent an increase of internal temperature (Kong, Li, Jiang, & Pecht, 2018). A cell-venting mechanism is designed to release gases and heat in a controlled way rather than an explosion. The reduction in the internal pressure can reduce the risk of an internal short circuit, which can reduce the risk of a sharp voltage drop (Kong, Li, Jiang, & Pecht, 2018).

The cell vent design can differ based on the battery type. One design in the 18650 LiB line was made with vent "windows" in the positive feed to release internal pressure while another has a low ductility cap that fractures when a certain level of pressure is reached (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). Without these vent designs, the pressure in the batteries will continue to expand until they either ignite or explode. The International Electrotechnical Commission (IEC) has no specific requirement for vent design in the IEC document (Kong, Li, Jiang, & Pecht 2018).

The European Council for Automotive Research and Development (EUCAR) listed hazard levels ranging from zero to seven, with the more difficult situation at a higher level. The classification for LiBs fires is level four (venting), if there is no fire or flame, no rupture, or no explosion, and if weight loss is greater than or equal to the electrolyte weight.

The third category is on measures to take to extinguish LiB fires post thermal runaway. Per the National Fire Protection Association (NFPA), There are five different categories of fire; A, B, C, D, and K, see Table 2.4 below. The category that a LiB fire falls under can vary but is generally under classes A, B, or C (Kong, Li, Jiang, & Pecht, 2018). There are some cases where the primary power source of the fire is LiB, and then fire is directly involved with electrical devices or where the fire from LiB can spread and ignite nearby materials. Fire extinguishers for LiBs vary based on the agent they contain, such as carbon dioxide, water, foam, halons, dry chemicals, and dry powders (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). Carbon dioxide can be used to suppress the fire, but it cannot cool the battery down. Putting out a LiB fire refers to both extinguishing the flames and decreasing the battery's temperature simultaneously (Kong, Li, Jiang, & Pecht, 2018). If the flames are cooled but the battery temperature is not, once the battery exceeds a specific temperature, the battery will probably reignite. For example, in 2013, the Fire Protection Research Foundation conducted LiB fire testing on full-scale-model vehicles. In one of the tests, the battery reignited 22 hours after the open flame was extinguished (Gao, Zhang, Xiao, Gao, Wang, & Piao, 2019). In 2017, there was a LiB fire incident in California involving an electric vehicle. The potential electrical hazard for firefighters convinced them to use carbon dioxide fire extinguishers (Kong, Li, Jiang, & Pecht, 2018). Although the carbon dioxide extinguishers were successful, NFPA, claimed that water would have worked to cool down the car and prevent reignition (Kong, Li, Jiang, & Pecht, 2018).

Table 2.4: Classification of fires Source: Kong, Li, Jiang, & Pecht (2018)

Class	Description
A	Fires in ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics.
B	Fires in flammable liquids, combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases.
C	Fires that involve energized electrical equipment.
D	Fires in combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.
K	Fires in cooking appliances that involve combustible cooking media (vegetable or animal oils and fats).

Although not a deterrent, some researchers are proposing a change in the conductive components to fewer flammable ones, thus mitigating fires before they happen by not providing a scenario where it is a possibility or at least reducing it significantly. These new batteries are called - 4.0 V Aqueous Li-Ion Batteries. The proposed changes would be with the use of a saline (Water in Salt Electrolytes / WiSE or Water in Basalt Electrolytes / WiBE) system to counteract the volatility of the batteries while not losing the batteries capacity to hold a charge once the structure of the cell had been compromised (Yang, Chen, Qing, Fan, Sun, Von Cresce, Ding, Borodin, Vatamau, Schroeder, Eidson, Wang, Xu, 2017). Most WiSE/WiBE solutions have a lower conductivity rate than is permissible with lithium-based materials, the most commonly referenced being Li graphite (Yang, Chen, Qing, Fan, Sun, Von Cresce, Ding, Borodin, Vatamau, Schroeder, Eidson, Wang, Xu, 2017). However, by using a gel WiSE/WiBE and potentially solidifying it using polyvinyl alcohol (PVA) or polyethylene oxide (PEO) the gel can consolidate into a hydrogel with a level of viscosity capable of reducing the degeneration of the cells charge (Yang, Chen, Qing, Fan, Sun, Von Cresce, Ding, Borodin, Vatamau, Schroeder, Eidson, Wang, Xu, 2017). Additionally, the conductivity rate of the lithium material is not lost due to the phenomena of competitive water reduction with the addition of an inhomogeneous electrolyte as the basis for the WiSE/WiBE (Yang, Chen, Qing, Fan, Sun, Von Cresce, Ding, Borodin, Vatamau, Schroeder, Eidson, Wang, Xu, 2017). Thus, maintaining a current and stable temperature post puncture or rupture of the LiBs casing effectively reducing the capacity of a fire happening.

The series of 4.0 V class aqueous Li-ion batteries, has state-of-the-art energy densities but with significantly less safety issue. The cycling stability of 4.0 V class aqueous lithium-ion batteries needs further research for improvement, but this is a step towards closing the gap between aqueous and non-aqueous batteries. With further perfection of the interphase chemistry, aqueous LiBs could be the energy source of the future without the safety concerns.

Conclusion

In this chapter, I covered the academic literature done on the topic of recycling lithium-ion batteries. The purpose of the literature review is to give background information and point out any gap or inconsistency in the research. As mentioned before, there was no academic research addressing the policy issue of the fires caused by lithium-ion batteries. However, I discussed three themes I found in my research: (a) battery extended producer responsibility, (b) recycling processes of the lithium-ion batteries, and (c) the technology of lithium-ion batteries, which provides a foundation of knowledge for addressing this thesis question.

What I learned from the literature is that countries are addressing the negative externalities from battery disposal by implementing extended producer responsibility legislation. Although EPR puts responsibilities of end-of-life battery management on producers, consumers will pay for part of that expense through increased prices of products. Up to this point, EPR has had much success in the European countries in diverting electronic waste from landfills. According to Turner and Nugent (2016), to improve the EPR program, even more, the legislative language of the programs should include the green design of products to reduce environmental impact. Ideally, green design or environmentally friendly design means the product has less environmental impact/carbon footprint during the creation of the product. In addition, the product may have secondary or third re-usage availability after its intended use. Additionally, the product should be easily recyclable, and the valuable materials/minerals should be captured for reuse or resale. Capturing valuable metals from lithium-ion batteries is one of the main goals of the recycling process. Another important consideration should be whether the process causes environmental harm due to the use of heavy chemicals or through long transportation. The recycling processes need to be evaluated for an environmental and a net economic gain.

Lastly, EPR and proper recycling process conversations cannot happen until the make-up of the lithium-ion battery is understood. I believe the future design of lithium-ion batteries should address the thermal runaway process. Without the mitigation of the thermal runaway process, the batteries will always have a safety concern. Thus, there will always be a risk of fires during the usage of the batteries or the recycling processes. Therefore, the development of aqueous lithium-ion batteries like 4.0 V class aqueous Li-ion batteries that do not catch fire would be a promising development. I believe, for these things to happen, producers, regulatory authorities, and recyclers need to come to the table and have a conversation about their ideas and challenges. These are some policy options I will consider for my research alternatives.

Chapter Three

METHODOLOGY

Evaluating the desirability of various solutions to a public policy problem is a complex activity. Bardach's (2012) Eightfold Path for Policy Analysis offers one way to do this with clarity and sensible efficiency. In Bardach's Eightfold Path, the first step is to define the problem, and the second is to assemble evidence, which I have done in the first two chapters. Step three is constructing alternatives for policy analysis, and step four is selecting criteria (Bardach, 2012). Both steps three and four are represented here by a Criteria Alternatives Matrix (CAM) Analysis. I use interviews of key stakeholders to inform the development of the CAM used here. In this chapter, I will describe the CAM process, the interview process, the stakeholders I decided to interview, and the questions I will ask.

Bardach's step three recommends constructing two or three alternatives; by alternatives, he means "policy options" or a series of sensible potential policy solutions to solve the problem defined in step one (Bardach, 2012). The problem statement examined in my thesis is that the current method(s) of recycling Lithium batteries in the State of California is causing too many costly fires. Bardach encourages looking at *best practices* policy design efforts made by others, but, as mentioned in my literature review, lithium-ion battery fires is a new policy problem, and I have not been able to find best practices. Thus, I will rely on self-design alternatives.

I will analyze the projected outcomes of each alternative through a list of criteria. The criteria are measurement tools that policymakers use to evaluate the projected outcomes of each of the alternatives (Bardach, 2012). Using the criteria, I will consistently evaluate each projected outcome. However, not all criteria are valued the same, so each should be weighted differently according to its level of importance (Bardach, 2012). Comparing each criterion and assigning appropriate weight is a subjective task; it will be limited by my knowledge and my view of which criteria is more critical to the success of the policy outcome than others. In chapter four, I will explain my selection of each criterion and my justification for each weight.

The policy alternatives and criteria I use will mainly come from my literature review and interviews. Before I conducted interviews, there were a few steps I needed to complete. First, I completed and passed the Research Ethics and Compliance Training required by the Internal Review Board (IRB). Then, in the IRB's application process, I explained how I would contact my interviewees, conduct my interview process, and store and eventually destroy the raw data collected. I also outlined potential benefits/risks of the process of how I would mitigate or eliminate those risks, and how I would report results. Additionally, I submitted the interview questions that I plan to ask for review and approval by IRB before continuing. Once approved, I reached out to my interviewees to confirm their participation. The IRB process is a rigorous one, but in order to conduct proper interviews, it is a necessary step.

Due to the limited academic articles I found regarding lithium-ion battery fires, I am mainly relying on interviews in order to form policy alternatives and criteria. As mentioned in my literature review, lithium-ion battery fires affect many stakeholders, which is why I want to interview different experts in the field. To make the interview process comfortable for the interviewees, I decided to keep the interviewees' anonymous and only list their areas of employment.

Interviewees

I will be interviewing an individual in the upper management of Resource Recycling Systems (RRS). RRS is a consulting firm in the areas of organic management, waste recovery, and global corporate sustainability. RRS serves a wide range of clients, including public agencies, recovery infrastructure, manufactures/commercial businesses, trade groups, retail, universities, and healthcare (RRS, 2019). RRS has clients all over the nation, which is why I want to interview one of their staff to understand the national perspective on lithium-ion battery fires better. This interview will provide me with a better idea of how this issue is affecting the U.S. in general.

I will also interview an individual in the upper management of Fire Rover to understand the national perspectives on this issue better. Fire Rover is a company that offers portable fire suppression systems that are stationed at facilities and use thermal cameras to monitor 24/7 in order to detect and extinguish fires before they become uncontrollable (FireRover, LLC, 2015). Fire Rover provides service to different facilities that have a high risk of fire, such as recycling, chemical, and oil facilities (FireRover, LLC, 2015). The person I will interview has kept track of fires that have happened in facilities all over the U.S. within the past two years. This person has noted that lithium-ion batteries caused many of these fires. Therefore, an interview with the upper management of Fire Rover will provide information on this topic within a national perspective.

To balance the national perspective, I will be interviewing another individual in the upper management from RethinkWaste to ascertain the Local Government's perspective on this issue. RethinkWaste, also known as the South Bayside Waste Management Authority (SBWMA), is a joint powers authority of twelve public agencies in San Mateo County, California: Atherton, Belmont, Burlingame, East Palo Alto, Foster City, Hillsborough, Menlo Park, Redwood City, San Carlos, San Mateo, the County of San Mateo and the West Bay Sanitary District (RethinkWaste, 2019). RethinkWaste owns and manages the Shoreway Environmental Center, which receives all of the recyclables, organics, and garbage collected in its service areas (RethinkWaste, 2019). The primary goal of RethinkWaste is to provide cost-effective waste reduction, recycling, and solid waste programs to member agencies through franchised services and other recyclers to meet and sustain a minimum of 50% diversion of waste from landfill (RethinkWaste, 2019). From this interview, I hope to understand what the local government plans to do/or has done regarding lithium-ion battery fires.

Another desired interview is with an individual representing a battery manufacturer because they are an important stakeholder. The person I have in mind is in the upper management of the company Call2Recycle. Call2Recycle is a non-profit, battery stewardship organization, created by a group of battery manufacturers (Call2Recycle, 2019) in the U.S. and Canada. I hope that Call2Recycle will help me understand the manufacturer's perspective about what steps can be taken to address lithium-ion battery fires.

I also plan to complete another product stewardship interview and have chosen the California Product Stewardship Council (CPSC). CPSC consists of local governments, non-government organizations, businesses, and individuals supporting EPR policies and projects (CPSC, 2019). CPSC is a leader and an expert on Product Stewardship and EPR programs. An interview with their staff would hopefully lead me to understand their view on battery EPR program and their potential solution(s) for the lithium-ion battery fires.

Another significant stakeholder for this issue is battery recyclers. I have chosen to interview one of the largest electronics recyclers in the state, Electronic Recyclers International (ERI). ERI is a certified de-manufacturer, recycler, and refurbisher of electronic devices. ERI also has seven other facilities across the U.S. that recycle an estimated five percent of all e-waste recycled in the U.S. (ERI, 2018).

Although ERI cannot speak for all recyclers, by speaking with one of the biggest e-waste recyclers, I would have a better understanding of their experience and struggles with lithium-ion battery fires.

To understand California's State Government's perspective, I will interview policy advisors from the Department of Toxic Substances Control (DTSC) and the Department of Resources Recycling and Recovery (CalRecycle). DTSC's primary responsibility is to oversee the management of hazardous waste in California. Their mission is to protect Californians and the environment from harmful effects of toxic substances by restoring contaminated resources, enforcing hazardous waste laws, reducing hazardous waste generation, and encouraging the manufacture of chemically safer products (DTSC, 2019). All batteries fall under DTSC's purview because batteries are a hazardous waste in California. I plan to speak with DTSC and ask what steps they are taking at the policy level to address the lithium-ion battery fires.

The proper management of batteries is also an interest of CalRecycle. CalRecycle has introduced Assembly Bill 1509 (AB 1509): Lithium-ion Battery Fire Prevention Act; at the time of writing this chapter, it is currently in assembly. If passed, this bill would establish the Lithium-Ion Battery Recycling Program, which would require covered entity (manufacturers, retailers) to annually achieve specified collection and recycling rates of LiBs (California Legislature, 2019). This bill also requires a covered entity to establish a stewardship program and a take-back program

(California Legislature, 2019). Additionally, the bill would require a covered entity to pay the department an administrative fee (California Legislature, 2019). The idea is that AB 1509 would create a recycling program for both loose Li-ion batteries and those embedded in products to prevent them from being improperly disposed of in the waste stream. I want to speak with CalRecycle's staff to ask how this policy (or other policies the state is considering) would address the lithium-ion battery fires.

Interview Questions

Once the prospective participants have agreed to the interview, I will email them the questions in advance. I prefer to meet with these individuals for an in-person interview; however, if that is not possible, I will interview them over the phone. Below is the list of questions I would like to ask in the interview. It is broken up by questions that I will ask everyone and some additional questions that are relevant to the respective stakeholder.

Since Call2Recycle is representing manufacturers, I will ask if any lithium-ion battery design changes/improvements are being considered to mitigate/eliminate the fires. I would also like to know how effective their education/awareness campaign was. If it is practical, I might consider a policy alternative focusing on consumer awareness. Lastly, I will ask them about how likely it would be to combine the efforts of manufacturers and recyclers to create a better recyclable battery, which was a concern brought up by a recycler during the CalRecycle's Lithium-Ion Battery Workshop.

During the same workshop, Call2Recycle and local government stakeholders mentioned the success of the curbside program for battery collection. However, throughout my literature review research, I found several mixed opinions about the curbside program; thus, I want to learn more details about the program from the local government's perspective.

The additional questions I ask from the recycler's perspective focus on their cost associated with lithium-ion batteries and what they plan to do about it. As for the state government's perspective, I want to know what DTSC is doing for this issue and if any steps have been taken. I know CalRecycle has taken some steps to address the issue (by introducing AB 1509); nevertheless, I would like to know how they plan to implement it.

Interview Questions for Everyone

1. Please describe your organization and the work you do.
2. The policy problem I am investigating in my MPPA thesis is: The current method of recycling Lithium-ion batteries in the State of California causes too many costly fires.
    a. Do you agree that this is a relevant public policy problem in CA?
3. What do you think are some possible solution(s) to the fire threats caused by the recycling of lithium-ion batteries?
4. What criteria would you suggest in evaluating the desirability of alternative policy solutions to this problem?

   a. Rank the criterions from first to least important. Why this order?

5. What is the true cost of recycling lithium-ion batteries?
6. What is your view on a form of the policy solution of extended producer responsibility (EPR)?
   a. Would EPR lead to more green design (batteries made for easy recyclability/batteries that can have second use or repurposed for another use before recycled)?
7. What is your view on adding batteries to the covered electronic waste (CEW) recovery and recycling program?
8. What is your view on the efficacy of consumer informational or educational campaigns to influence this issue?
9. What are your thoughts on the Aqueous Li-Ion Batteries?
10. Is there anything else you would like for me to know?

<u>Manufactures- Call2Recycle</u>

From my research, I have come to understand that the thermal runaway process affects the battery temperature, voltage, and pressure. These three factors can lead to a fire or an explosion on the battery. To make batteries more resistant to fires, flame-retardants, or fail-safe measures such as separator shutdown and cell venting can be added.

1. Are you aware of any steps being taken to make lithium-ion batteries resistant to fires?

2. Are you aware of any steps being taken to make lithium-ion batteries easier to recycle?
3. What conversations do you believe need to happen to create any needed changes in how lithium batteries are manufactured?
4. What was the result of the education steps Call2Recycle took to raise consumer awareness?
5. How many of your collection sites completed the certification training regarding proper battery collection? Was there a noticeable improvement in safely at the collection sites after the safety training?
6. What changes do you think manufacturers could make to improve the recyclability of lithium-ion batteries post-consumer usage? How willing do you believe they would be to work with recyclers to identify improvements?

<u>Local Government- RethinkWaste</u>

1. What was the result of your curbside program? Are the batteries that are mixed in with other recyclables decreasing?
2. Do the benefits of using red bags to recycle batteries outweigh the costs?
3. Are there any steps being taken at the local government level to address this issue?

<u>Recycler - ERI</u>

1. Has your facility/facilities experienced fires?

a. If so, was it due to lithium-ion batteries?

b. What is the cost of these fires?

2. Do you think the cost of recycling LiB is similar for recyclers all across California?

    a. What can be done to bring the cost down?

    b. What are your thoughts about the future cost of recycling lithium-ion batteries?

3. Has your company taken any steps to address this issue? If so, what?

4. Has your company considered any fire suppression system or any special training? If so, what are the pros and cons?

State Government – DTSC

1. What steps is DTSC taking to address the fire threats from the lithium-ion battery?

State Government - CalRecycle

1. What are the pros of cons of adding batteries to the CEW program vs. EPR?

    a. How realistic is it to implement?

    b. How would it be managed?

    c. Would this increase in recycling rates of lithium-ion batteries?

2. How is AB 1509 supposed to address the battery fires?

Conclusion

In this chapter, I first provided an overview of the process of developing a policy alternative and a set of criteria to evaluate the outcome of those alternatives. Then I explained the interview process and listed the stakeholders I would like to interview, why they are relevant to the interview, and what I expect to learn from the interview. Lastly, I listed my interview questions. In the next chapter, I will cover the results of my interviews. Also, based on my interviews, I will specify my CAM matrix by listing my policy alternatives, criteria, and weight of each criterion. In the last chapter, chapter five, I will report my CAM analysis results and policy recommendations.

Chapter Four

ANALYSIS OF THE DATA

In the first three chapters of the thesis, I defined the problem, assembled the evidence, and described my methodology. In this chapter, I will address steps three through six from Bardach's (2012) eight-step method: construct the alternatives, select the criteria, project outcomes, and confront the trade-offs. I will utilize the results of my research and apply what I learned from the interviews to do so. The usual outcome of Bardach's methods is to suggest the one policy alternative, or a hybrid of multiple alternatives, that best addresses the political problem. As described in the previous chapter, after interviewing different stakeholders, I decided that one policy solution would not best address the issues of fires caused by Lithium-ion batteries. After discussing the results with my advisor, I decided that offering a hybrid-solution is more appropriate, and thus there is no need to complete a Criteria-Alternative-Matrix (CAM) analysis on all the alternatives. The hybrid-solution is a "three-pronged" solution: (1) consumer education, (2) governmental oversight program, and (3) a fire suppression system in facilities. I will discuss this in more detail in chapter five. In this chapter, I will explain whom I interviewed, what they said, and why this resulted in the choice just described. Nevertheless, the CAM analysis will still provide guidance because I will do a mini-CAM analysis for two governmental oversight program alternatives.

Interviewees

Due to scheduling conflict, limited time, or no response I was not able to interview anyone from: Resource Recycling Systems, California Product Stewardship Council and Department of Toxic Substances Control. However, I had the pleasure of interviewing six stakeholders. Interviewee #1 (IN1) is a distinguished individual who is focused on bringing innovative safety solutions to the market regarding the fire problems facing the waste and recycling industries. Interviewee #2 (IN2) is part of the upper management from Call2Recycle, whom I took to represent the perspective of some manufacturers. Interviewee #3 (IN3) is upper management from Electronic Recyclers International, who provided a perspective from Electronic-Waste Recyclers. Interviewee #4 (IN4) is part of the upper management of RethinkWaste, who represented a perspective from local government. Interviewee #5 (IN5) and #6 (IN5) are two upper staff members from CalRecycle, who are very knowledgeable in their field. I took their perspectives as the California state government perspective. It is essential to point out that the individuals I spoke with represent only their perspectives. Their opinions do not represent or speak for the rest of their industry/organization. I shall take their responses as a loose baseline of their industry/organization.

I found the interviews very helpful because I gained more in-depth knowledge about this policy issue. It also helped me understand each stakeholder's views and concerns regarding both present and future issues. Some of the interviewees suggested that I change the wording of my thesis questions to identify both the core issues and the proposed solutions more accurately to them. Thus, I am updating my thesis question from that initially proposed:

"The current method(s) of recycling Lithium batteries in the State of California is (are) causing too many costly fires."

To:

"In the State of California, the current management of Lithium batteries throughout the disposal process is causing too many costly fires."

In this new problem statement, the word "management" includes the collection and handling of lithium batteries (LiBs). The "disposal process" covers when the consumer no longer uses the LiBs to the proper (or improper) disposal of it, to the batteries' collection, transportation, and recycling process. Most interviewees discussed a lack of recycling methods for lithium batteries in California, one of the results of not having proper methods of recycling, ultimately leading to these fires.

Government Oversight Programs

The two governmental oversight policy alternatives I compared are Alternative 1- EPR program for Lithium-ion batteries, and Alternative 2- Adding Lithium-ion batteries to the Covered Electronic Waste (CEW) Recycling Program.

<u>Alternative 1- EPR Program for Lithium-ion Batteries</u>

Extended producer responsibility is a policy approach in which producers take responsibility for the management of the products when they are no longer useful for consumers. This end-of-life product responsibility may be fiscal, physical, or a combination of the two. EPR allows the incorporation of the costs of treatment and disposal into the total cost of a product. It places primary responsibility on the producer, or brand owner, who makes design and marketing decisions. It also creates a setting to include a mixture of economic, environmental, and social factors in the market that accurately reflect the environmental impacts of a product, and to which producers and consumers respond. Extended producer responsibility is a product-focused strategy that encourages environmentally friendly design and disposal of products through the transfer of this responsibility to product producers (Surak, 2018).

EPR and Batteries

An EPR battery take-back program(s) can be a crucial strategy to prevent environmental impacts, return valuable materials to the circular economy, reduce greenhouse gases, and create recycling jobs. An EPR program may be voluntary or regulatory. Call2Recycle is a voluntary EPR industry program to collect and recycle batteries. Twenty-five years ago, five battery companies founded Call2Recycle. The main concern at the time was the proper handling and disposing of nickel-cadmium batteries. There have been two notable issues with the current battery EPR program: *free-riders* and low collection. EPR program participation is voluntary, but this enables free-riders. Free-riders are a burden to participating manufacturers because manufacturers cover the recycling cost of all batteries. Furthermore, even though Call2Recycle collects about 160 million pounds of all types of batteries

(IN2), the U.S. only recycled 12% to 15% of rechargeable batteries (Product Stewardship Institute, 2010). The percentage of single-use batteries is even lower. According to the 2002 *Household Universal Waste Generation in California*, there were 507,259,000 batteries sold in California in 2001, and Californians only recycled 0.55% of these batteries (CalRecycle, 2019).

A robust EPR battery program would ideally require all battery producers to sustainably finance and run convenient recycling programs for all battery types. However, for this thesis, I will only look at LiBs. This way, EPR systems create a level playing field that shares responsibility fairly among all producers. A successful battery EPR program prioritizes consumer convenience by having a plethora of collection locations through retailers that accept both single-use and rechargeable batteries (Product Stewardship Institute, 2010). Another benefit of a robust EPR program is it relieves local and state governments from the costs of disparate local battery recycling efforts. Lastly, a successful battery EPR program would have high-performance goals for collection and recycling, state government oversight, and include significant consumer outreach and education initiatives.

CalRecycle EPR Requirement

Calrecycle has created an *EPR Legislation Checklist* (CalRecycle, 2017), which lists criteria for the government to consider for any future EPR program. If CalRecycle creates an EPR battery program, they should include at least these requirements:

Scope:

- Manufacturers/Producers (MFR/PR) may carry out their roles and responsibilities either individually or as members of a stewardship organization (SO).
- Covers new, historic, and orphan products.
- Covers all sales, including Internet sales.
- Requires statewide coverage, both urban and rural areas.
- Considers harmonizing with EPR legislation in other states to reduce the administrative and operational burden.

Measurement & Effectiveness:

- The SO or individual MFR/PR should set goals that are meaningful, clear, quantitative, and enforceable.
- The goals should be set in statute or provide a date by which state oversight agency must set goal(s). However, IN2 strongly cautions that the focus (goal) cannot be on the collection rate. The consumers and recyclers need to learn about the proper collection and handling of LiBs; otherwise, a higher collection rate will cause more fires.
- Require the SO or individual MFR/PR to demonstrate the program performance.

- The SO or individual MFR/PR should submit an annual report and budget for the state oversight agency to determine if the SO or individual MFR/PR are achieving their goals.

Financing:

- SO or individual MFR/PR should pay for the EPR program costs because they benefit from the products.
- SO or individual MFR/PR should internalize the program costs, like other costs of doing business.
- Authorize state oversight agency to recover its full costs associated with oversight and enforcement.
- Authorize an account at state oversight agency to accept fees/penalties dedicated to program-related enforcement and oversight activities.

Transparency & Accountability:

- The SO or individual MFR/PR to identify where batteries are in a product and how to remove it safely so the recyclers can easily dismantle without resulting in accidental fires.
- SO should organize as a non-profit organization exempt from taxation.
- SO or individual MFR/PR should provide a plan, annual report, and budget submission and approval process. SO or individual MFR/PR should periodically update their plan, or upon state oversight agency request.

- SO, individual MFR/PR and brands should post online: plans, annual reports, budgets, and lists of compliant

Environmental Protection:

- SO or individual MFR/PR should adhere to California's solid waste hierarchy and ensures products are managed for highest and best use (e.g., address source reduction and reuse in addition to recycling; incineration is not considered recycling in California).
- Encourage domestic processing and utilization of recycled materials.
- Require best management practices and program performance levels for materials management operations (e.g., reuse, recycling, disposal) that minimize adverse environmental outcomes within the state and elsewhere.
- Ensures products are appropriately managed for disposal if they are hazardous and not recyclable.

Fairness:

- Establish and collect penalties for non-compliance or provides incentives to encourage participation that levels the playing field among MFR/PRs.

Education & Outreach:

- SO or individual MFR/PR should take the lead role for marketing, outreach, training, and educating all stakeholders, including consumers.

Product Design:

- State oversight agency should provide guidance mechanisms/incentives/fee structures to encourage products designed for reuse or recycling for environmental benefits.

All interviewees very confidently stated that the EPR would not make batteries "greener," meaning batteries designed for reuse or easier to recycle. IN2 said, in Europe, certain individual companies took on battery recycling since the early 1990s, and the official Battery EPR has existed since 2000, and it has not led to any "greener design" of the batteries. IN2 argued that lithium-ion batteries are greener than lead and Nickel-cadmium batteries. IN2 asked, “what needs to be greener?” and followed up with “It is not realistic to think business and market will change the best way to do business because of the EPR. I mean, is paint any different now because of the EPR?” Product design for LiBs may be a problematic criterion to push for the EPR program.

Based on my research and the responses of IN1-6, I extrapolated the following points:

Key advantages of a LiBs EPR approach are:

- The state would have significantly lower administrative costs (source: IN5 and IN6).
- Product designers and manufacturers are responsible for product end-of-life management (source: Product Stewardship Institute, 2010 and IN1-6).

- Manufacturers have the flexibility to design a program that works best for their industry (source: *EPR Legislation Checklist* CalRecycle, 2017).
- The Legislature would only need a majority vote, and the Legislature seems to prefer the EPR program (source: *Future of Electronic Waste Management in California* CalRecycle 2018 and IN5 and IN6).

Key disadvantages of a LiBs EPR approach are:

- The possibility that today's manufacturers may have to assume responsibility for legacy devices from manufacturers that are no longer in business (source: IN2, IN5, and IN6).
- It is unclear how would California EPR program hold other manufactures from other states and other countries accountable (source: IN1).
- Risk of orphan batteries coming in from other states and other countries (source: *EPR Legislation Checklist* CalRecycle, 2017 and IN2).
- Small recyclers and collectors could be at a competitive disadvantage (source: IN5).
- The stewardship organization may have inherent self-interest to keep recycling costs as low as possible. The manufactures will pressure the recyclers to bid for the lowest cost. As a result, the management of LiBs might not be at their highest and best use (source: IN5 and IN6).
- A lack of a strong governmental oversight can lead to not meeting program goals and inefficiency (source: IN3, IN5, and IN6).

Alternative 2- Adding Lithium-ion batteries to the Covered Electronic Waste (CEW) Recycling Program

Every year in California, consumers purchase more than 120 million electronic devices and upgrade those devices in just 18 months. If those devices are not properly recycled, they end up in the landfill. Beyond the environmental risks, electronic devices have monetary value because they contain materials such as gold, silver, and copper. Worldwide, the international economy suffers a loss of $55 billion every year because the electronics go to the landfill (CalRecycle, 2018). To address growing concerns about the proper disposal and recycling of unwanted electronic waste, the California Legislature passed the Electronic Waste Recycling Act of 2003 (Senate Bill 20). This act created the Covered Electronic Waste (CEW) program, which established infrastructure to provide convenient recycling for Californians, reduce illegal dumping of specific electronic devices, and, most importantly, protect public and environmental health by ensuring the responsible management of hazardous materials. This program significantly relieved local jurisdictions and businesses of the cost burden of managing these wastes. The electronic waste management program has over 400 locations for consumers to recycle CEW for free. As a result, the program has been highly successful and properly collecting and recycled over 2.2 billion pounds of covered electronic waste generated in the state of California (CalRecycle, 2018). Consumers fund the CEW program when they pay a fee at the point of purchase of covered electronic devices.

Approved recyclers and collectors of the CEW program subsequently receive payments to offset the average net cost of appropriate recovery, processing, and recycling of these devices. California is unique in handling electronic waste because no other state has a fee and payment system like California.

CEW and Batteries

The CEW only covers video display devices with screen sizes larger than four inches. This size restriction is one of the most significant limitations of this program. The electronic industry is rapidly evolving, and electronics are becoming more intricate, specialized, and ubiquitous. For the CEW program to be successful, it needs to accommodate more of the current deceives and innovations. Calrecycle's (2018) whitepaper on the *Future of Electronic Waste Management in California* recommends the addition of batteries to the CEW program.

LiBs are hazardous and banned from landfills, just like the covered deceives under the CEW program. Certain covered deceives (like laptops and tablets) contain LiBs embedded in them. When the recyclers dismantle these devices, they can claim the laptops and tablets, but the state does not reimburse the recycler for the LiBs. IN6 said, "it would be easy to add the LiBs of the embedded products to the program, and we have the infrastructure already in place" IN2 and IN5 also said it would make sense to add the LiBs from embedded products but unsure about if the loose LiBs can or should be added. IN6 also said consumers need to have an incentive to drop off the loose LiBs, referring to the bottle and can CRV program.

On top of helping build upon the current CEW program, there are other benefits to adding LiBs in the CEW program. IN6 explains it will alleviate the cost from local governments to collect and recycle LiBs. The CEW program would adequately collect and recycle LiBs. Since infrastructure already exists, the LiBs' collection rate would increase. In the long term, new LiBs recycling facilities might appear due to the popularity of electric vehicles. Lastly, IN6 also pointed out the recyclers and collectors would appreciate one program for all electronic recycling. If a battery EPR program were to exist, they would need to report to the SO and CEW program.

The major drawback of adding batteries to the CEW program is political accessibility. The CEW program is a fee system, which would require a fee at the point-of-purchase. For this to pass through the Legislature, it would require a two-thirds vote. IN5 said in our current political system that is highly unlikely. Another drawback is, the CEW program does not specify how to add loose LiBs into the program. Lastly, the state government, CalRecycle, would take on the burden of recycling and disposing LiBs, which would increase its cost. However, the CEW program has been doing well to support itself and created jobs for recyclers and collectors in California.

According to the *Future of Electronic Waste Management in California* (CalRecycle 2018) and the interview comments of IN5 and IN6, the key advantages of adding LiBs to the CEW program are:

- The CEW program would be stronger with the addition of another electronic device, especially since the market is phasing out cathode-ray tubes, which has been the backbone of the CEW program.
- It is easy to add LiBs because they are already embedded in the covered devices.
- One recycling program for covered electronics and batteries, it would be easier for recyclers and collectors.
- It would increase the collection rate of LiBs
- There is no need to create a new program; the CEW program already exists as well as the infrastructure.
- This program could create more jobs and add new LiB recycling facilities in the next ten years.

According to the *Future of Electronic Waste Management in California* (CalRecycle 2018) and the interview comments of IN5 and IN6, the key disadvantages of adding LiBs to the CEW program are:

- Consumer pay a direct fee at the point-of-purchase
- In it is unlikely for the CEW program to add loose (or single-use) LiBs.
- It would require a two-thirds vote from the Legislature to pass.
- The burden of recycling LiBs would fall into the state government.
- The consumer might need an incentivize to recycle LiBs.

CAM Criteria

To effectively solve a public policy issue, Bardach (2012) recommends comparing the outcomes of each alternative with criteria for equal comparison. The four criteria I used are effectiveness, cost, political acceptability, and fairness. These criteria served as measurement tools that allowed me to systematically weigh the benefits and drawbacks of each alternative's intended outcomes.

As I discussed in chapter three, I did not choose to weigh all criteria the same. Weighing the criteria is a subjective task, and as such, I used my best judgment to assign each criterion using my research and interviews as reference. To keep it simple, the weights for each of the criteria are in decimal, and the four criteria add up to one. Table 4.1 shows how I weighed each criterion.

Table 4.1: Measurement Criteria and Weighting	
Effectiveness	0.35
Cost	0.25
Political Acceptability	0.20
Fairness	0.20
Total	1.00

To rank how well each alternative satisfies each criterion, I rated each alternative from a scale of one to five. A rating of one is considered "very weak satisfaction of criterion," two is considered "somewhat weak satisfaction of criterion," three is equal to "moderate satisfaction of criterion," four is equal to "somewhat strong satisfaction of criterion," and five is equal "very strong satisfaction of criterion." The criterion score equals to the rating of the alternative multiplied by the weight of the criterion. I will add all the scores of the criteria to obtain a total score for each alternative. At the end of the analysis, I will choose the alternative with the highest total score as the recommended policy solution.

Effectiveness

Effectiveness refers to how well the alternatives address the policy issue of reducing the fires from LiBs. The most effective program will altogether remove or alleviate the threat of fires caused by LiBs. As IN1 said, "it doesn't matter how good the program is if it does not address the fire, what is the point. It may not be possible to remove fires completely, but at least the goal is to mitigate the negative consequence of the fires". All the interviewees also agreed that reducing or mitigating fires should be the top consideration for a successful policy solution. A policy will also be useful if the program is sustainable. For a policy alternative to be successful, the program should have a beneficial impact beyond the scope of the immediate application. A policy alternative will receive high marks (a rating of five) for effectiveness if it eliminates or reduces fires caused by LiBs. It must also support itself while keeping a high standard of success years after its original installation. For these reasons, I gave the most weight (importance) to the criterion effectiveness. Out of one, I weighted effectiveness as 0.35.

Cost

The second most important criterion is, cost; I weighed it at 0.25 out of one. The cost criterion evaluates how much it costs to implement each alternative. This criterion will measure an alternative's ability to get the most value in return for the money spent to implement the program. It would be easy to evaluate cost if I was able to estimate program implementation based on the actual dollar amount; however, I do not have those numbers. Cost is an essential factor in assessing alternatives. Successful implementation of a program is highly dependent upon the available resources and whether it is fiscally feasible to initiate a program. For this thesis, there are many stakeholders, and I will mainly consider the cost-efficacy for the state government to implement the program. When rating the satisfaction of a criterion by an alternative, a rating of one would indicate the alternative has a high cost associated with the program, and the returned value from the program is low in comparison. A rating of five would indicate the alternative has the most returned value compared to the money spent when implementing such an alternative.

Political Acceptability

The LiB fires affect many different stakeholders; for a policy solution to be successful, it needs to receive political support from these stakeholders. Therefore, I chose the third criterion as political acceptability. During the interviews, each stakeholder had slightly different concerns and posed different solutions. It was interesting to see that although all stakeholders agree there is an issue with LiB fires, there was no consensus on the best way to address these fires. IN5 was the only interviewee to consider it as a criterion and addressed it as "easy to implement.". IN5 and IN6 were very helpful in explaining the political atmosphere regarding implementing alternative one and alternative two. This information matched what I read in CalRecycle's (2018) *Future of Electronic Waste Management in California* whitepaper. For this criterion, a high rating (a rating of five), would mean that all stakeholders and key decision-makers will support and endorse the implementation of the proposed policy alternative. I weighted political acceptability as 0.20, which is equal to the fourth and last criterion, fairness.

Fairness

To properly evaluate policy alternatives, the fourth applicable criterion is fairness; I weighed it at 0.20. Fairness is an important criterion to consider because LiB fires affect multiple stakeholders, ranging from manufacturers, retailers, collectors, recyclers, local and state governments to consumers. This criterion considered the effects of the proposed policy on each stakeholder. Due to the nature of LiB, no one is equally impacted. Fairness is an important condition for both IN3 and IN4. IN4 felt very strongly about it and brought it up multiple times during our interview. IN4 indicated that for this criterion to be considered adequate, the policy alternative should hold accountable the stakeholders who are most responsible for LiB fires. A high rating for an alternative would indicate the stakeholders who benefits most from LiBs would take most of the responsibility, and not put an unnecessary burden on the stakeholders who are not as responsible. Both fairness and political acceptability criteria directly consider the stakeholder, and I theorize, accurately conveying fairness may lead to higher political acceptability.

CAM Analysis

Table 4.2 is a matrix of the qualitative CAM analysis. In the qualitative CAM analysis, I listed my alternatives in the columns, and my criteria are listed in the rows. Using my reasonings from Table 4.2, I rated the effectiveness of each alternative in Table 4.3. For the quantitative analysis, I multiplied each rating with its weight to calculate each criterion's score. Afterward, I totaled all the scores for each alternative.

Table 4.2: Qualitative CAM Analysis				
	Criteria			
	Effectiveness	*Cost*	*Political Acceptability*	*Fairness*
Alternative 1- EPR program for Lithium-ion batteries	A capable Battery EPR program can reduce fire threats from LiBs. MFR/PR can educate retailers on how to handle LiBs dropped off by consumers. IN2 discussed how Call2Recycle requires their retailer to watch an online safety video as one of the qualifications for the program. IN2 also states that an educational campaign run by Call2Recycle can reduce safety incidents by 50-70%. Plus, MFR/PR should identify the location of LiBs in products for recyclers, which would result in fewer fires. The requirements of a strong EPR program would include: MFR/PR the flexibility to design a program that works best for their industry. It would eliminate the free-rider issue because all MFR/PR would participate. With strong governmental oversight holding MFR/PR accountable, there could be a higher collection of LiBs (embedded and loose). It could lead to open conversations between MFR/PR and recyclers to	Manufacturers/Producers (MFR/PR) would pay for the cost of LiBs disposal, and all the MFR/PR in the industry should share the cost. MFR/PR will also fund the cost associated with the state's oversight. Little to no cost associated with local and state governments. MFR/PR will also provide educational programs for retailers and consumers. IN2 estimates it would take $2M-$3M to run a statewide campaign. For consumers, the retail price of the LiBs would include the recycling cost and not charged separately.	IN5 and IN6 both said an EPR program would pass in the Legislature if there is a majority vote. A majority vote is easier to achieve than a two-thirds vote in the Legislature. The Legislature, the state, and local governments are in support of a battery EPR program. On the other hand, MFR/PR does not support the EPR program. Due to the strict rules of the EPR program, I predict MFR/PRs would vigorously resist it.	IN4 very strongly emphasized, those who benefit from LiBs, MFR/PR, should be responsible for the end-of-life management. All interviewees said the EPR program will increase the price of the batteries for consumers. Although it would increase the cost for consumers, the new price is closer to the "true cost" of LiBs. On the other hand, today's MFR/PR will assume the responsibility for LiBs from MFR/PR that are no longer in business. MFR/PR will be responsible for orphan and online batteries. Also, the small recyclers and collectors could be at a competitive disadvantage.

	find the best way to recycle LiBs and might even lead to greener design.			
Alternative 2- Adding Lithium-ion batteries to the CEW Recycling Program	Adding batteries to the CEW program can reduce fires because the chain of transportation will be short, from consumers to collector/recycler. CalRecycle would require MFR/PR to identify the location of LiBs in products for recyclers, which would result in fewer fires. This program would be sustainable because it has already proven to be a successful program, and adding LiBs would ensure the continued success of the CEW program in California. Also, existing infrastructure would make it easy to add LiBs, and the collection rate of LiBs would increase. Also, CalRecycle would not need to rely on an outside entity (like SO) to implement the program.	Increase in administrative, enforcement costs for both DTFA and CalRecycle. There will be little to no cost for MFR/PR and Retailers. For consumers, there will be multiple fees at the point of retail sale, which can result in consumer confusion. The recycling fee for LiBs would most likely be a separate charge from the current "electronic fee" (which covers the recycling fee for covered devices like a T.V.). The CEW program evaluates the recycling fee every other year to ensure it accurately reflects the recycling cost of those deceives; CalRecycle can include the LiB recycling fee in that research.	The CEW program is a fee system; for this reason, IN5 and IN6 both said the program would require a two-thirds vote from the Legislature to pass. IN5 said in our current political system that is highly unlikely. IN6 seems to be more in support of adding batteries to the CEW program. IN6 also said the recyclers and collectors would prefer this program because it would be convenient to have one electronic recycling program.	For consumers, this is equally fair, as the EPR program reflects the end-of-life cost. Consumers should be equally response to pay for end-of-life cost because they are benefiting from LiBs. However, all responsibilities would fall on the state government, CalRecycle, to fund, administrate, and enforce this program.

Table 4.3: Quantitative CAM Matrix					
	Criteria				
	Effectiveness	*Cost*	*Political Acceptability*	*Fairness*	*Total Score*
Alternative 1- EPR program for Lithium-ion batteries	Rating: 4 Weight: 0.35 Total: 1.40	Rating: 5 Weight: 0.25 Total:1.25	Rating: 3 Weight: 0.20 Total: 0.60	Rating: 3 Weight: 0.20 Total: 0.60	3.85
Alternative 2- Adding Lithium-ion batteries to the CEW Recycling Program	Rating: 3 Weight: 0.35 Total: 1.05	Rating: 3 Weight: 0.25 Total: 0.75	Rating: 3 Weight: 0.20 Total: 0.60	Rating: 2 Weight: 0.20 Total: 0.40	2.80

Conclusion

In this chapter, I addressed steps three through six from Bardach's (2012) methods: construct the alternatives, select the criteria, project outcomes, and confront the trade-offs. To do so, I listed who I interviewed and their field of expertise. I used the information from the interviews and my research to create a qualitative and quantitative CAM analysis. The two policy alternatives I evaluated are alternative 1- EPR program for Lithium-ion batteries and alternative 2- Adding Lithium-ion batteries to the CEW Recycling Program. The final score of the CAM analysis is alternative 1, 3.85, and alternative 2, 2.80. Thus, I believe that the two governmental oversight programs alternative 1 is the better policy. In the next chapter, I will conclude my recommendation by describing my three-prong hybrid solution.

Chapter Five

CONCLUSION AND RECOMMENDATION

The purpose of my thesis was to suggest a possible policy solution at the state-level for the increasing occurrence of Lithium-ion battery fires in California. In order to solve this policy problem I followed Bardach's (2009) "Eightfold Path for Policy Analysis" which includes: (1) define the problem, (2) assemble the evidence, (3) construct the alternatives, (4) select the criteria, (5) project the outcomes, (6) confront the trade-offs, (7) decide, and (8) tell your story (p xvi). In this chapter, I will address the last two steps: decide and tell your story. I will discuss my *three-prong* approach, my thesis limitations, and other concerns.

Three-Prong Solution

As I described in chapter four, after I conducted my interviews, I decided a one-policy solution would not be ideal for addressing the lithium-ion battery fires. A better solution would be a hybrid solution, which includes: (1) consumer education, (2) governmental oversight program, and (3) a fire suppression system in facilities.

Consumer Education

The one possible solution all interviewees agreed on was the importance and the need for consumer education. It makes sense because consumers are involved in the purchase and disposing of lithium-ion batteries (LiBs). Consumers need to be aware of the fire risk that can occur with improper LiB disposal. To some extent, consumers are aware of the fires created by LiBs. For example, in chapter one, I mentioned the Samsung smartphones that caught on fire because of the LiBs in them; there was a lot of media coverage of these fires because of popularity over the Samsung Galaxy smartphones. However, most consumers are not aware of the LiB fires caused by improper disposal (Fogelman, 2018), which occur during collection, transportation, recycling facilities, and landfills. The level of importance each interviewee gave consumer education differed. Some thought it was one of the most critical steps the state government could take, while others thought it would be helpful but would not solve the issue of fires caused by LiBs.

IN3 believes consumers are the "first line of defense" regarding LiB fires. IN3 said when consumers purchase devices containing LiBs, the packaging lists the dangers of LiBs, but most do not read it due to over complexity or do not remember the information years later when they are disposing of the product. IN3 thought the point-of-sale educational campaign might be effective, so the consumers remember to recycle their old product when buying a new one. IN2 considers consumer education to be one of the most significant steps to reducing LiB fires. IN2 believes education should be the focus on more than collection. IN2 stated, "if you educate properly, it will lead to more collection the correct way, which would lead to fewer fire incidents." After interviewing IN2, I realized education programs should not focus on just consumers, but everyone involved in the LiB chain, such as retailers, transporters, collectors, and recyclers. IN2 explained, Call2Recycle requires their retailers to have training regarding the handling of LiBs, IN3 explained the workers who dismantle LiB devices are trained to lower fire risk. I do not know about the rest of the chain; farther research on this topic would be valuable.

IN1 focused on how education is part of the solution but not the entirety of it. IN1 thinks, "consumer education is good, but it is expensive." IN1 explained that education is expensive because it cannot be a one-time campaign. Education needs to be constant, and that can add up in cost. Furthermore, education needs to target everyone in the State of California. IN3 agrees that consumer education can be expensive, but IN3 also believes the value of consumer education would outweigh the alternative. IN3 states, "the risks heavily outweigh the actual financial impact when a LiB can burn down a multimillion-dollar building and even kill many people."

The interviewees were not able to estimate how much an education campaign would cost or confidently state how effective the education program would be. IN2 attempted to answer this by relying on a similar study done by Call2Recycle. In 2018, Call2Recycle implemented an educational program in San Francisco. According to IN2, the reasons they chose to do a test-educational-campaign in San Francisco were: (1) the Bay Area had fire incidents, (2) there's a substantial amount of technology adoption in the use of mobile devices, (3) there is a much higher awareness of environmental issues, (4) and the freestanding media market was indispensable for the education of consumers. The result of this campaign was a 90 percent reduction in safety incidents. Applying similar methods throughout the State of California, Call2Recycle estimates would take about two to three million dollars a year, and it would reduce safety incidence by 50 to 70 percent.

IN4 states for an educational campaign to be successful, it needs to be clear and concise. However, there is no reason to have a consumer education program in place without having the infrastructure to take the LiBs. IN5 and IN6 also stated similar concerns; both said educational efforts would be necessary, but without a convenient system to take in the LiBs, education would not be worthwhile. Thus, I suggested a substantial governmental oversight program to collect and recycle LiBs as part of the three-prong solution.

IN4, IN5, and IN6 are taking into consideration that consumers make *human* decisions and need to be *nudged* to make the right decision. According to Thaler and Sunstein (2008), in the book *Nudge,* a nudge is a behavioral economics concept which proposes positive reinforcement through indirect suggestions to influence the behavior and decision making of individuals. Thaler and Sunstein (2008) also stated there are two types of people, "human" and "econ". Econ is a very logical-thinking type of person who seeks to optimize utility-maximizing outcomes, meaning they are mainly concerned about maximizing benefits and minimizing costs. *Econs* are imaginary people who always reason evenly, and are impervious to the various *human* factors such as misinformation, inertia, optimism, denial, lethargy, the inability to delay gratification, and false assumptions. Parallel to *econs*, *humans* are (what we might consider) *real* people who make *real* human decisions driven by human emotions and uncertainties (BusinessBalls, 2013). A crucial aspect of the Nudge theory recognizes that *econs* do not exist in terms of broad societal behavior, whereas *humans* definitely do. If LiB consumers were *econs*, they would be aware of the dangers of not recycling LiBs properly; they would make sure to dispose of the LiBs in designated battery recycling areas properly. Realistically, people are *humans* in that some people are uninformed and do not know the dangers of placing a LiB in the trash can or recycling bin. Some never took the time to learn about proper LiB disposal because it was not important to them. Some may not want to take LiBs to proper battery recycling areas because it is too far or inconvenient. As IN4, IN5, and IN6 suggested, a successful consumer education program would be an easy and convenient program that nudges consumers to dispose of LiBs properly.

However, nudges are not mandatory, and it must be easy to do and cheap to avoid (BusinessBalls, 2013). Nudges are more effective because people do not feel forced; they can participate if they like or avoid it without any significant loss. A great nudge program from CalRecycle is the Beverage Container Recycling, where consumers have cash incentives to recycle bottles and cans properly. Recycling bottles and cans are not mandatory, and if someone does not recycle, they only lose a few cents. Also, there are many *bottles & cans* redemption centers that recycle, which makes it convenient for consumers (CalRecycle, 2019). If proper recycling of LiB could be the consumer's *default*, it would yield the best results. *Default* is the best form of Nudge because it is a pre-set course unless otherwise specified by the decision-maker. *Default nudge* works best to overcome the human tendency for inaction related to such issues as insurance, retirement, organ donor, and voter registration (Thaler and Sunstein, 2008). Whether consumer education is a nudge program or direct education of how to handle LiBs in the LiB chain, an education program must be a mandatory part of the Governmental Oversight Programs.

Governmental Oversight Program

The educational program should be an embedded part of the governmental oversight program. In chapter four, the two alternatives I compared included an educational portion built-into the program. The result from my qualitative and quantitative CAM analysis (Tables 4.2 and 4.3), is Alternative 1: A Battery EPR program would be most effective. A Battery EPR program would be effective because it would include both LiBs embedded in electronic devices and loose LiBs and it would hold all Manufacturers/Producers (MFR/PR) responsible. It would be cost-effective for the State because the stewardship organization or MFR/PR would fund the education campaign and the end-of-life cost for the LiBs. As for the recycling cost of LiBs, IN3 explained there is a vast variance based on the type of electronic device the LiB is in because some LiBs are easier to remove than others. The cost of removing the LiB from a device ranges from 15-20 cents per pound to 50-75 cents per pound. There is an additional cost of transportation and appropriate recycling of these separated LiBs; the cost ranges from $1.50 per pound to $4.50 per pound. The battery EPR program should take these costs into consideration in calculating program costs.

The main trade-off of not choosing the CEW program is the ease of implementation. Adding embedded LiBs to the CEW program would be more straightforward than creating a whole new Battery EPR program. However, as I discussed in chapter four, the CEW program does not address the loose LiBs. Also, adding LiBs to the CEW program would require a two-thirds vote from the legislature. If the bill does not pass, it will not address the LiB fires/recycling if LiBs at all. If the State of California introduced another bill after revising the first bill, it would take longer to go through the approval process. I believe the LiB fires are a significant public policy issue that the State needs to address sooner rather than later. For these reasons and the reasons stated in chapter four, I believe compared to the CEW program, adding an EPR battery program would be a more comprehensive solution, in terms of effectiveness and cost. Lastly, even though MRF/PR may resist the program, it is fairer to hold them responsible for the products they create instead of burdening other stakeholders.

Fire Suppression System

Throughout my research and interviews, only one solution came up that addressed the LiB fires directly: a fire suppression system. The installation of a fire suppression system into the waste facility is vital because it monitors and uses a combination of dry chemicals to suppress fires while also alerting the respective authorities of potentially hazardous scenarios. IN1 discussed the fire suppression system, Fire Rover, in detail. Fire Rover is a unique portable fire suppression system that effectively and efficiently prevents fire 24/7. A key component in the Fire Rover system is FLIR A310F, a top-grade military thermal camera, combined with award-winning human verification and response (FireRover, 2016). IN1 explains that Fire Rover's goal is to avoid large scale fires since, "the earlier you get to a fire, the less chance you have of that fire getting out of control." Due to the thermal surveillance system, Fire Rover can identify abnormalities remotely and apply cooling suppression before the fire becomes big or dangerous. A fire suppression system in the waste/recycling facility can attempt to put out the fire immediately long before the firefighters arrive at the scene. Another advantage of Fire Rover is the 24/7 monitoring, which, with human verification, can monitor thermal abnormalities, apply coolant efficiently and call the fire department (FireRover, 2016).

Having a remote system can not only address fires sooner but also make the scene safer for firefighters. An issue with fires at a waste/chemical/recycling industry site is that firefighters must exercise extreme caution when approaching a building that has different types of chemicals. IN1 explained that this is another reason why firefighters may take longer putting out these types of fires. IN1 gave an example of how one of their facilities caught a 3,000-degree fire in a facility that had over 361 chemicals, and Fire Rover was able to put it out in four and half minutes before firefighters even arrived at the scene. Fire Rover has over 100 waste/recycling facilities all over the county, and according to IN1, they have not had any major fires in any of their facilities. Fire Rover even won the gold Edison award in the innovation and industrial safety category.

Naturally, I asked IN1 about the cost of Fire Rover and if it was realistic for waste/recycling facilities to own this system. IN1 explained for smaller scrap-metal/junkyard facilities, it is not realistic, but for the more extensive waste/recycling facilities, it is "realistic and feasible." The investment is "less than a quarter-million dollars, [which is] less than 50 thousand a year." It may seem a high cost up-front, but IN1 explained the trade-offs would be major uncontrolled fires, facility damage, increased insurance, facility shut-down, and loss of business.

Based on IN1's comments, the Fire Rover system seems to be the most efficient way to address LiB fires (or any fires) in waste/recycling facilities. However, this system does not address fires that might occur during collection and transportation for LiBs. Due to this, I believe a hybrid approach is more encompassing as it attempts to remove single points of failure and provides a more stable environment for the LiBs recycling process from its source to final reclamation and repurposing.

Limitations and Other Concerns

It is worth noting some limitations of my thesis. Due to the nature of my thesis, and the time limit, I was not able to adequately research the best consumer education method or research the best fire suppression system. For future research, I would suggest a CAM analysis for both methods. One question is whether the State should subsidize costs or give grants for education campaigns and/or fire suppression systems.

Another limitation is, I would have liked to interview more people. I reached out to the California Product Stewardship Council (CPSC) and the California Department of Toxic Substances Control (DTSC). However, due to the schedule conflict, time limit or no response, I was not able to schedule an interview with them. CPSC is an expert on California's EPR movement, and DTSC oversees reducing hazardous waste generation and enforcing those laws. I wanted to obtain CPSC perspectives on the advantages/disadvantages of the Battery EPR program, what should be EPR requirements and any EPR limitations. From DTSC, I would have liked to know their concerns about LiBs and how DTSC plans to address the potential fires caused by LiBs. Also, I would like to interview CalRecycle's EPR staff to learn more about EPR's limitations and challenges.

An important issue that came up during my interview with IN2 is that there is no place that both accepts and extracts materials from LiBs in North America. He explained the whole process. Retailers like Home Depot offer collection services for unwanted LiBs, then ship the LiBs to a sorting facility in Mesa, Arizona. Workers sort all the LiBs into drums and ship them to a recycling coordinator in Akron, Ohio. In Ohio, they discharge and shred the LiBs into tiny little pieces. Then they take the battery shreds and ship it to Langeloth, Pennsylvania, where the shreds are calcined. Calcined refers to a process that burns the paper and plastic, leaving a black powder. After shipping the black powder to Glencore in Sudbury, Ontario, Canada, it goes through an extraction process that results in cadmium nickel and many other materials. Currently, Glencore no longer accepts whole batteries but will take battery dust and process it. On the other hand, Ohio will take whole batteries and shred and calcify the batteries, but they will not extract from them. In short, a LiB travels all over the United States and finishes its processing in Canada. The extracting of materials is an energy-intensive process that is unavoidable. However, the transportation of LiBs throughout North American is energy-intensive and adds to carbon emissions. In the future, there should be a conversation about ways to lessen the transportation of LiBs to process them. With the increasing popularity of electric vehicles, LiB recycling may become profitable, and more processing facilities may open, it is uncertain whether this would benefit household LiBs. California should take the lead in creating a facility that processes LiBs from start to finish. This facility could be state-run or subsidized by private operators. If some environmental laws or regulations discourage a LiB processing facility, an examination of those laws is necessary. There is a need for more research regarding the cost and barriers for this type of facility. It is counter-productive to encourage the use of reusable batteries like LiBs in households and electric vehicles to reduce greenhouse gas emissions when to recycle those batteries we transport them all over North America.

Lastly, as I discussed in chapter one, the nature of LiBs and their design makes the batteries prone to catching on fire. The best solution would be to improve the design of these batteries, so they do not catch on fire. As I found from my literature review and the interviews, that technology is currently too far from being a reasonable alternative. At best, the technology may take another five to ten years until it can be a viable option for the consumer. Even if this technology were ready for consumer use at a reasonable price, it would not solve the issue of all the LiBs that are already out in the market and homes. I did not suggest a policy alternative focusing on investment in technology because it would take too long to implement, and it would not address the proper collection and recycling of batteries that are already out in society.

Conclusion

The government adopts a policy in response to some issue or problem that requires attention. The government generally implements a policy for the benefit of the public. The problem I researched for my thesis is, "In the State of California, the current management of Lithium batteries throughout the disposal process is causing too many costly fires." To solve this policy issue, I followed Bardach's (2009) eight-step method to policy analysis: (1) Define the problem, (2) Assemble the evidence, (3) Construct the alternatives, (4) Select the criteria, (5) Project the outcomes, (6) Confront the trade-offs, (7)Decide, (8) Tell your story. In chapter one, I defined the problem by explaining what LiBs are, how they came to be popular, and their continuing popularity. I then explained how they catch on fire, the cost of these fires, and laws regarding LiBs. In chapter two, I assembled evidence through my literature review, and I explained EPR, LiB recycling process, and LiB technology advancement. In chapter three, I explained my methodology, the CAM analysis, and my interview process. In Chapter four, I constructed the alternatives, selected the criteria, projected the outcomes, and confronted the trade-offs. In this chapter, chapter five, I decided on my hybrid-policy solution and explained my three-prong approach. I also addressed the thesis limitations and other concerns for future research. I hope that California Policymakers take my hybrid-solution of (1) consumer education, (2) governmental oversight program, and (3) a fire suppression system in facilities into consideration when discussing how to address the issue of LiB fires.

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