

Implementing Plastic Pyrolysis Into Chile's Plastic Recycling Infrastructure

by
Kylee Mockler Martens

A THESIS

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Oregon State University

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Dr. Skip Rochefort

With the incredible technological advancements that have come from the introduction of plastic many problems have arisen. Once plastics were created the value of items once they reached their end of life were lowered. Considering the majority of all plastics created are for packaging with single-use intentions people now dispose of almost all their items after they have been used.

This type of thinking has brought many problems to the environment from the emissions created from their production and disposal, pollution, and valuable space they take up in landfills. The ideal method for waste management is to recycle. There are multiple types of recycling including re-extrusion, physical treatment recycling, chemical recycling, and energy recovery.

Chemical recycling, a plastic to oil technology, is considered for implementation in Chile's current waste management infrastructure. Pyrolysis is advantageous because of its ability to manage a mixed feedstock and produce high quality products and applications from all aspects of its products. The Unit of Technological, a research and development firm in Chile, has successfully designed a pyrolysis system at bench-scale and is working on increasing it to industrial scale so that it can be implemented as the first pyrolysis facility in South America.

Key Words: plastic, plastic recycling, waste management

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I understand that my project will become part of the permanent collection of Oregon State University. My signature below authorizes release of my project to any reader upon request.

Kylee Mockler Martens, Author

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Chapter 1. Introduction to Plastics

1.1 Plastic Consumption

After plastics were industrialized during World War II all industries changed and adapted to the benefits of plastic. Plastic has become an essential commodity with many household and industrial uses. The first industrial scale production of plastic began in the 1940s. Since then, production, consumption, and waste generation has only increased. In 1990 an individual produced 250 kg municipal solid waste a year, by 2000 the amount had doubled (Al-Salem et al., 2009). However, the amount of plastic consumed depends on what part of the world you live in. For an individual living in Europe or North America, they consume 100kg of plastic whereas in comparison someone living in Asia only consumes 20kg of plastic the WorldWatch Institute found. "Waste plastic generation is expected to increase each year due to the increasing population and continuous growth in living standards" (Rapsing & Espinosa, 2017). Considering 90% of plastics used today are synthesized from non-renewable fossil fuels reinforcing the necessity to integrate waste management schemes into plastic production cycles with the increasing rates of use (Al-Salem et al., 2009).

The plastic industry is huge, globally the plastic industry generates a yearly revenue of \$600 billion (Gourmelon, 2015). In 2013, 299 million tons of plastic was produced globally (Gourmelon, 2015). The world produces more than 3.5 tons of garbage a day, which is 10 times more than a century ago. Globally, the largest plastic producers are China at 24.8%, Europe at 20%, and NAFTA-USA, Mexico, and Canada at 19.4% ("Tackling Complex Recycling Plastic Recycling Challenges" 2015).

Of the plastics produced, the packaging industry is one of the leading problems to the excessive waste since they are used once and immediately disposed of. Landfills receive up to 10,000 tons of waste per day which release methane, a greenhouse gas that traps heat in the atmosphere and are harmful to the environment and people's health. There is so much waste that at this rate by 2050 the plastic will outweigh all the fish (Amovic & Johansson, 2009). Scientists estimate that there are currently 5.25 trillion plastic particles currently in the ocean which equivalates to 270,000 tons (Van Lohuizen, 2017). It is imperative that actions be taken be local and international governments to create an incentive and need to reuse and recycle items after they have completed their useful life cycle.

1.2 Problems with Plastics

Plastics have transformed everyday life and have many benefits, including medical and technological advancements. Almost all aspects of daily life now include plastics-transportation, telecommunication, clothing, footwear, packaging materials, and more. Plastics have a wide range of applications due to their variety of characteristics enabling them to fulfill lightweight and durable materials, their implementation has improved all areas of our daily lives. It is estimated that since its creation, 8.3 billion metric tons of plastic have been produced (Cortina, 2018). They are inexpensive and are derived almost completely from petrochemicals from fossil oil and gas which are non-renewable resources. Not only does the process require fossil fuels, but the energy to fuel the process

requires fossil fuels as well. Plastics account for 8% of the world's oil production (Thompson et al, 2009). When plastics were industrialized 70 years ago they were advertised as being colorful and free of rust, at the time no one had considered the future implications involving its production, waste management, and debris. The amount of plastic produced in the first years of the 21st century equal the whole 20th century (Thompson, 2009). A serious concern is that the plastics source, fossil fuels, is a non-renewable resource whose amount is only declining while the consumption of plastic and population are increasing. The demand for plastic materials is only increasing considering high consumerism, need for convenience, and low cost of plastic products. The total amount of plastic produced is projected to reach 12 billion metric tons by 2050 based on current trends (Wallace, 2017).

It is critical that plastic be recycled considering plastic is produced from non-renewable fossil fuels. Every year 1.3 billion tons of waste is generated which costs 205 billion dollars in collection costs (Navarette-Hernandez, 2018). Plastics make up about 10% of a municipal waste stream with packing plastics making up its majority (Thompson, 2009). According to the Environmental Protection Agency, in 2012, US produced roughly 32 million tons of plastic waste with only 9% being recycled. It is estimated that 79% of the plastic ever created is now piling up in landfills (Cortina, 2018). Consumers see little return value in recycling plastics so they end up just throwing out their waste which pile up in landfills and never decompose. (Matheson, 2014). One problem comes from the fact that approximately 50% of plastics products are meant for single-use such as packaging, agricultural films, and disposable consumer items (Hopewell et al., 2009). If consumers were educated to see the energetic potential of plastic and other waste the amounts of items reused and recycled would significantly increase.

Since plastics never disintegrate their method of disposal is extremely important. Currently, the most common route for plastics at the end of their life is to be landfilled which are already reaching their capacity and also release toxic emissions and pollute. The US relies heavily on landfills with 75-80% going to landfills ("Plastic Recycling Processes in Industrialized Nations", n.d.). The EPA stated that there are over 3,000 active landfills currently and over 10,000 old municipal landfills. A decrease in plastic waste or diversion would mean less space needed for landfills.

In addition to landfills, plastics pollute the ocean and environment. Oil and water do not mix which creates plastic gyres in the ocean with plastics that will break down into small nurdles but never degrade completely. These nurdles are particularly impactful because they attract and concentrate other harmful pollutants such as DDT or PCBs at highly toxic levels. Plastics represent 50-80% of plastic debris along shorelines (Thompson, 2009).

The only way to prevent plastics from reaching landfills or polluting the environment is through thermal destruction. New technological advances including plastic pyrolysis are creating more sustainable methods of managing plastic waste. The only way to permanently eliminate plastic waste is either through combustion or pyrolysis (Geyer, Jambeck, & Law, 2017). Plastics are a global problem dependent on a depleting natural resource or oil whose production and waste can lead to environmental pollution. Plastic to

oil conversion technologies can offer solutions worldwide through changes in economic policies, environmental regulations, and societal views.

Chapter 2. Waste Management

2.1 Routes for Plastic Post-Useful Life

Most commonly, plastic items are utilized only once before being disposed of. Plastic items must be reused multiple times to make up for the energetic input in its production before it is sustainably recycled. Currently, there are multiple methods for handling municipal solid waste. Once plastic items have completed their useful life cycle they are most often disposed of and sent to landfills. Almost 10,000 tons of waste is sent to landfills each day globally (Van Lohuizen, 2017). Plastics that end up in landfills waste their potential hydrocarbon energy and their ability to produce new products or energy. If they are not sent to landfills, they will be incinerated for energy. For much of the plastic that is not landfilled or incinerated, it reaches our waterways and makes it to the ocean. EcoWatch reported that 8 million tons of plastic is dumped into the ocean each year. The ideal, yet most uncommon, route for plastics post-useful life is to be recycled. Of the plastic waste created, 9% was recycled, 12% incinerated, and 79% accumulated in landfills or the natural environment (Geyer, Jambeck, & Law, 2017).

2.2 General Steps in Waste Management

The goal for an integrated waste management system is to "control the waste generation from processes to meet the needs of a society at minimal environmental impact and at an efficient resource usage by activating the potentials of waste prevention, re-use, and recycling. For all recycling processes technical and economic feasibility and overall commercial viability of advanced recycling methods must be considered in each step of the recycling chain" (Al-Salem et al., 2009). In order for the waste management system to be successful for its full completion it requires a constant cheaply acquired feedstock and a favorable market for the recycled products. An integrated waste management system includes waste generation; waste handling, sorting, and processing at the source; collection; separation and processing; transfer to the handling station and transporting the waste; and disposal. The entire waste collection and recycling process must be analyzed and improved to increase efficiency and recycling rates.

Chapter 3. Plastic Recycling

3.1 Recycling Overview

Recycling which began in 1970 is currently the most important action to reduce the negative impacts plastics have on the environment by reducing carbon dioxide emissions from oil usages and the amount of plastics being sent to the landfill. Recycling can decrease material and energy usage by using the recovered material to produce a new product or create energy. Products entering waste streams can be reduced if products are designed for reuse, repairs, and re-manufacturing.

Within the plastic recycling system, the general steps are collection, sorting, shredding, cleaning, melting, and the making of new but lower quality products. Recycling reduces the need for virgin material and also produces useful energy. In the recycling process, plastic waste is fed directly into a combustion unit to fuel industrial processes which produces 30-40 GJ of energy per ton while replacing the need for coal, oil, diesel, and natural gas (Astrup et al., 2009). The type of cleanliness of the plastic does not affect its energetic capabilities. However, for the plastic to be reused for the production of a high-quality product, the plastic must be clean and of one plastic type in order to substitute virgin plastic. Conventional recycling, the current method of plastic recycling, is unable to meet quality levels. The quality of plastic decreases with every reprocessing with the need of some virgin plastic granules for production (Astrup, Fruergaard, & Christensen, 2009). Additional challenges with recycled plastic product quality include mixed feedstocks with varying plastic type, color, or contamination.

Sorting plastic waste is the most important step in the recycling loop (Al-Salem et al., 2009). Automated sorting technologies have helped advance recycling by separating by color and transparency through an infrared spectrometer to separate polymer types. Technology advancements now achieve a 99.99% pure product from recycling. However, not all plastics can be recycled, those that can't be recycled should be used to fuel waste to energy facilities. Black plastics are not recyclable because sorting systems cannot detect the carbon in the plastic since there is no light reflection ("Tackling Complex Plastic Recycling Challenges", 2015). Sorting can also be done by density-based air-classification systems or laser-sorting. Improvements in sorting and washing technologies have increased the types of plastics that can be recycled (Hopewell, 2009). Mechanical recycling is not ideal because the quality of the plastic decreases with every reprocessing requiring an input of virgin plastic materials for production. New technologies are implementing alternative recycling methods such as plastic to oil technologies which are preferable in specific scenarios of plastic waste management. Through the combination of action from the public, industry, and governments recycling systems for collection, sorting, and reprocessing are advancing to divert plastics at the end of their useful life cycle (Hopewell et. al, 2009). It is essential that education and awareness of recycling needs be spread to ensure less plastic waste reaches landfills.

Plastic recycling is the key to reducing the need for virgin polymers. Life cycle analyses for the net environmental impact of plastic-recycling systems have found that recycling saves more energy than the energy produced from energy recovery. A study found there

are greater positive environmental benefits to mechanical recycling over landfill and incineration with energy recovery. For example, the recycling of PET plastic bottles gives reduces greenhouse gas emissions by 1.5 tons of carbon dioxide per ton of PET (Hopewell et al., 2009).

Energy recovery is an alternative recycling method. However, energy recovery is not as effective at improving environmental conditions because it still requires the use of virgin plastics for new product production and produces emissions. Another method for waste management involves incineration of plastics for energy which directly solves limited landfill space problems. Although incineration doesn't solve all problems because it still releases toxins into the atmosphere. The amount of energy recovered varies depending on whether it's used for electricity generation, heat and power, or directly to fuel. Energy recovery is the most suitable for highly mixed plastics. However, energy recovery does not reduce the demand for fossil fuels.

Downgauging, another alternative to eliminate plastic waste involves the reduction of the amount of plastic packaging for products which decreases the amount of waste plastics. There are manufacturing standards to how much plastic packaging individual items need, however, for aesthetic purposes many manufacturers increase packaging amounts for marketing benefits. Stricter regulations should be placed on packaging standards so that companies cannot waste plastic for aesthetic purposes.

The methods and ease of plastic recycling vary depending on polymer type, package design, and product type. Producing resins from recycled plastic waste is a challenge due to the different immiscibility and processing requirements. Thus, it is not possible to add recovered plastic to virgin polymer without decreasing the quality including color, clarity, and strength. The complete substitution of recycled plastics in virgin plastic's place depends on the purity of the recovered plastic feed (Hopewell et. al, 2009).

3.2 Recycling Methods

Plastic recycling reduces the need for oil usage and greenhouse gas emissions from the production of the virgin polymer. There are four possible recycling for plastic solid waste. Primary, re-extrusion, has the capability to reproduce products of similar materials in a closed-loop system but mostly within the same process line. This can be challenging considering the multiple polymer components in a single product. The only plastic waste stream that has been consistently recycled in a closed-loop cycle are clear PET bottles. Secondary, mechanical recycling, is the most common form of plastic recycling which employs a physical treatment to the plastic at the end of its life as the feedstock. A challenge with mechanical recycling is that the process is costly and energy intensive. The general steps used are shredding and cutting the plastic, separating the contaminants, separating the plastics by density, milling, washing and drying, agglutination, extrusion, and quenching. However, this process downgrades its quality, however, it can still eliminate the need for virgin plastic products in certain industries. In this type of recycling up to 25% of recycled resin can be utilized with virgin resin for production of new products (Ehrig,

1992). Tertiary, chemical recycling, has a wide range of technologies and is used to produce either fuels or petrochemicals through the depolymerization of its hydrocarbons. Chemical recycling has the ability to produce high quality products eliminating the need for virgin oil for new plastic product production. Often, chemical recycling is considered uneconomic because of the currently low price of petrochemical feedstock which could be altered with new environmental policies. Quaternary recycling involves the use of plastic waste for energy recovery and is less sustainable than chemical recycling. Each method has advantages and disadvantages; however, primary and secondary recycling are the most established and widely applied. Each are uniquely applied with different applications, locations, and requirements.

The products of chemical recycling have been proven to be suitable for use as a feedstock for petrochemicals and plastics as well as being useful for fuels. In order for chemical recycling to be successful, the collection, processing, and marketing of the process are essential. "The technology behind its success is the depolymerization processes that can result in a very profitable and sustainable industrial scheme, providing a high product yield and minimum waste" (Al-Salem et al., 2009) from utilization of all product components. There are many types of chemical recycling including pyrolysis, gasification, liquid-gas hydrogenation, viscosity breaking, and steam or catalytic cracking. Chemical recycling has the advantage of requiring minimal treatment since the process can handle contaminated polymers.

Plastic pyrolysis is a type of thermolysis which treats the plastic solid waste in the presence of high heat under controlled temperatures in the absence of oxygen. "The pyrolysis process is an advanced conversion technology that has the ability to produce a clean, high calorific value gas from a wide variety of waste and biomass streams. The hydrocarbon content of the waste is converted in a gas, which is suitable for utilization in either gas engines, with associated electricity generation, or in boiler applications without the need for flue gas treatment. This gas will typically have a calorific value of 22-30 MJ/m³ depending on the waste material being processed" (Al-Salem et al., 2009). The process is also able to produce liquid products of crude oil which can be sent to refineries for further processing. Solid products from the process are waxes from the heavier hydrocarbons which have a wide range of applications and char which is from the input of any contaminants or non-hydrocarbon material. Vapor products that are produced from incondensable gases can be captured and utilized to energize the process creating a self-supporting system.

There are many advantages to plastic pyrolysis processes. Operation advantages come from the use of its products for high quality purposes and that no flue gas clean-up is required. Environmentally, pyrolysis provides an alternative solution to landfilling and reduces greenhouse gas and CO₂ emissions. Financially, pyrolysis produces a high calorific value fuel that could be easily marketed and used in gas engines to produce electricity and heat. Several obstacles and disadvantages do exist for pyrolysis, mainly the handling of char produced (Ciliz et al., 2004) and treatment of the final fuel produced if specific products are desired. In addition, there is not a sufficient understanding of the

underlying reaction pathways, which has prevented a quantitative prediction of the full product distribution” (Al-Salem et al., 2009).

In order for any alternative plastic recycling method to be successful it is essential to have an ensured feedstock which in many cases comes from community donations and a customer that plans to purchase the product in order to ensure an economical and environmental practice. If recycling technologies are considered more valuable then companies will have an increased economic incentive to recycle polymers. Governments need to create environmental regulations or subsidies that will promote alternative recycling methods.

3.3 Societal Views on Plastic Recycling

A common problem creating low recycling rates is inconsistent recycling programs in all municipalities that discourages citizens to recycle. Within the home it can be difficult to encourage citizens to recycle especially when each of the 9,800 recycling programs have their own regulations ("In the Bin", 2015). However, there has been an increased awareness for the effects that plastic has on the environment. In 1970 people in the US recycled 6% of their waste whereas in 2015 citizens recycled up to 35% of their total waste, which is higher than the percentage of people who vote (Mayorga, 2015). Many communities have initiated recycling programs and educational programs to educate people on its importance. Changes in waste management behavior must be made for individual households and companies. Many communities still do not recycle any of their goods, sending most of their waste straight to the landfill. The mentality of consumers needs to be altered so that individuals recognize the value and energetic potential that all waste has. Even though many individuals care about the environment, their recycling rates are surprisingly disappointing. Municipalities should make recycling all recyclable waste mandatory. A study in 1990 found that municipalities in the United States with mandatory recycling programs had almost twice as high of a recycling rate than voluntary programs (Folz & Hazlett, 1991). It can be expected that similar results would be reached if similar measures were implemented in other developed countries.

The volumes of post-consumer waste are significantly higher than industrial waste with rates up to five times higher meaning both post-consumer and post-industrial waste need to be managed (Hopewell et al., 2009). Recently, there has been an increase in public awareness on the necessity of sustainable production and consumption with manufacturers developing products with recycled content and local authorities organizing collection of recyclables. People are beginning to recognize the severity of the problem with plastic consumption regarding the limitations of oil and its environmental effects. Marketing studies have found that there is a significant portion of consumers who use environmental qualities in their purchase decision making (Hopewell et al., 2009). In her book "Plastic: A Toxic Love Story," Susan Freinkel discusses how individuals are more likely make a change if they are informed that it is the social norm to do so. People are more likely to recycle or use reusable items if they believe that everyone in their community is doing the same. This creates an even more powerful motive than personal incentive to make

sustainable decisions. Municipalities and communities should work to improve the mentality of their citizens to encourage each other to recycle.

Chapter 4. Plastic to Oil

4.1 Introduction to Processes and Methods

Chemical recycling is capable of converting a plastic feedstock into crude oil for use in many high quality industrial applications. Waste conversion technologies include pyrolysis, gasification, anaerobic digestion, and hydrolysis. The liquid products from a plastic to oil process can be sent to oil companies for further refining to be upgraded to fuel products varying depending on the customer needs. The vapor products can be used to energize the operation creating a closed loop system. Gasification converts a feedstock to syngas, a gaseous mixture of carbon monoxide and hydrogen, it is an endothermic reaction that requires a heat source which could come from syngas combustion, char combustion, or steam. Issues with gasification involve excess residue and the need for sorting, shredding, and drying before the process can begin (American Chemistry council, 2012). Hydrolysis is the degradation of a polymer from contact with water. Anaerobic digestion is the degradation of a polymer from the use of a microorganism in the absence of oxygen. Pyrolysis is the thermal degradation of the hydrocarbons in a plastic waste material in an inert environment. Each conversion technique has their own preferred scenarios based on type of feedstock and desired product.

Plastic to oil technologies are not considered a complete replacement to existing traditional recycling systems but as a feasible addition. Conventional plastic recycling is preferable over chemical recycling for some plastic wastes, specifically polyethylene terephthalate water bottles. Chemical recycling is preferred with contaminated or mixed feedstock due to its ability to process a variety of materials and produce applicable products.

4.2 Plastic Pyrolysis

Pyrolysis, thermal cracking, is an endothermic process in a non-reactive, oxygen starved environment that decomposes a carbon-based material to produce liquid, vapor, and solid products (Trager, 2014). Plastic pyrolysis provides the opportunity to convert plastic waste into a resource as an alternative method for the treatment of mixed and contaminated waste plastics. Challenges with pyrolysis are that char can be produced as up to 15-20% of the feedstock which accounts for the contaminants and non-hydrocarbon material from the process. Conversion rates vary greatly by plastic. Polystyrene as an example can be converted into usable liquid fuel with a 70% conversion rate with the product used as a fuel or sent to a refinery to further improve its quality (Rapsing & Espinosa, 2017). Through pyrolysis, the volume of plastics that needs to be incinerated or landfilled will be minimized thus reducing carbon emissions and the need for virgin oil.

The waste plastics that are the feedstock of the process come from many sources with varied quality and prices. Pre-use plastics, production scrap, includes waste from industrial plastic production products. Post-use plastics include household, industrial, and commercial waste recycling that is collected after its usage (Terrell, 2017). In many cases the feedstock comes from donations within the community assisting the plant in having a free resource to produce products and energy creating significant revenue and increasing the process feasibility.

The main steps for plastic pyrolysis are treatment where the size of the material is reduced and then cleaned, then the plastic feedstock is heated and converted into a gas which is then condensed into a liquid in the condenser. The products obtained are fuel, natural gas, wax, and char. Liquid fuels are the main product from the process and after further distillation stages produce transport fuel including petrol or diesel which create the revenue for the plant. The gases produced from the system that are too light to condense into fuels are combusted as energy to fuel the process. The char can be converted to activated carbon for a variety of uses including water treatment. Waxes that are produced can be utilized for hydrophobicity. Plastic to oil processes can operate as a relatively closed system with low emission levels since it does not involve the incineration of the recycled plastic making them highly advantageous.

4.3 Plastic Pyrolysis Challenges

There are scenarios when chemical recycling is not preferred. Mechanical recycling is the preferred method for polyethylene terephthalate in all cases which is used to produce packaging materials and plastic water bottles. It must be considered that the products from the process might not be easily utilized as the feedstock for a new high-quality product. Depending on the type of polymer input into the process, some of the liquid products might not be useful for plastic production- however, other applications are still possible.

Different process designs are possible for the process. Challenges arise from either batch or a continuous process. Continuous processes pose challenges because the char that is produced needs to be removed from the equipment so that there is no build up. Agilyx has patented a system for utilizing two screws simultaneously in their extruder to self-clean so that the continuous process may proceed.

Pyrolysis is a challenging process to make commercially feasible because it is so complicated. The process can only survive if it is considered profitable which can take years of technological developments with the necessary funding and investments. Models have been created to extensively analyze the profitability of pyrolysis plants.

4.4 Current Successful Pyrolysis Plants Globally

There are multiple major pyrolysis technology vendors across the United States. Agilyx is a company in Portland, Oregon which could utilize commingled plastics 1-7 as feedstock for their process and convert it to synthetic crude oil. It must be noted that their process has changed from plastic to oil technologies to polystyrene to styrene monomers due to the decrease in oil prices. Their previous technologies became unprofitable when their pyrolytic oil price was compared to crude oil prices in 2015. Their daily production rate had a conversion of 10 tons of plastic to 60 barrels of oil through pyrolysis. The process had a high efficiency from the process being able to handle any type of plastic feedstock and contamination level. Their process was able to be scaled up or down depending on the feedstock. Agilyx's crude oil was refined into ASTM-spec products including ultra-low sulfur diesel. Light gases such as methane, propane, and butane were extracted from their system as waste material because they don't condense and are treated by an Environmental

Control Device (American Chemistry Council, 2012). The company had a competitive advantage because they already had a customer base which is essential for the success of a conversion technology company. Agilyx is currently successful now that the company has opened their new process due to the donated Styrofoam from the Portland area and their committed customers.

Envion is a company in Derwood, Maryland that converts plastic waste into oil with a ton of plastic converting to 3-5 barrels of petroleum through pyrolysis. Their process can be scaled up or down through the addition or elimination of reactors. For the functionality of their process, plastics must be grinded down to 1.5 inches with a processing rate of 1.22 tons of raw feedstock per hour. Polystyrene, high density polyethylene, low density polyethylene, and polypropylene are the preferred feedstock since they produce the best oil yield. Crude oil exits as an oil gas and separates into three streams: process gas stream, product oil stream, and water stream. Envion utilizes their gas stream for electrical generation. The final oil products can vary depending on the customer preference, some of their products are kerosene, jet fuel, and gasoline fuels which have a large market base (American Chemistry Council, 2012).

Global Climax Energy, a pyrolysis company in Georgia produces high quality synthetic oil and wax from plastic waste. The process' feedstock is mixed and post-consumer plastics. Their process has byproducts of light gases of C1-C4 with a process efficiency of 75% and no external fuel needed to facilitate the operation. Global Climax Energy receives their feedstock from municipalities and companies within a 50-mile radius. The company processes about 20 tons of plastic feedstock a day (American Chemistry Council, 2012).

JBFI, a plastic to oil company in Niagara Falls, New York converts mixed, non-recycled plastic waste to diesel, gasoline, and light-fraction gases. The company has been operating commercially since 2010 and runs on a continuous process converting up to 20 tons of plastic per day. JBFI's recovery efficiency is 92% with a ton of plastic producing 1734 pounds of gasoline and diesel (American Chemistry Council, 2012).

Renewlogy, a company founded by Priyanka Bakaya, converts plastic into crude oil which can be sold to refineries. The process is able to convert 10 tons of plastic per day into 60 barrels of oil with zero toxic emissions. A barrel is produced at \$35 and sold to a refinery for \$100. The goal of her company is to end landfilling of plastic by creating a cost-effective system that breaks down nonrecycled plastics into oil while reusing the gas product to fuel the operation. The company would like to work towards ending landfilled plastics domestically and globally and also produce sufficient oil so there is no need for oil refineries. Plastic-to-oil concepts are not new, however in the past they have been too energy inefficient. Renewlogy is efficient because of its innovative design and continuous operation since batch processing wastes money and energy (Matheson, 2014).

Vivex Engineering is an environmental consulting firm in the United Kingdom that converts all polymer wastes into crude oil and carbon black through pyrolysis. Alucha, a recycling company based in Barcelona Spain utilizes pyrolysis to transform mixed plastic and other waste into natural resources including oil and minerals which also limits the

amount of waste going to landfills or through incineration. Alucha's mission is to establish smaller treatment centers next to waste feedstocks so as to eliminate its need for transportation which minimizes greenhouse gas emissions. Enval Limited is a company from Cambridge, United Kingdom that specializes in pyrolysis for plastic aluminum laminates which is technically challenging to recycle. Enval processes 2,000 tons of this specific waste per year and redirects the aluminum and hydrocarbon products for other purposes. Pyrocrat Systems LLP is a company in India that works to establish plastic to oil facilities and pyrolysis plants throughout the country with a pyrolysis oil output of 50-90% and carbon black at 3-25%.

Chapter 5. Environmental Policies

It is well researched and understood that plastic production and disposal creates environmental hazards from their fossil fuel feed source, emissions from production and incineration, and inability to degrade and be removed from the environment. Environmental policies must be put into place to ensure that alternative recycling methods are implemented to reduce the amount of plastic waste that is sent to landfills, pollutes the ocean, or is incinerated.

Commercializing new technologies requires solving challenging technical and organizational problems including new technology proposals, a need for vendors, mergers and acquisitions, and strong waste management systems that can implement the new methods. Barriers for emerging conversion technologies in North America include legislation and regulatory challenges such as permits for solid waste handling, water quality, air quality, and local or county planning. Without these permits, the implementation of these new plants cannot happen. In addition, before a plant can be built, the market must be developed to ensure a feedstock so the system can be optimized at a set flowrate. In order for the process to be financially feasible, clients for the oil and gas products must be guaranteed which can be difficult to ensure when the price of a barrel of virgin oil is low (American Chemistry Council, 2012).

Some governments around the world use policies to encourage post-consumer recycling which extends the producer responsibility. Many countries globally are working to find solutions to plastic waste related problems. China may be the world's largest greenhouse gas emitter, but they are also the largest investors in renewable energy. China has recently changed its policies and will no longer be the world's dumping ground. From the China National Sword Initiative, more than 70% of the world's plastic waste goes to China and now must be diverted elsewhere. They have strengthened their "green fencing" regulations to restrict types of plastic waste materials they won't accept. Their new regulations prevent hazardous materials from ending up in their landfills and have "turned the global recycling industry on its head" ("Plastic Recycling Processes in Industrialized Nations", n.d.).

Europe is increasing their strict regulatory policies which are creating incentive for higher plastic recycling rates. In 2012, plastic recycling and energy recovery reached 61.9% and 26.3% respectively in Europe ("Plastic Recycling Processes in Industrialized Nations", n.d.). There is still a discrepancy within the European countries; some have introduced landfill bans for plastic waste while others still landfill more than 60% of their plastic waste and some European nations still rely entirely on landfills for the disposal of their plastic waste. PlasticsEurope is advocating to implement a ban on landfilling high-calorific plastic waste by 2020 would prevent 10 million metric tons from going to the landfill each year in the UK, Italy, Spain, France, and Poland ("Plastic Recycling Processes in Industrialized Nations", n.d.). The European Union established a policy that requires all plastic packaging within the EU market to be recyclable by the year 2030 which will make plastic recycling profitable for businesses and increase technological investments within plastic recycling. Laws must be passed to stimulate higher quality recycling to utilize the full hydrocarbon potential.

In September 2015 a defining moment in history came when the international community came together to solve immense world problems at the World Economic Forum. This resolution comes at an imperative time since plastic usage is predicted to double in the next 20 years (American Chemistry Council, 2016). All 193 United Nations countries decided to take steps towards a better future. The countries decided they would like to foster cross-industry collaboration that increases standards of living while reducing demands for finite raw materials. Cross-industry collaboration is essential to increasing recycling rates since plastic usage is so widespread across all industries. The UN hopes to create a New Plastics Economy which will transform this influential sector of the world economy while helping the environment. The plastic industry can be changed to resolve multiple problems that plastic brings.

Currently, there is no legislation requiring companies to include recycled plastics in their recycling processes. If the right legislation is implemented within the waste management infrastructure, a closed-loop approach for plastics would be feasible reducing the need for virgin resin ("Tackling Complex Plastic Recycling Challenges", 2015). Implementation of manufacturing policies to promote standard environmental design principles will be able to increase the amounts of items that can be recycled. Advancements in sorting and separation with a recycling plant will allow a plant to produce higher recycling volumes (Hopewell et al., 2009).

Many big companies and industries are becoming more sustainably inclined. Coca-Cola committed to using 25% recycled plastic in its products by 2015 and Walmart planned to utilize 3 billion pounds of recycled plastic in its packaging ("In The Bin", 2015). However, these companies are challenged to meet their goals considering the supply of recycled plastic is so limited. Recycled materials should be more inexpensive than virgin materials, however, the US disposes of the majority of their waste making it hard to create sufficient recycled materials which altered environmental regulations could improve. Walmart, Coca-Cola, and eight other large companies have invested in the recycling structure by creating a \$100 million Closed Loop Fund which provides loans to cities to improve their recycling systems from collection to sorting. The cities are able to repay the loans from the earnings they make from diverting their waste from landfills and incineration. Intel, Eaton, and Texas Instruments, who are among the highest corporate polluters have made efforts to meet environmental commitments. They each recycle more than 85% of their waste; have received environmental certifications for their efforts; and have created environmental management systems through objectives, targets, trainings, and performance records. Intel has also set goals of reaching 0% landfilling for hazardous waste and 90% recycling of non-hazardous waste by 2020 (Cortina, 2018).

Chapter 6. Potential for Plastic Pyrolysis Markets and Economic Feasibility

The European Commission estimated that only 5% of the value of plastic material is retained within the economy considering the high single-use rates and low recycling rates ("First-ever Europe-wide strategy on plastics", 2018). The plastic market has huge potential that is not being utilized globally since the majority of its material is disposed of after a single use. The hydrocarbons used to create plastics store valuable energy that can be regained from recovering and recycling.

There are two key economic factors that influence the viability of plastic recycling. One driver is the price of the recycled polymer compared to the virgin polymer. Prices for virgin plastic are influenced by the price of oil which affects the feedstock for plastic production. If the price of the virgin plastic is significantly cheaper, most companies won't pay more even to select a more sustainable recycled plastic. However, some countries that rely on crude oil imports have begun to implement plastic to oil processes which has increased sales of plastic to oil systems globally. The second economic driver is the cost of recycling compared to alternative forms of acceptable disposal. Primary methods of disposal have been landfilling or incineration which can be costly and vary by country. High disposal costs to landfills or incineration would create an economic incentive for companies to switch to recycling or energy recovery.

The primary driver for the development of waste conversion technologies include alternate disposal methods, waste goals and targets, and developing alternate energy sources. Along with being more sustainable, recycling advancements can also improve the economy by raising the quality of recycled resin because of its broader applications and viability (Hopewell et al., 2009). It is expected that conversion technologies will reach commercial viability by 2017-2022 (American Chemistry Council, 2012). Environmental reviews of waste conversion technologies have found significant environmental benefits in energy savings and greenhouse gas emission reductions when compared to landfill disposal. Research found that pyrolysis of plastic waste saves 1.8-3.6 MMBTU and 0.15-0.25 TCE emissions per ton when compared to landfill disposal (American Chemistry Council, 2012).

From an analysis by the American Chemistry Council, in 2012, there were 86 waste-to-energy facilities in the United States. The two conversion technologies utilized were pyrolysis and gasification. Pyrolysis was suited to handle feedstock from waste plastics and gasification is preferred for accepting municipal solid waste. Waste conversion technologies are capable of fuel products at lower costs than landfill disposition. It costs \$50 to process a ton of waste through pyrolysis or gasification and \$35-75 per ton for land disposal and recycling (American Chemistry Council, 2012).

Plastic pyrolysis is the largest technology segment of the global recycled plastic and plastic waste to oil markets, in 2014 pyrolysis reached more than 50% of the global share ("Recycled Plastic and Plastic Waste to Oil Market", 2016). Pyrolysis dominates due to its

lower capital expenditure than gasification or catalytic depolymerization processes. In 2014, the global recycled plastic and plastic to oil market had reached a value of \$542.8 million. MarketWatch predicts that the plastic to oil market could reach \$1.9 billion by 2024. The compound annual growth rate is expected to expand by a rate of 12.6% between 2016 and 2024 ("Recycled Plastic and Plastic Waste to Oil Market", 2016). Companies should invest in pyrolysis as a plastic to oil technology considering its predicted potential.

The American Chemistry Council performed research to quantify the direct effects of private investment in plastics to oil facilities in the US. They found from an analysis of publicly available data that the US could support 600 plastic to oil facilities which would provide 38,900 jobs, \$6.6 billion in capital investment by the industry to build new facilities, \$8.9 billion in US economic output from the plastic to oil operations. These new facilities would also eliminate the landfilling of 6.5 million tons of non-recycled plastic each year (American Chemistry Council, 2014). Investment in plastic to oil technologies is critical because they lead to sustainable development, create jobs, and contribute billions of dollars to the economy, while reducing negative environmental impacts.

Chapter 7. Implementing Plastic Pyrolysis Infrastructure in Chile

7.1 Waste Management Systems in Developing Countries

Municipal solid waste is a huge problem for developed and developing countries. It is important to maintain a municipal waste management system because it directly relates to the citizens quality of life and indirectly improves other government responsibilities including health care, public education, and subsidies for water and electricity consumption. A large problem for waste management comes from the legal responsibility of governments to maintain a clean city while managing their municipal solid waste which can be expensive. Developed countries are able to manage and improve their waste management infrastructures easier than developing countries. However, developed countries face greater challenges and need economic sustainability valuation to find alternative methods to recycling of municipal solid waste (Vasquez et al., 2014).

Globally, the concern for the environment has been growing which has created a strong movement in developing countries to reduce their volume of waste as well. They are able to follow developed country examples who have shown positive developments in their waste management systems to begin making changes. All countries share the common problem of landfill's negative environmental effects from leaching and polluting groundwater and releasing carbon dioxide and methane emissions when the waste breaks down. Globally, all remaining landfill space is limited forcing alternate plastic waste routes everywhere.

Waste tends to do the most damage to the people who are the most economically or socially marginalized who also happen to produce the least waste since they have the lowest consumption rates. Developed countries who are the source of the issue are obligated to work towards a solution. It is agreed upon globally that improvements to waste management systems need to be made but as to how varies. It is still being debated how governments should manage the imbalances of development and the effects of these advancements on people of all societal levels. Most countries don't have formal waste recycling systems in place, instead, waste pickers retrieve reusable materials and resell them. In developing countries plastic trash has become a form of currency from people collecting plastic waste and selling it to manufacturers. If value is added to the plastics they are less likely to end up in landfills or waterways because people will see the value and need to collect plastic items. Not only does this benefit the environment, but it also helps the poor gain a source of income. The global recycling industry employs more people on this planet than almost any other industry, it is only second to agriculture. National governments should utilize this population to assist in resolving the municipal solid waste management problem. These workers would be able to provide a sustainable solution to the immense problem that affects 3 billion people who lack access to waste services by resolving the sanitation crisis (Navarrette-Hernandez, 2018). Additionally, a reliable feedstock for alternative recycling methods would be found. In Latin America, the solid waste management system has a labor-intensive system, it is made up of workers which makes recycling an important social component. Latin America should upgrade waste

management and industrial recycling systems while also formalizing and integrating the "informal" recycling sector to improve collection services and recycling rates.

"Many international projects aiming to change the waste management situation in developing countries have failed in the past due to a lack of knowledge and understanding of the context where they were intended to be implemented. This problem led to select waste systems and treatment techniques that were not suitable for the situation in these countries" (Bracamonte & Valiente, 2006). Before implementation of new waste management techniques are employed, the developing country waste management system, government, and recycling potential should be analyzed to ensure its success. It must be considered that each developing country requires a unique solution to each drastically different waste management situation. Developing countries have additional challenges to resolve their waste management issues including technical, financial, institutional, economic, and social constraints. Varying problems could involve poorly maintained or out of date equipment that doesn't fit local conditions; financial problems caused by instabilities and imbalances between income and rising costs; and social problems which only create further challenges to resolving their waste management problems. These countries are in need of technical expertise with sufficient knowledge and experience to work on the issue as well as environmental awareness among the citizens. Limited funds are provided for developing waste management systems because the need is not prioritized making solutions harder to reach. Developing countries lack proper legislation to implement new waste management policies. With a weak economic base, these countries struggle to maintain and develop their waste management methods. Large corporations and financially stable governments should help finance the technological advancements for their waste management infrastructure since a large portion of the waste reaching their country came from developed countries.

7.2 General Overview of Chile

Chile is a long narrow country with a lengthy coastline of 2,600 miles and an average width of 110 miles. Official demographics show about 40% of the country's 17.9 million people to live in Santiago, the capital. The country is filled with natural wonders from Torres del Paine, the Atacama Desert, Easter Island, and Patagonia. The current president, Sebastián Piñera recently took office in March 2018 ending President Michelle Bachelet's term. Since the fall of the Pinochet dictatorship in Chile in 1990 and the transition to a democracy, the country has experienced strong economic developments. They have had the highest national growth rate out of all of Latin America reaching 5.1% in 2007 (Amovic & Johansson, 2009). With this significant growth, Chile could be a leader in South America by being the first to take these groundbreaking steps towards alternative means to manage waste considering its financial and economic stability. The country also has a considerably low unemployment rate of 7% from 2017 whereas Venezuela and Brazil have rates of 26% and 13% respectively. In January 2018 Chile had 14.1% of the population below poverty lines which is comparatively lower than the Latin America average of 31% (Amovic &

Johansson, 2009). However, with this increase in standard of living comes an increase in waste creating which increases the need for strong waste management programs.

After more than a century of developments to transform the country, in 2010 Chile became the first country in Latin America to join the Organization for Economic Cooperation and Development (Larroquet, 2013). All of South America is transitioning to the developed world, Chile has been a leader in economic growth. Chilean President Sebastián Piñera implemented important economic, social, and industrial reforms that initiated Chile's path to economic and social progress. These reforms are based on economic models that focus on the power and potential of the private sector. This economic model also boosts entrepreneurship, competition, trade, investment, and savings. A social policy that the president worked towards focuses on the impoverished people and developing services for them including waste management. Chile has the workforce potential of people in the lower class to collect the waste items and bring them to larger recycling establishments for pay which would encourage higher recycling rates and improve its social stigma and also lower poverty and unemployment rates. The Chilean government should protect these waste pickers through formal regulations to ensure that recycling companies continue to obtain feedstock to produce new materials.

However, despite the numerous efforts that Chilean presidents and politicians have put in to develop the country, there are several obstacles based on their geography. Chile has had additional struggles to maintain their economic and social growth after the damages created by the February 2010 earthquake and tsunami. The 2010 tsunami was the 6th strongest recorded earthquake in history and caused damage to more than 50 cities and 900 towns which house 75% of the country's population. The damages caused an estimated loss of \$40 billion which is equivalent to 18% of the country's gross domestic product which has prioritized their government spending. However, in the last 30 years Chile has been able to progress based off their economic freedom, public policies, and rule of law. In 1980, Chile had the seventh highest per capita income in Latin America whereas now it is the highest in the region (Larroquet, 2013). South America may not be thought of as a high waste producing continent, however, they produce about 16% of the worlds solid wastes which totals at over 120 million tons per year and needs to be managed (Taylor, n.d.). Chile has shown a significant increase in development based on decreased poverty rates and unemployment rates which should help Chile focus on its waste management infrastructure.

7.3 Recycling in Chile

Significant environmental movements could not occur in Chile until after the Pinochet's dictatorship ended, however, progress was eventually made. Currently, Chilean Officials are concerned and committed to making environmental changes because Santiago has tested as one of the most polluted cities in the world by the United Nations World Health Organization. In 2004 their air quality tested 75% above the allowed standards. The high pollution rates are estimated to cause 1000 deaths per year (Amovic & Johansson, 2009).

Possible solutions could begin with Chile forcing industries to follow specific laws that meet strict emission requirements. With implementation of environmental policies, educational programs should be established to educate Chilean citizens on the importance of recycling.

Information provided by Chile's National Commission for the Natural Environment shows that the Santiago Metropolitan Region generates close to seven million tons of waste per year. It was estimated that this amount will increase by about 3.5 million tons per year. About 60% of municipal solid waste goes to landfills, 95% of them located in Santiago. Problems have arisen in Santiago regarding the excessive landfill usage creating socio-political, environmental, and land scarcity problems. Due to its geographical location, Santiago is highly concerned with their land usage because of its limitations between the Andes Mountain Range and the Coastal Mountains. Chile's surface measures only 15,400 square kilometers which is the smallest in the world and the highest population at 6 million inhabitants making it the highest population density (Bracamonte & Valiente, 2006). Considering the huge population and minimal land space, it is expected that the landfills will have reached capacity and improvement on Chile's waste management system needs to be prioritized. Alternative routes of plastic after its useful life cycle need to be considered.

In Santiago waste-pickers account for 70% of the waste that is recycled in the municipality and play a vital role in the infrastructure. In Santiago it is estimated that there are 6000 waste-pickers working for both cooperatives and independently who collect materials for recycling and sell the items to a middleman who will sell it as raw material for local industries. The Chilean Government estimates that one waste picker has the potential to 2-15 tons of recyclables per month. Globally, their work removes 810 tons of waste from landfills every day. Waste-picking is detrimental to sustainable development, it increases the amount of waste collected, reused, and recycled; prevents pollution; extends the useful life of landfills; and provides jobs for more than 15 million poor people in developing countries. Waste-pickers should remain a part of the waste management system even as the infrastructure improves because their role resolves societal problems along with environmental issues (Navarrete-Hernandez, 2018). The Global Alliance of Waste Pickers held their 5th Chilean Waste Picker's Conference in 2018. They have stated that they perform more than 60% of the country's recycling. In order for their work to be more efficient they believe that the government needs to put a higher focus on new laws, education, and incentive to recycle materials and see the potential value that waste contains.

Chile has made progress with their waste management system, in 1994, an environmental law was implemented that was socially and economically viable that encourages environmental sustainability, producer responsibility, and the development of the most efficient technology. It became the municipalities' responsibility to collect, transport, and eliminate all municipal waste. Since the creation of the Extended Producer Responsibility Law, producers must manage their product after its useful life, however, few companies complete this requirement. Producers are considered organizations that introduce priority products into the Chilean market for the first time. They must create a legal entity whose

sole purpose is managing their waste who would work with municipalities and waste management firms.

Through research and evaluation of the amount of municipal solid waste separated voluntarily and the cost to be a part of the recycling program, Santiago was determined to have favorable conditions for the implementation of an alternative recycling program (Vasquez, Alvarez, & Pincheira, 2014). Economic analyses of systems are critical because recycling programs might not be always be viable for that district. Factors that are deemed important are the estimated demands for recycling services, the inhabitant's willingness to pay for the service, and how the municipality's funds for the infrastructure can be optimized. Implementing new recycling programs is a complex problem that requires engineers, economists, psychologies, and municipal representatives to evaluate the valuation of a recycling program.

Santiago utilizes 10% of its budget towards municipal solid waste (Amovic & Johnsson, 2009). With their budget it is essential that the city maintains and optimizes short term and long-term goals to successfully make changes. From a short-term perspective, the city must maintain their collection and transport methods and long-term goals need to consider reducing municipal solid waste generation by changing consumer patterns and increasing recycling awareness. Through their research, over 50% of the Chilean population has a positive attitude towards separating municipal solid waste and 90% identified recycling as the solution to the system. However, a problem Chile faces is that only 5% of their citizens recycle and 26.9% of the population doesn't even know where to take their materials to be recycled ("The App to Catalyze Next-Generation Recycling in Chile", 2017). Data shows that the citizens do care about improving the environment through the recycling, they just need the education on an improved waste management system to recycle their household waste.

Official seminars in Chile with the assistance of Sweden determined the top priorities needed for the country's development and determined the needs to be the development of a system for sustainable waste management which needs to include material recycling and energy recovery. Studies found that a 100MW waste to energy plant will not only reduce greenhouse gas emissions, but the plant will also be economically profitable. Greenhouse gases could be reduced yearly by 196, 935 tons carbon dioxide equivalents (Amovic & Johnsson, 2009). The specific goals for this waste to energy plant will reduce the amount of plastic going to landfills, generate a new energy source, and reduce the amount of emissions contributing to the greenhouse effect.

There are companies working on improving the waste management system. Comberplast, a Chilean plastic recycling company is working towards creating a circular economy through utilizing the country's plastic waste as feedstock for new products. Comberplast works on an industrial scale and accepts large manufacturing company's waste and recycles their waste into supplies that can be sold back to the firm for a cheaper price. The company also works with retailers such as Sodimac, a home improvement store, to collect plastic waste items that can earn store customers "clean points." Historically, Chile's remote

location and long shape of the country have posed challenges making the transport of waste a challenge. An additional problem is that the majority of the focus on improving the waste management infrastructure has been on Santiago. Focus should be put on establishing local recycling centers to eliminate the emissions of transportation.

7.4 Policies in Chile

Sustainable waste management is a significant challenge financially and administratively for developing countries with both formal and informal methods of collection utilized. There are government policies regarding waste-pickers that can be considered for a municipality to integrate the informal sector with the formal. Policy creation and the legalization of waste-picking brings challenges with equitable distribution of benefits to the waste pickers by investing in their material progress, technical upgrades to their work, and building the capabilities of their associations (Navarrete-Hernandez, 2018). Fortunately, Chile has the Global Alliance of Waste Pickers which supports the laborers and their rights. Implementation of new policies that support both the informal and formal sector will help improve the Chilean waste management system.

In 1980, Article 19 was created in the Constitutional Organic Law of Municipalities within the Chilean Constitution that enforces that right of its citizens to live in a pollution-free environment. By 1994, the Framework Environmental Law was created to establish controlled landfill usage for waste disposal. Improvements were made to the waste management system, in 2005 the Integrated Waste Management Policy was approved with the objectives of minimizing health effects from improper waste management, improving environmental education programs, and increasing recycling program participation rates. In 2010, Chile legalized the National Movement of Recyclers organization which works to protect waste pickers while changing society's negative image perception of waste collectors. Chile has made progress in establishing laws and policies that promote recycling, although, improvements are still needed.

Strong local policies need to be made which need a deep understanding of the local infrastructure in Santiago. The citizens must also be willing to collaborate with the waste-pickers and provide them collection items, this system cannot work if Chileans do not provide their plastic waste to the waste pickers who provide the feedstock to recycling companies. The city has made policies that relate to waste-pickers involving economic efficiency, individual productivity, the impact on local industry, poverty reduction, energy saving and prevention of waste entering landfills and negative externalities including their physical health, child labor, waste dispersion, and working conditions. These policies must work towards coordination and collaboration with the waste pickers and waste truck pick-ups and schedules with the promotion of household waste separation prior to collection. Positive local government involvement will help to integrate a sustainable waste management system in developing countries (Navarrete-Hernandez, 2018).

President Bachelet of Chile enacted the Recycling and Extended Producer Liability Law in May 2016. Chile is the first country in Latin America to adopt this type of legislation which shows Chile to be a country that is ready to initiate sustainable change and lead other countries to do the same. The legislation requires producers and importers to take responsibility for their products at the end of their useful life. The plastic items they produced must be returned to the industries where they were manufactured or warehouses where they were distributed. She said "it is everyone's responsibility to protect the environment, fight climate change, and protect ourselves against its most critical harmful effects, because they threaten our future and that of future generations" (Government of Chile, 2016). Meeting these recycling goals will fall on companies and citizens, individual responsibility from individual households to corporations and the government. This regulation will increase the country's reuse rates which are currently at 10% thus reducing the amount of waste sent to landfill and promote cultural change regarding waste and its life cycle. Her goal is that not only will this policy reduce pollution but will also stimulate the economy and promote environmental education. The ministry will be responsible for implementing and managing a registry system, reviewing and authorizing management plans, designing and implementing educational programs, and the implementation of environmental penalties (Government of Chile, 2016).

7.5 Technology Implementation in Chile

In order for the implementation of a new technology strategy like plastic pyrolysis to be successful, each process at all operation levels must be well managed. There are five generic processes to technology process management frameworks including the identification of technologies important to the business, the selection of technologies that should be supported by the organization, the acquisition and assimilation of selected technologies, the exploitation of technologies to generate profit, and the protection of knowledge and expertise embedded in products and manufacturing systems. These categories are related to innovation and development processes for new products. Three levels within an organization must be considered for implementation of new technologies including the corporate level, business, and operational (Phaal, 2001). Current Chilean companies working to scale-up their plastic to oil technologies must collaborate with current industries to ensure their technology can survive in the economy. It is essential that all components of the business structure collaborate.

For implementation of new technologies and methods, there are a couple stages that must be analyzed including benchmarking, a business environment analysis, and an economic analysis. Chile has utilized the current waste management infrastructure in Sweden as an example and has analyzed how their methods could be implemented in Santiago, the capital. The municipal solid waste problem in Chile has considered Sweden's success in handling waste because of their environmental strategies, cutting edge environmentally friendly technology, and their advanced treatment of solid waste. The benchmarking procedure includes waste policies and strategies, waste responsibility, civilian

participation, government roles, commitment to waste management research, collection and transportation, waste composition and amount, and waste treatment. The business environment analysis stages show business factors that positively affect its implementation including investors providing financial support and the encouragement of renewable energy due to the increasing prices of energy. The economic analysis considers the feasibility of the waste management solution and the inflows and outflows of the project and economic requirements.

Through environmental policies, the Swedish government was able to reduce the amount of hazardous waste in landfills through the promotion of material recycling and energy recovery from waste which is something Chile would like to emulate. In 2005, the two countries created the Partnership Fund Chile-Sweden which organizes the experience and transfer of technology and experience between small and medium companies. This type of mentorship and guidance should help Chile implement new waste management strategies and successfully maintain them.

Sweden's technological advancements and environmental policies have led to an increase in recycling. Recycling waste materials is beneficial because it reduces the demand for raw materials, protects habitats, reduces pollution and the amount of waste associated with the extraction of raw materials, leads to lower transportation costs and pollution from new products, saves energy in the production process when compared to energy consumed from using raw materials, reduces emissions from the production process, and reduces landfill additions. It will be challenging to implement a new waste management system in Santiago's current waste management infrastructure because previously the only method was landfilling. Specific concerns Chile and Sweden have worked on are waste policy and strategy, waste responsibility, waste economy, civilian participation, role of the government, commitment to waste management research, collection and transport, waste composition, and waste treatment. Sweden recognized that waste is a resource that must be utilized which gives Chile multiple options for routes of their post-consumer waste for high-quality applications (Bracamonte & Valiente, 2006).

An additional challenge Chile has faced while following the Swedish model of municipal solid waste management is the ease of civilian participation. People still lack the basic knowledge and understanding of what their reduction of waste and proper disposal could do to improve the countries waste management system whereas in Sweden the general population prioritizes protecting the environment. The Swedish Government promotes the development of new waste technologies that implement sustainable methods with high national targets and strong policies to produce positive results. Economic means of control is how the Swedish Government directs the Swedish waste management towards their environmental goals. In contrast, the Chilean Government has created national and regional environmental regulations that give Chilean officials the ability to improve the waste handling. Their method lacks specific regulations that resolve the problems with waste management. A reason for the failure is that the Government lacks a global vision that would handle all components of the municipal solid waste management.

However, Chile has developed a positive and welcoming environment for foreign and domestic technology entrepreneurs in Chile. The government of Chile created the Start-Up Chile program which works to establish Chile as a new technology hub and change's the Chilean society's view on entrepreneurship. Chile was the first of its kind to create a program like this in the world and has inspired 50 similar programs globally. The Chilean government created a new technology visa that is now obtainable within 15 days of application setting Chile up to soon be a country leading the technology industry (Legros, 2018). Start-Up Chile has invested more than \$40 million into the entrepreneurship programs in Chile which new recycling technologies should consider. This innovative organization will attract talent from all over the world who should have the capabilities to resolve Chile's waste management problems.

7.6 Work at Unit of Technological Development (UDT)

The Unit of Technological Development (UDT) is a research and development firm in Concepcion, Chile, the second largest city. The city is situated 310 miles South from the capital Santiago on the Pacific Ocean with a population of 230,000. The company has projects in biomaterials, bioenergy, bioproducts, environmental services, and technology management. There are not many other companies in South America that are making the same progress as UDT.

Kylee Mockler Martens had an internship at UDT in summer 2017 funded by the National Science Foundation through the University of Maine's Research Experience for Undergraduates Forestry Bioproducts Research Institute program. She worked on the bench-scale plastic pyrolysis plant with the objective of creating a piping and instrumentation diagram for the process while learning to understand and operate the system. The team was testing pure plastic feedstocks to create a product through pyrolysis that would meet the industrial standards for various uses. Their solid wax products obtained from polyolefins have similar performance to materials used to make wood panels water resistant. The lighter hydrocarbons products are comparable to diesel fuel.

The team is currently evaluating the results from different plastic feedstocks, mixtures, and the effects of residues in post-consumed plastics. Their feedstock supply comes from donations made by the community. The drawings were utilized to scale-up the process from bench-scale to industrial scale to test its techno-economic feasibility. Eventually, the team hopes to transfer their knowledge on the process to industries in Chile to become the first full-scale plastic pyrolysis process in South America. This would create significant progress towards a more sustainable waste management system in Chile. UDT predicts their process to be successful and particularly necessary after the new Law of Recycling Promotion and Extended Producer Responsibility was implemented. Manufacturers around the country must now look to innovative solutions to handle their waste, investing in UDT's project will help resolve their waste disposal issues. The company also predicts a growing need for hydrophobic waxes and industrial liquid fuel ensuring success when they reach industrial scale.

7.7 Feasibility of Plastic to Oil Technologies in Chile

In order for these technologies to be successfully implemented the company in charge of the process must be able to conform and adapt their technology to fit the local community and needs. These processes need scalability since a common problem is obtaining sufficient feedstock for the process. The plastic to oil facility should be established directly next to the waste feedstock for convenience and also to eliminate unsustainable transportation methods. Feasibility studies for the implementation of the technology in Chile need to consider operating costs, labor costs, production costs, and the pricing of the product in Chile. The feasibility of the process is different in various parts of the world based on salaries, building costs, utilities, and gas prices. Global trends show the price of crude oil increasing daily and consistently meaning that at this rate, pyrolytic oil will soon be preferable financially over virgin oil.

A detailed feasibility study performed by Mr. Kevin DeWhitt, the founder of PDO Technologies, was able to find that the implementation of a plastic to oil conversion technology similar to PDO Technologies' in Chile as feasible. The detailed analysis considered current costs of oil; labor costs for engineers and operators; building fees; and more for Chile specifically. This hypothetical model is based on the successful and profitable process that PDO Technologies utilizes for a batch plastic to oil process from high density polyethylene. The model assesses the implementation for sets of four reactors with a cycle time of 6.5 hours. Based on the plastic to oil facility in the U.S., the batch size would be 1600 lbs with a yield of 80% liquid and 7% solids. If the process is similar to PDOs product, the liquid product, crude oil will be rated as 50° from American Petroleum Institute with a density of 6.5 lbs/gal. A 50° petroleum is preferable because of its high conversion ability to gasoline. Annual project labor cost assumptions based on Chilean pay scales utilize \$183,683 for payroll which factors in costs for shift supervisors, operators, and technicians. Feedstock acquisition costs are free because of the provided donations. The model considers annual operating costs for Chile including electrical costs, building costs, annual insurance, and corporate tax rates. This hypothetical model estimates the total project costs to be \$2,447,500 annually. The PDO Technologies model based on Chilean expense rates is able to produce diesel at a value of \$2.21 per gallon based on a liquid product production of 903,965 gallons per year for this hypothetical facility. Compared to diesel sale prices in Chile at \$3.49 per gallon, a facility following the PDO Technology model would have a revenue of \$1.28 per gallon. In summary of this model, based on Chilean energy and material costs and salaries, a plastic to oil facility producing diesel would be feasible.

7.8 Future of Plastic Recycling in Chile

Chile has minimal fossil fuel supply of their own creating significant supply instability. Currently, the majority of the petroleum used in Chile is imported from Argentina, Brazil, Nigeria, and Angola meaning alternative sources of fuel should be considered (Amovic & Johansson, 2009). If Chile were to invest in plastic to oil facilities, there would no longer be a need to import their oil resources. Chile is such an isolated country geographically that plastic to oil conversion technologies would be more sustainable from the elimination of

importations. With the help of Start-Up Chile, new plastic recycling technologies should be able to develop. If plastic to oil technologies popularize, they have the potential to change the way plastic is managed globally.

Chile has a goal of 60% clean energy by 2025 through harnessing the solar power from the Atacama Desert, an infinite fuel source (Elena, n.d). Chile is considered the poster child of renewable energy with its massive solar and wind resources. With the future of energy recovery from pyrolysis this goal can be reached. The country has set goals for increasing their sustainability which confirms their desire to improve other industries including plastic recycling. In 2017, Chile became the first American country to ban the distribution of plastic bags from all coastal cities in the country which is effective considering the majority of Chile is coastline.

In addition to the government making official regulations to encourage recycling, individual groups have begun to work to make change as well. Reciclapp, an innovative app in Chile helps improve the country's currently low recycling rate by providing citizens with an Uber-like experience where they can select the type of waste they have and it'll be collected and recycled properly. Currently, Reciclapp can be used in Santiago, Valparaiso, and Antofagasta with hopes of expansion to other parts of the country soon. The goal for the app is to not only increase Chile's recycling rate but to also improve the waste pickers collection process which is essential considering the high impact waste pickers have on the waste management system. The used plastics and other items can be sold to large companies who need these items for their feedstock. Educating the Chileans is a long, slow process; however, it can be done through creative methods such as Reciclapp.

Chile has optimum conditions to reeducate their citizens to be more sustainable with their consumer choices. Since Chile has the highest rate of population in the middle class in Latin America, they are well equipped to improve education on sustainability programs. Since Chile has had such an increase in living standards and domestic spending on products, it is even more important now that Chile recycles. The Guardian, a U.S. newspaper found in a survey that Chile is the most environmentally aware country in Latin America. Chile was selected as one of three countries to test a new Education for Sustainable Consumption Program, an initiative led by The Marrakech Process which assists countries in developing their green economies, incorporate green business models, and encourage consumers to alter their consumer choices to be more sustainable. Specific areas that can be focused include reducing their waste and recycling the plastic waste they do accumulate. Chile has been selected as a test city for this program because it was recognized for its awareness on sustainability issues. Changing educational programs is challenging, however, Chile is working to organize the citizens, government, and infrastructure so that positive changes can be made for educational programs. Fundacion Casa de la Paz, Foundation House of Peace, is currently working in Chile to increase environmental awareness and develop informal sustainability education programs. If positive developments occur in Chile from the implementation of the new programs, these programs will be emulated across Latin America.

Chapter 8. Conclusion

Since China has established their Chinese National Sword Initiative, cities, countries and governments are trying to make improvements continually. Environmental awareness is increasing globally, different solutions are being implemented to manage accumulated waste. Europe produced on average 25 million metric tons of post-consumer waste from 2006-2012 and is the global leader in recycling and diverting plastic waste from going to landfills through waste-to-energy programs ("Plastic Recycling Processes in Industrialized Nations", n.d.). San Francisco and New York have a "zero waste" goal, Amsterdam hopes to burn less and recycle more, Tokyo, uses incinerators to convert waste into energy, Sao Paulo has garbage picking and scavenging as a recognized profession (Van Lohuizen, 2017). Chile and many other developing countries have created goals for waste reduction and clean energy programs. In 2010, the UK implemented a landfill tax which creates incentive for waste diversion. Environmental change is occurring globally which will help develop plastic to oil technologies to provide plastic feedstock to manufacturers and also provide alternative energy.

The American Chemistry Council found that post-consumer non-recycled plastics have the potential to be one of the largest sources of feedstock for plastic to oil facilities which guarantees a continuous feedstock supply. In 2011, the amount landfilled reached 35.2 million tons in the US alone which has great energetic potential from its hydrocarbons (American Chemistry Council, 2014). The results from their research shows the positive abilities plastic to oil facilities have to recover energy, create thousands of new jobs, reduce amount of waste sent to the landfill, and produce billions of dollars in US economic output. Similar predictions can be expected for other countries. The marketplace for conversion technologies is past ready for implementation, only the proper legislation and community are needed.

Plastic to oil technologies should be implemented globally to help supplement existing waste management systems. Pyrolysis is able to provide feedstock for new high-quality products while eliminating the need to use virgin resin. The process also produces a vapor from its incompressible vapors which can be captured and converted to electricity to power the process. PDO Technology's model for the implementation of a pyrolysis facility in Chile found the economic and market conditions favorable for the process. Whether Chile invests in pyrolysis specifically, their government and communities are making sustainable decisions that will help them improve the lives of their citizens while positively impacting the environment. Chile is setting itself up to be a leader for environmental change in Latin America.

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Appendix: Oral Thesis Presentation Notes

IMPLEMENTING PLASTIC PYROLYSIS INTO CHILE'S PLASTIC RECYCLING INFRASTRUCTURE

KYLEE MOCKLER MARTENS
INTERNATIONAL DEGREE THESIS DEFENSE
2PM THURSDAY, MAY 31ST

PRESENTATION OVERVIEW

- Problems from plastic manufacturing and low recycling rates
- Recycling methods
- Internship at Unit of Technological Development in Concepcion, Chile
- Proposed solution to plastic waste management in Chile
- Future of plastic recycling in Chile



PROBLEM

- Plastic has improved our lives since WWII
 - 8.3 billion tons plastic produced since creation, 12 billion tons by 2050
 - Amount of plastic produced in 21st century equals 20th century
- Societal Views
 - 50% of plastic products are single-use
- Non-renewable resource
 - 8% of world oil consumption for plastic production
- Most common route for plastic waste is landfill
 - Landfills receive up to 10,000 tons of waste per day
 - US Recycling rate of 9% in 2012
 - 79% of all plastic ever created in landfills now
- Pollute the environment
 - 5.25 trillion plastic particles in ocean
 - By 2050 more plastic in ocean than fish



[3][6][18][19][20]

PROPOSED SOLUTION

- Minimize amount of plastic going to landfill- waste of hydrocarbon energetic potential
- Thermal destruction
- Establish plastic pyrolysis facilities globally

ROUTES FOR PLASTIC POST-USEFUL LIFE

- Landfill/pollute ocean and environment- 79%
 - 10,000 tons of waste sent to landfill daily globally
 - 8 million tons plastic dumped into ocean yearly
- Incineration- 12%
- Recycled- 9%



[10][19]

SOCIETAL VIEWS ON PLASTIC RECYCLING

- Low recycling rates
 - 9,800 recycling programs in the US
 - Many cities don't even have recycling programs
- Increasing environmental awareness globally
 - Increased recycling rates for total waste in US- 6% in 1970 and 35% in 2015
- Need to change citizens' waste management behavior
 - Single-use society
- Make recycling mandatory
 - Twice as high of a recycling rate for municipalities with mandatory recycling program over voluntary



[9][13]

GENERAL STEPS IN WASTE MANAGEMENT

- Control waste generation to meet needs of society with minimal environmental impact
- Entire waste management system must be analyzed/improved to increase recycling rates
- Integrated Waste Management System
 - Waste generation
 - Waste collection
 - Waste handling/sorting
 - Transfer to handling station
 - Transportation of waste
 - Disposal

PLASTIC RECYCLING OVERVIEW

- Key to reducing need for virgin polymers
- Recycling began in 1970- most important action to reduce negative impact of plastics
- Conventional recycling most common
- General steps:
 - Collection, sorting, shredding, cleaning, melting, manufacturing of new product
- Sorting plastic is most important step in recycling loop
- Energy recovery not as effective as recycling-30 GJ energy per ton from combustion



[4]

RECYCLING METHODS

- Method/ease of recycling depends on polymer type, package design, and product type
- Primary- re-extrusion
- Secondary- mechanical recycling
 - Up to 25% of recycled plastic can be used with virgin resin for new products
- Tertiary- chemical recycling
- Quaternary- energy recovery

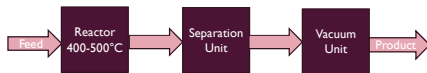
[7]

PLASTIC TO OIL PROCESSES

- Gasification, hydrolysis, hydrogenation, anaerobic digestion, pyrolysis
- Depolymerization of hydrocarbons
- Preferred with contaminated/mixed feedstock
- High-quality applications and alternative to landfilling
- For economic/environmental success
 - Ensured feedstock, committed customer, subsidies to promote pyrolytic oil, environmental regulations, increase in oil price
- Products
 - Liquid- crude oil
 - Vapor- energize process

PLASTIC PYROLYSIS

- Endothermic process in non-reactive oxygen starved environment
- Decomposes carbon-based material to create alternative energy resource
- Conversion rates vary by plastic type
- Steps:
 - Material reduced
 - Heated and converted into gas
 - Condense liquid
- Products
 - Liquid- crude oil
 - Vapor- incompressible light gases captured for energy
 - Solid- char and wax



CHALLENGES WITH PLASTIC PYROLYSIS

- Complex process with unique challenges for every feedstock type
- Commercial feasibility
- Continuous processes
- Char can be produced up 15-20%
- Possible low purity liquid fuel products

PYROLYSIS FACILITIES GLOBALLY

- Agilyx-Tigard, Oregon
- Envion- Derwood, Maryland
- Global Climax Energy- Georgia
- JBI, Niagara Falls- New York
- Renewlogy- Salt Lake City, Utah
- Vivex Engineering- UK
- Alucha- Barcelona, Spain
- Pyrocrat Systems LLP- India



Reduces.
Produces.
Creates.



ENVIRONMENTAL POLICIES

- Necessary to ensure alternative recycling methods are developed
- Barriers for new technologies in North America
 - Legislation and profitability
- Extended Producer Responsibility
- China National Sword Initiative
 - China used to accept 70% of world's plastic waste
- Europe creating strict regulatory policies- Green Dot Program
 - Require all plastic packaging within EU to be recyclable by 2030
- World Economic Forum 2015
 - Cross industry collaboration
- Companies becoming more sustainably inclined: Coca-Cola, Walmart, Intel, Eaton, Texas Instruments

[14]

MARKET POTENTIAL FOR PLASTIC PYROLYSIS

- Waste plastics have huge potential not utilized
- PTO Market to reach \$1.9B by 2024
 - Pyrolysis is largest technology segment of PTO markets at 50%
- US could support 600 PTO facilities
 - 38,900 jobs, \$8.9B economic output, eliminate landfilling of 6.5 million tons plastic yearly
- Key economic factors
 - Price of recycled polymer vs virgin polymer
 - Cost of recycling compared to other disposal methods
- Drivers for development of waste conversion technologies
- Investment in PTO technologies is critical

Cost of Pyrolysis Per Ton	Cost of Land Disposal or Recycling Per Ton
\$50	\$35-75

[2][15]

WASTE MANAGEMENT SYSTEMS IN DEVELOPING COUNTRIES

- Globally, environmental consciousness is growing
- Waste management is a huge problem for both developed and developing countries
 - Directly relates to citizen's quality of life and improves government responsibilities
- Developed countries are able to manage waste systems easier than developing countries
 - Waste tends to do most damage to those economically/socially marginalized
 - Waste management systems not prioritized in developing countries
 - Technical, financial, institutional, economic, and social constraints
 - Each community requires unique solution
- Waste pickers
 - Plastic waste has become form of currency
 - Provide solution to waste problems that affect 3 billion people globally
 - Benefits environment and provides income to impoverished
 - Global recycling industry employs more people on planet than any industry other than agriculture
 - Can formalize the informal recycling sector to provide more benefits



[14]

CHILE OVERVIEW

- Long, narrow country of 2600 miles
- 40% of country's 17.9 million population lives in Santiago
- Highest GNP in Latin America, 5.1% in 2007
 - Highest per capita income in Latin America
 - 7% unemployment rate in 2017
 - 14.1% below poverty line in January 2018
- Economic, social, industrial reforms
- Obstacles to improve municipal solid waste management system



[3]

RECYCLING IN CHILE

- Latin America produces 16% of world's solid wastes, 120 million tons yearly
- Santiago generates 7 million tons of waste per year
 - 60% to landfills, capacity to be reached soon
 - Estimated increase in 3.5 million tons per year
- Santiago tested as one of most polluted cities in the world (UN World Health Organization)
 - Tested 75% above allowed standards in 2004
 - Estimated 1000 deaths yearly
 - Trapped between Andes and coastal mountains

[3][5][18]

CHILEAN POLICIES

- Sustainable waste management challenging for developing countries
- Chile didn't prioritize environmental practices during Pinochet's dictatorship
- Framework Environmental Law (1994)- establish controlled usage for waste disposal
- Integrated Waste Management Policy (2005)- minimize health effects from improper waste disposal
- National Movement of Recyclers (2010)- protect waste pickers and change society's negative perception
- Extended Producer Liability Law (2016)
- Waste picker policies
 - Global Alliance of Waste Pickers in Chile
 - Integrate informal and formal recycling sectors to improve Chile's waste management system

TECHNOLOGY IMPLEMENTATION IN CHILE

- Technology process management
 - Identification of technologies important to the business, selection/acquisition of technologies, exploitation of technologies to generate profit, protection of knowledge and expertise in manufacturing systems
- Corporate, business, and operation levels should be considered for implementation of new technology
- Necessary stages for implementation of new technology
 - Benchmarking, business environment analysis, economic analysis
- Positive environment for foreign/domestic technology entrepreneurs in Chile
 - Start-Up Chile
 - Become leader in the technology industry
 - Invested more than \$40 million in new ventures
 - Viss available within 15 days of application

CHILE COLLABORATION WITH SWEDEN

- Partnership Fund Chile-Sweden (2005)
 - Organizes transfer of technology/experience between small/medium companies
 - Goal: reduce demand for raw materials and reduce pollution
 - Waste policies and strategies, waste economy, civilian participation, role of the government, waste treatment



UNIT OF TECHNOLOGICAL DEVELOPMENT (UDT)

- Projects: biomaterials, bioenergy, environmental services, technology management
- Internship on bench-scale plastic pyrolysis project
- Test pure/mixed feedstock to compare products to industrial standards
- Process particularly necessary after Extended Producer Liability Law implemented



FEASIBILITY OF PTO FACILITIES IN CHILE

- Conform/adapt technologies to local community needs
- Processes need scalability
- Build next to feedstock supply
- PDO Technologies Model
 - Feedstock acquisition, salaries, utilities, building fees, revenue from diesel product for Chile
 - Process feasible based on implementation of PDO Technologies facility in Chilean market conditions

Cost to Produce Diesel Per Gallon	Chilean Diesel Price Per Gallon	Chilean Model Revenue Per Gallon
\$2.21	\$3.49	\$1.28

FUTURE OF PLASTIC RECYCLING IN CHILE

- Poster child for renewable energy
- Chile became first American country to ban plastic bags in 2017
- Start-Up Chile should invest in pyrolysis projects
- Reciclapp
 - "Uber of recycling"
 - Improve waste pickers collection processes
 - Increase recycling rates
- Educating Chileans is long, slow process
 - Optimum conditions for consumer change
 - Most environmentally aware country in Latin America (The Guardian)
 - Santiago selected as test city for Education for Sustainable Consumption Program



