Modeling Circular Urban Metabolism in Santiago de Chile

Waste Tire Management

Masters Project Final Report

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Abstract

Cities account for over 70% of greenhouse gas emissions and consume over two-thirds of the world's energy. With the continued rise of urbanization, 68% by 2050 as projected by the UN, cities must be redesigned to ensure emissions, and the associated negative impacts of climate change, do not also increase proportionately. One framework through which a city's sustainability can be analyzed is through the lens of urban metabolism; the inflows, use, and outflows of a city's resources are viewed as analogous to the functions and processes of an organism.

To truly become sustainable, city metabolisms must become "circular," with high quality resources being recirculated and reused throughout the system, thus diminishing the rate of resource exploitation. Through better understanding of a city's urban metabolism, governments can implement policies targeting the points of the system with the biggest impact and increase their city's environmental resilience. Our research focus is on Santiago de Chile, Region Metropolitana, and future management of waste tires. Santiago, as a densely populated city experiencing economic growth paired with rising inequality and environmental sustainability challenges, is an ideal testing ground for innovative environmental policies that could be applied elsewhere in urban Latin America. This material flow is particularly topical as it is one of six products covered by the new Ley de Responsibilidad Extendida del Productor (REP), an extended producer liability law that shifts responsibility of a products' end-of-life phase from the consumer to the producer. REP is a critical area of interest for the Chilean Ministry of the Environment as well as our client, the EARTH Institute at Universidad Adolfo Ibáñez.

We conduct a Material Flow and Impact Analysis of future tire streams in Santiago. Using this analysis, we compare scenarios for managing end-of-life tires (ELTs) to understand which tire circularity strategies will have the greatest positive environmental, social, and economic impact. We find that promoting ELT management strategies that focus on energy-recovery will best promote environmental sustainability and human health while minimizing consumption of water and fossil fuels. There is a tradeoff as energy recovery is more expensive and has a minimal impact on material circularity compared to a baseline scenario and we discuss a potential impact score through the lens of Chilean environmental policy. We further recommend that both an Advanced Disposal Fee (ADF) and a Deposit Refund System (DRS) are considered as potential economic policy instruments to facilitate ELT collection.

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Acronyms

ADF	Advanced Deposit Fee
CE	Circular Economy
CFC	Chlorofluorocarbons
CINC	Cámara de la Industria del Neumático del Chile (Chamber of the Tire Industry)
DRS	Deposit Refund System
EF	Ecological Footprint
ELT	End-of-Life Tires
EPR	Extended Producer Responsibility
GDP	Gross Domestic Product
GWP	Global Warming Potential
LCA	Life Cycle Analysis
LFI	Linear Flow Index
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
MMA	Ministerio del Medio Ambiente (Ministry of the Environment)
OTR	Off-the-Road
PPP	Purchasing Power Parity
PRO	Producer Responsibility Organization
REP	Responsabilidad Extendida del Productor
RM	Region Metropolitana
TDF	Tire Derived Fuel
UM	Urban Metabolism

WTE ……………...……………….…………….…………... Waste to Energy

Introduction

As the main contributors of negative environmental impacts in the world, responsible for 75% of global resource use and 65-70% of global energy consumption, cities are in need of major redesign (C40 Cities, 2020). The understanding of urban resource use by means of the study of material flows is required in order to redesign current urban systems of material, water and energy management according to an integrative and ecological perspective.

One framework through which a city's sustainability can be analyzed is through the lens of urban metabolism; the inflows, use, and outflows of a city's resources are viewed as analogous to the functions and processes of an organism (Kennedy, 2007). The term "linear metabolism" is used to describe the current approach of urban metropolises where cities use high quality resources and dispose of them as low-quality flows, negatively affecting their surroundings. With the continued rise of urbanization, 68% by 2050 as projected by the UN, cities will expand and the environmental impacts of linear metabolism will expand as well (UN DESA, 2018).

To truly become sustainable, city metabolisms must become more "circular," with high quality resources being recirculated and reused throughout the system, thus diminishing the rate of resource exploitation. In contrast, nature works circularly, meaning resources are recirculated within the system by means of the intricate web of connections between organisms which allow for a harmonic exchange of resources without compromising the system's long-term performance. Through better understanding of their city's urban metabolism, governments can implement policies targeting the points of the system with the biggest impact and increase their city's environmental resilience.

The project's client, the Earth Center at Universidad Adolfo Ibanez (UAI or "the client") has a mission to create and implement innovative technologies and policies in areas such as energy, water, and materials that promote sustainable development. The client has identified the need for resource flows modeling for Santiago, Region Metropolitana (Santiago or Santiago RM) to analyze both the economic impact and potential viability of different circular resource management options. Santiago, as a densely populated city experiencing economic growth paired with rising inequality and environmental sustainability challenges, is an ideal testing ground for innovative environmental policies that could be applied elsewhere in urban Latin America. This project focuses on one such material flow, tires under fifty-seven inches, which are particularly relevant due as they are the first material category of focus under the Extended Producer Responsibility Act (ley de Responsabilidad Extendida del Productor, "REP," Ley 20920).

This University of Michigan SEAS Master's Project forecasts future tire flows and the impact of different end-of-life management strategies for Santiago through the lens of environmental, economic, and social outcomes. Further, we conduct a comparative analysis of different policy pathways to facilitate successful achievement of the tire collection and valorization targets set forth by REP are achieved. This information will advise UAI's researchers on policy avenues that can be pursued with key industry and government partners in order to manage end of life tires (ETLs) in such a way that improves the circularity of Santiago's economy.

We began with a literature review of urban metabolism studies, Chilean environmental priorities and legislation. This information was used to narrow the focus of our analysis, the specific goals of which are outlined in "Objective." We analyzed the circularity of the flow of tires throughout the Santiago region ("Methodology") and explored the implications of our findings on policy decision making ("Results" and "Discussion").

1. Urban Metabolism Overview

1.1 Basis of Urban Metabolism Studies: Framework

Urban metabolism (UM) studies take a similar approach to those of Material Flows Analysis (MFA) (Dijst et al., 2017). This type of framework quantifies the flows (inputs and outputs of a system) and the stocks (accumulation of materials residing in a system). One of the drawbacks of material flow analysis is that it fails to quantify the environmental impacts of the flows (García-Guaita et al., 2018). Consequently, to complete a comprehensive impact assessment of a city's flows and stocks, a multi-criteria based indicator method needs to also be employed. Process level LCA and Economic input-output LCA are two methods of evaluating the environmental impact of processes (Elia et al., 2017).

The framework for UM studies is typically as follows (Sahely et al., 2003):

1. Define the study goals
2. Specify the research system boundaries
3. Collect inventory data and conduct MFA
4. Impact assessment

The vague nature of this framework has engendered a lack of standardization across the field of urban metabolism. Kennedy et al. has proposed a standard approach to determining the inventory of a system and associated emissions from waste (Appendix A, Figure A1). A gap in the existing literature that is noted by multiple UM studies is a standard method for linking the material flow analysis to social and economic impact indicators (Dijst et al., 2018). Dijst et al. (2018) notes that there is no defined positive correlation between a circular economy, an improved standard of living, and social equity. For example, Burton (2000) found that transitioning to more efficient energy and resource use through denser population distribution could result in a decrease in the socioeconomic indicator of average living space, the impact of which would be disproportionately felt by different communities within the population (Burton, 2000).

1.11 Flows in UM studies

The four fundamental flows in urban metabolisms are water, materials, nutrients, and energy. While this report focuses mainly on material flows, water, nutrients, and energy flows are discussed in detail in Appendix A, Figure A2.

1.111 Material Flows

While most contemporary cities have a linear metabolism with high through flow of materials, material flows in sustainable cities aim to develop more holistic approaches to urban design that integrate greater recycling of materials (Sahely et al., 2003). The study of material flows traditionally includes an aggregate overview of solid, gaseous, and liquid materials from domestic extraction and physical imports. The pivotal study by Wolman (1965) used national data on water, food and fuel use, together with production rates of sewage, waste and air pollutants to determine per capita inflow and outflow rates for a hypothetical American city of 1 million people. His method to ascertain material flows, even with the omission of important inputs such as electricity, infrastructure materials, and other durable goods, helped focus attention on system-wide impacts of the consumption of goods and the generation of wastes within the urban environment (Kennedy et al., 2011).

MFA has been increasingly used as a basis for analyzing and planning waste management and recycling systems. MFA reports stocks and flows of resources in terms of mass, where a city's material flow is expressed as a mass flux (Moriguchi, 2016). The material components that are vital to an urban metabolism for a city include 1) The tonnage and composition of landfill waste (percentage food, garden, paper, wood, textiles, industrial, other/inert) from all sectors; and 2) The masses of steel, cement and other materials or chemicals produced or imported in the city causing non-energy related industrial process emissions (Kennedy et al., 2011).

1.2 History of Urban Metabolism Studies

Kenneth Boulding's 1966 essay on Spaceship Earth is frequently credited with introducing the concept of a circular economy and questions whether a fully 'closed-loop' economy is compatible with the goals of a society (Boulding, 1966). The concept of Circular Urban Metabolism partially stems from 'urban environmentalism,' which gained traction in the 1980s as a means to redevelop urban industrial centers via industrial metabolism projects (Prendeville et al, 2018). Schott (2004) explains that researchers exploring technology networks within cities expanded their framework to depict cities as an 'urban metabolism' (Schott, 2004). This conceptualization allows for a refocusing on environmental changes caused by the 'colonization of nature' — "the sum of all purposive changes made in natural systems that aim to render nature more useful for society"— on both resource inputs and outputs (Schott, 2004, p.523). Kennedy et al. (2007) pinpoints Abel Wolman's 1965 article in response to rapid urbanization as the origin of the urban metabolism concept that was precipitated by declining water and air quality in US cities, which harmed sustainable urban development (Kennedy et al., 2007). Kennedy et al. (2007) also points to Odum's work in 1971 that defines ecosystem metabolism as the production and consumption of organic matter, usually measured in terms of energy.

Recognizing that later urban metabolism studies included nutrient and material fluxes as well as the urban hydrologic cycle, Kennedy et al. (2007, p. 44) proposes that urban metabolism be defined as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste."

1.3 Considerations about Urban Metabolism Studies

Various authors argue that there is not a universally agreed-upon definition of circular urban metabolism (Kalmykova et al., 2018). The lack of common definition can make it difficult for policymakers, urban planners, government, and industry to create and implement policies that have a demonstrated effect in reducing natural resource burdens and improving public health. Prendeville et al. (2017) notes that the Circular Economy (CE) concept has predominantly followed a business-narrative that focuses on improving competitive advantage and is skeptical about how it is currently used in urban sustainability practices (Prendeville, 2018). Despite support from businesses and national governments, Korhonen et al. (2018) posits that the research and scientific material that CE is based on is neither comprehensive nor organized (Korhonen et al, 2018). They do think that CE can improve global net sustainability but needs to address challenges such as the predominant linear flow of energy and materials in the global economy (Korhonen et al., 2018). Their proposed definition of the circular economy can be found in Appendix A, Figure A3.

Millar et al. (2019) states that there is consensus that social equity, economic security, and environmental quality are adversely affected by typical human production and consumption practices, and that the traditional 'linear flow' model of energy and materials is a significant contributing factor (Millar et al., 2019). It is difficult to create a model that fosters economic growth without harming social equity nor the environment and the Circular Economy has been seen as a tool for achieving sustainable development. Millar et al. (2019) expresses concern that there is not a clear linkage between Sustainable Development and the Circular Economy, even positing that the CE and linear economy could have comparable outcomes. Geissdoerfer et al. (2017) similarly argues that a lack of a clear conceptual relationship between CE and sustainability has potentially adverse effects on both sustainability science and CE/sustainability practices (Geissdoerfer et al., 2017).

1.4 Characteristics of Circular Economy

According to the Ellen MacArthur Foundation, a circular, as opposed to a linear model, builds social, natural, and economic capital. This foundation's definition of a circular economy is widely utilized, especially among industry. The circular model hinges upon three principles: 1) Design out waste and pollution, 2) Keep products and materials in use, and 3) Regenerate natural systems (Ellen MacArthur Foundation, 2017). Their proposed outline of a circular economy can be found in Appendix A, Figure A4.

Geissdoerfer et al. (2017) base their definition off of the characteristics identified by the Ellen MacArthur Foundation, Webster, and Bocken et al., among others who point either to closing, slowing, or narrowing resource loops and flows, and conclude that the CE is a *regenerative* system (Geissdoerfer et al., 2017). They conclude that this can be achieved via long-lasting design, reuse, repair, maintenance, remanufacturing, recycling, and refurbishing.

Circular Economy concepts are valuable for countries transitioning from developing to developed countries because they can facilitate economic growth with diminished negative socio-environmental impacts compared to a linear economic model. Waste management tends to be a challenge in developing countries, both from a financial and human-health perspective (Margallo et al., 2019). According to Margallo et al. (2016), as emerging economies experience increasing urban population growth and economic expansion, they generate greater rates of municipal solid waste. Typically, in Latin America, this waste is disposed of in landfills or in open dumpsters, which is particularly concerning from a GHG emissions standpoint (Margallo et al., 2019). OECD countries have, on average, higher waste generation rates. If countries are transitioning to becoming developed economies then they need to be prepared to manage potentially higher rates of waste generation (Maragallo et al., 2019).

Another key difference between OECD and non-OECD countries' waste composition is that OECD countries have a high percentage of recyclable materials whereas non-OECD countries have a larger percentage of organic waste (Margallo et al., 2019). While both developing and developed countries would benefit from applying CE concepts, developing countries face limited budgets, infrastructure, and maintenance facilitates for waste management and stand to gain from CE practices that could reduce overall costs (Nizami et al., 2017). Santiago, as a major metropolis in an OECD Latin American country, has made great improvements in waste management practices, but can still apply CE practices to improve its resource flows.

2. Chilean Context

2.1 Chilean Context in Urban Metabolism

The Chilean government is striving to promote CE, as evidenced by the creation of the Circular Economy Office, formerly the Waste Office, at the Ministry of the Environment ("Guillermo González: "Llegó el momento de la Economía Circular", 2018). The Minister of the Environment, Carolina Schmidt stated in 2019 regarding restrictions on the use and sale of plastic bags that the government wants to work towards a circular economy and that they have started to implement the REP law, which not only decreases plastic bag usage, but also the consumption of other materials used in packaging (Burgos, 2019). Reducing packaging consumption is a valuable step and as the Director of the Circular Economy Office Guillermo González explained, the REP law is only the first step in a series of changes in the coming decades ("Guillermo González: "Llegó el momento de la Economía Circular, 2018).

A well-defined and researched concept of Circular Urban Metabolism will enable the MMA to be confident that the enacted policies will appropriately address resource flow challenges. For example, Millar et al. (2019) is concerned that despite a lack of consensus on whether continuous economic growth can be paired with environmental protections and improved social equity, Weber and the Ellen MacArthur Foundation promote CE as a solution (Millar et al., 2019). Since the end of the Chilean military dictatorship in 1990, high rates of poverty have declined, from 38.6% in 1990 to 7.8% in 2014, but social equity remains a challenge (Fernández et al., 2016). We chose to focus on Santiago because it is the most populous urban area of the country and is associated with dramatic economic growth, which tends to be correlated with increased resource consumption and greenhouse gas emissions. In 2014, the Santiago Metropolitan Region encompassed 41% of the national population and 49% of the Chilean economy (Leal Trujillo et al., 2016). Santiago is also the site of significant disparities in quality of life indices; in 2014 it contained both the 6 worst and best urban municipalities to live in in the country (Fernández et al., 2016). If promoting policies that improve a region's circular economy can also improve social equity, then Santiago is an impactful city to prioritize.

An ecological footprint (EF) was calculated for Santiago de Chile in 1998, which acted as the first systematic material assessment of the city. EF calculates the resources consumed, waste generated and translates these flows to a biologically productive area necessary to provide these functions (Wackernagal, 1998). Wackernagel warns of the increasing consumption patterns with the new market-based economy effect on resource flows. Chile's economy has grown rapidly since the end of the dictatorship in 1990, which combined with their large urbanization rate dictates an updated resource flow analysis necessary.

Since 1998, Chile has instituted a variety of laws that respond to increased consumption patterns. In 2005, the government adopted an Integrated Solid Waste Management Policy (Política de gestión integral de residuos sólidos/ PIGRS) with the goal of ensuring that waste management is carried out with minimum risk to the population's health and promoting waste management that ensures a sustainable development of the sector (Arpaia & Cantú Martinez, 2018). This law was significant in that it introduced a 'hierarchical strategy' of promoting the prevention of waste generation, and if that was not possible reuse, recycling, energy generation, with final disposal as the last option (Arpaia & Cantú Martinez, 2018). In 2008, Law 20.417 reformed environmental governance structures by creating the Ministry of the Environment (MMA), the Environmental Evaluation Service (*Servicio de Evaluación Ambienta*l (SEA)), and the Superintendency of the Environment (*Superintendencia del Medio Ambiente* (SMA)) (Arpaia & Cantú Martinez, 2018) The MMA is charged with, among other tasks, creating policies, norms, and plans related to waste management and promoting environmental education (Ministerio del Medio Ambiente, n.d.). The Circular Economy Office, which is housed within the Ministry of the Environment, is responsible for reducing the environmental impact associated with waste generation and promoting a circular economy model that changes the linear forms of production, consumption and business and incorporates ecodesign, re-use, recycling, and recovery ("Economía Circular," n.d.).

The Circular Economy Office's main objectives are REP implementation and advancing a circular economy model in Chile via supporting innovation and regulatory frameworks with that end in mind. REP was introduced in 2013 and passed in 2016, signed into law by President Bachelet and Minster of the Environment Pablo Badenier ("Nueva Ley de Reciclaje impone a las empresas el financiamiento y metas de recolección y valorización de los residuos que generan sus productos," 2016). REP goals include decreasing waste generation and promoting recycling via making producers responsible for financing waste management associated with the priority products they produce or import ("Ley REP," n.d.).

While EF and the metric of global hectares is easily communicable to a large audience, there is a need to understand how these flows through Santiago break down into environmental, social, and economic impacts. Our study will accomplish this objective and expand upon existing UM research into Santiago's water and solid waste management.

Santiago de Chile has a unique administrative governance structure that dictates how resources are managed. There are 15 administrative regions in Chile, with the centrally located Santiago Metropolitan region making up around 7 million people, or around 40% of the total population ("Estimaciones y Proyecciones de la Población de Chile 1992-2050," n.d.). The Metropolitan region includes the nation's capital, Santiago and is divided into six provinces which themselves are split into 52 communes. For our study, we will be focused on the Region Metropolitana and its 52 communes, spanning 15,403 km^2 (Encyclopedia Britannica, 2020).

Solid waste is a material flow of interest as it is directly related to patterns of unsustainable land use, energy consumption, and environmental pollution (Guibrunet et al., 2017). Waste management is a persistent problem in Santiago as the city generates three-quarters of the solid waste in the country. This can again be traced back to the privatization of the utility. Each of the 52 communes or municipalities in the Santiago Metropolitan Region are free to choose between two waste management methods; 1) Individually contracted private operated (KDM) or 2) A collective private utility company (EMERES) under the mayor's control. This creates an incentive for communes to contract out to private waste companies with lower quality standards. The largest private waste management operator in the region is KDM which accounts for 59% of the total volume of waste (Guibrunet et al., 2017).

There are three landfills in the region, Lama los Colorados, Santa Marta, and Santiago Poniente, respectively receiving 48%, 29%, and 15% of total waste in the region (Martínez et al., 2012). Waste generation in Santiago averages 1.5kg per person per day, with a significant difference in waste based on income, wealthy communes >2kg per day as opposed to poorer communes <1kg per day (Guibrunet et al., 2017). Since only ten percent of the country's trash is recycled, there is room for improvement (Alvarado & Sherwood, 2018). Our study will focus only on tires, given that it is a priority product under Chile's recycling law and has adverse environmental implications if not reused or recycled.

2.2 Chilean Political Context

As a country, Chile has positioned itself as an environmental champion through innovative regulatory processes outlined in its National Climate Action Plan as part of the UNFCCC. This includes policies such as the implementation of a carbon tax and renewable energy mandates ("Intended Nationally Determined Contribution of Chile Towards the Climate Agreement of Paris 2015," 2015). Chile has taken great strides to address sustainability challenges and we are excited to see Chile's progress as it implements new environmental policies. In 2017, Chile was one of the most centralized countries in the OECD and has employed an economic model that relies on 'the market' to distribute resources and restricts public intervention and a centrist political model ("Making Decentralization Work in Chile," 2017). One of the limitations of this model is that it has historically favored Santiago, mining other regions socially and economically ("Making Decentralization Work in Chile," 2017).

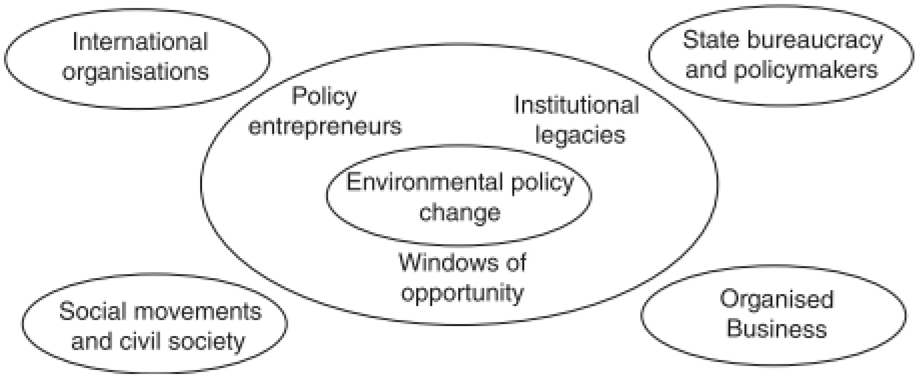
Santiago is not without its challenges: high levels of resource consumption, unequal access to resources and services, air pollution, water shortages, inefficient transformation and use of energy, and weak institutional control mechanisms (Krellenberg et al., 2010). Inostroza et al. (2016) argues that Santiago is representative of metropolitan areas in Latin America that face rapid population growth and an unequal distribution of positive environmental conditions, and an associated difference in social impacts of extreme weather. In 2017, Santiago residents were exposed to negative health impacts from the '*tormenta de fuego*' wildfires and the region is likely to experience more extreme fires (Bowman et al., 2018). Given how vulnerable Chile is to anthropogenic climate change's impacts at social, economic, and environmental levels, it is essential to address these challenges and help to "close the loop" on urban metabolism (Welz & Krellenberg, 2016). We view Chile's Extended Producer Responsibility law as one means of confronting the adverse environmental and human health effects of typical resource consumption.

In order to understand this law's potential impact, it is important to have an overview of Chile's recent political context and environmental laws. While our intended audience for this report, the Circular Economy Office at the Ministry of the Environment and the UAI EARTH Center, is intimately familiar with these policies, understanding the key policies and REP is critical context for others less familiar with Chilean environmental legislation.

Madariaga (2018) argues that there has been a demonstrable change in political priorities in Chile and that for the first time since re-democratization in Chile, there is not an explicit favoring of economic investment over environmental concerns. While economic growth does not need to be diametrically opposed to the environment, it has historically been challenging in Chile to support environmentally responsible policy under a neoliberal economic model. Deregulation and privatization, for example, tend not to favor environmental protection. Additionally, as argued by Mundaca (2013), government policies during the period 1971-2007 in relation to energy efficiency, climate change, and non-conventional renewable energy had modest impact. Considering how neoliberal economic practices can reduce the interventionist ability of the state (i.e. its ability to implement policy instruments that protect public goods), Chile faces challenges in enhancing recycling practices (Mundaca, 2013).

When examining the Chilean political context and recent environmental legislation, our team found it useful to apply Madariaga (2018)'s environmental policy change framework, which uses Kingdon's Multiple Streams Framework (Kingdon, 1984) outlined in Figure 1 below.

Figure 1
Environmental Policy Change



The actors referenced above (international organizations, social movements and civil society, organized business, and State bureaucracy and policy makers) have the capacity to impact environmental policy contingent upon the following conditions: windows of opportunity, the influence of policy entrepreneurs, and the impacts of institutional legacies.

Alvial-Palavicino et al. (2018) posit that state power is concentrated, industries tend to be driven by influential economic groups, and that decision-making can be easily co-opted because political and economic elites hold sizable sway in Chile. This suggests a need for opening the policy process to be more democratic and participatory, which is recommended from an environmental governance and environmental justice perspective (Baud et al., 2011).

Social movements have acted as catalysts for passing Chilean environmental legislation. For example, the movement to stop the construction of the HydroAysen mega-dam project, beginning in 2011 with a large protest led by the Patagonia Without Dams advocacy group, forced both legislators and investors to address environmental impacts and acknowledge citizens' political dissatisfaction (Jara, 2014). What initially was a localized environmental cause morphed into a series of protests about issues such as public education reform and centralization of national resources (Jara, 2014). Social movements also work to increase issue visibility and shape institutional agendas. Silva (2018) argues that increasing socio-environmental conflict and public-opinion pressure allowed environmentalists to demand environmental governance reform; presidential candidates listed it on their agenda in 2005 and President Bachelet was able to establish a ministry of the environment.

Nasirov et al. (2017) states that Chile is one of the most successful countries in South America with regard to political and institutional stability, market-oriented reforms, and solid macroeconomic policies. Understanding the prevalence and tendency towards market-oriented reforms in Chile helped us evaluate which policy instruments related to REP might be well-suited to its political context.

Chile has experienced an increase in support for and ability to pass environmental legislation, suggesting that laws focused on diminishing waste and improving a city's circularity, while may have unpopular components and technical challenges, are well-poised to be successful.

2.3 Chilean Environmental Laws

Environmental legislation is relatively recent in Chilean history; prior to the 1990s, Chile lacked a significant environmental regime (Carruthers, 2001). Chile certainly had environmental regulations prior to 1990, but they were not associated with a coherent policy, nor were they consistently enforced (O'Ryan et al., 2005). The Ley No. 19.300 in 1994, known as the National Environmental Framework Law (NEFL), created the National Environmental Commission (CONAMA). This law marked an important change because while the 1980 constitution did identify citizens' right to live in an unpolluted environment via Article 19 no. 8, it did not establish a means for enforcement (Guiloff Titiun, 2011). However, Tecklin points out that while the NEFL created CONAMA and a system for environmental liability, it did not offer substantial regulation. While our team did not explicitly focus on the lasting impact of the NEFL, understanding its criticism helped us appreciate the historical challenges in regulating industry in Chile. For example, by 2005 CONAMA found that the rest of the government had failed to legitimize its own coordinating model and it struggled with fragmented and ineffective enforcement (Tecklin et al., 2011).

International influences, such as Chile's interest in joining free trade agreements that had environmental provisions may have influenced the creation of the 1994 Framework law (Madariaga, 2018). Opportunities for regional prestige also influenced Chilean policymakers' interest in becoming an environmental leader (Madariaga, 2018). External pressure from multilateral funding organizations, NGOs, and international organizations helped establish the framework law (Nasirov et al., 2018). Tecklin argues that environmental policymaking's impetus stems from external forces associated with globalization instead of domestic political changes that have fomented environmental change elsewhere (Tecklin et al., 2011).

There was a window of opportunity associated with the first Piñera presidency (2010-2014) in that civil society was increasingly active. Such support for environmental policy set the stage for the second Bachelet administration (2014-2018) in which she was able to channel social support and utilize political conditions to move forward with an array of environmental policies (Madariaga, 2018). The table below outlines her administration's legacy.

Table 1

Environmental Policy under Bachelet (2014-2017)

	Institutions	Legislation	Policies
Climate Change	Climate change agency Division of climate change (Ministry of Environment)	Ratification of Paris Agreement	
Energy		Modifications to auctions process	Energía 2050
Environment conservation	Biodiversity Service Forestry Service	Glacier protection law	Forestry policy New land and ocean conservation areas
Pollution		Carbon Tax	Air pollution plans Clean production agreements
Water		New water code	
Waste		Recycling law	Banning plastic bags in coastal cities

Source: Madariaga, 2018, Table 1

Recent key legislation that demonstrates Chile's growing commitment to environmental sustainability includes the National Action Plan for Climate Change 2017-2022 (PANCC II) under the Bachelet administration, and the Energía 2050 National Strategy ("Chile launches new National Action Plan for Climate Change," 2017). Energía 2050 included a process of participatory policy design and the National Action Plan intentionally involved civil society (Badenier Martinez, 2016). The National Action Plan for Climate Change is recognized as the first Chilean policy instrument that was developed as a direct response to Climate Change and was a critical step in confronting Chile's vulnerability to climate change, associated with its geographic diversity and high levels of exposure to climate variability (Arriagada et al., 2018). Considering that Chilean environmental governance institutions are relatively new and hierarchical and face the challenge of including extra-governmental stakeholders in decision-making processes, PANCC demonstrated increased governmental interest in including diverse actors, thus supporting knowledge co-production and public participation (Arriagada et al., 2018).

Chile has been promoted as a country that has successfully navigated the energy transition via public policies that promote renewable energies (Flores-Fernández, 2020). If the government has demonstrated the ability to transition away from non-renewable energy sources through Energía 2050, perhaps these policy tools can be applied to a transition away from a linear resource-consumption economy. Flores-Fernández (2020) argues that energy transitions, as political processes, have the potential to promote more democratic models of energy development, but also strengthen current power relations. We are curious to see how political dynamics shift during the circular economy transition.

Progressive waste management legislation is a key means for addressing negative environmental impacts associated with resource consumption. In 2012, the Operation Guide for the National Program of Solid Waste (Resolución Exento Nº: 12359/2012) was approved, which included the goal of increasing the percentage of household waste disposed of in environmentally adequate landfills, closing unauthorized waste dumps, and supporting regional waste management planning capacity ("Guía Operativa Programa Nacional de Residuos Sólidos (PNRS) | Subdere," n.d.). The National Solid Waste Policy 2018-2030 determined the responsibilities of waste generators, managers, importers, and exporters and responded to the international commitments associated with OECD membership ("Marco Normativo e Institucional Aplicado al Sector de Residuos Sólidos en Chile," 2018). It also establishes the regulatory framework for enforcement related to infractions and sanctions ("Marco Normativo e Institucional Aplicado al Sector de Residuos Sólidos en Chile," 2018). Lastly, the Emission Standard for Incineration, Co-incineration and Co-processing (D.S. N° 29/2013 del MMA) affects the co-processing associated with cement ovens that use non-traditional fuels and intends to prevent negative health and environmental impacts (MMA, 2013).

Simsek et al. (2019) asserts that Chile has primarily had voluntary support mechanisms for energy efficiency and that they recommend mandatory and economic support mechanisms if Chile is to reach its national target. While this is not directly tied to the REP legislation, it emphasized the importance of federal regulations and enforcement mechanisms.

Madariaga (2018) argues that the success of future environmental policies is contingent upon stakeholder coalitions' ability to oblige businesses to support environmental agendas. The 2016 Framework Law for Waste Management, Extended Responsibility of the Producer and Promotion of Recycling, known as Law n° 20.920 or Ley REP, is a key means of ensuring corporate responsibility.

2.31 REP

The Recycling law establishes new powers for the Ministry of the Environment for managing waste, including: certification and labeling, a deposit and refund system, Ecodesign, mechanisms of separation at source and selective collection, mechanisms for environmentally sound waste management, and mechanisms to prevent the generation of waste ("Ley de fomento al reciclaje,"n.d.). The REP law has six priority categories, each with different timelines and percentages for recycling: lubricant oils, electronics, containers and packaging, tires, and two types of batteries. These products were prioritized because they are majorly consumed, comprise a significant volume of waste, the majority are dangerous, are feasible to price, and it is possible to regulate them ("Ley de fomento al reciclaje,"n.d.).

Concerns over climate change and stimulating the economy, among others, inspired REP. President Bachelet expressed that enactment of the law assumes individual responsibility for waste management, from households, to corporations, to the government ("[ARCHIVO] President Bachelet enacts the Recycling and Extended Producer Liability Law," 2016). She argued that this law is a step towards promoting cultural change and strengthening environmental protection. The law recognizes that waste management generates high social and environmental costs and that municipalities face high economic costs (Biblioteca del Congreso Nacional de Chile, n.d.). Such costs had been partially addressed by an array of legislation, but a comprehensive framework would more strategically address the complex challenge of waste generation and management. Additionally, the law aims to systematize efforts of stakeholders to decrease pollution and stimulate the economy and formalize the labor of over 60,000 grassroots recyclers ("[ARCHIVO]…", 2016).

Successful Extended Producer Responsibility legislation in European countries, such as Spain, Finland, and Belgium, among others, played a role as reference points in designing REP (Biblioteca del Congreso Nacional de Chile, n.d.). Lastly, REP addresses the OECD's 2005 Environmental Performance Review recommendations that Chile promote waste recovery (Biblioteca del Congreso Nacional de Chile, n.d.; OECD, 2016).

The timeline below is not a complete picture of REP's development, but details key aspects of its legislative development and implementation status.

- Legislative history:
    - September 10, 2013: first legislative procedure of messaging associated with REP at the Commission on Environment and Natural Resources of the Chamber of Deputies, approved January 14, 2015. Approved at the general Chamber of Deputies April 1st, 2015. On June 9th, 2015,approved in the Senate (Font, 2019)
    - On June 1st, 2016 law 20.920, or Ley REP published in the *Diario Oficial*/official journal (Font, 2019)

- Priority product-specific guidance:
    - November 20th, 2018, end of public consultation on collection and treatment goals for tires (Molina Alomar, 2018)
    - March 27th, 2019 the Council of Ministers for Sustainability the Supreme Decree that establishes the collection and treatment goals for the tire sector, that will enter into effect on January 1st, 2021 published (Font, 2019)
    - May 10th, 2019 30-day public consultation announced for packaging announced (Ministerio del Interior y Seguridad Pública, 2019)
    - June 10th, an extract of the preliminary draft of the decree that establishes the collection and treatment goals for packaging was published (Font, 2019)
    - Second semester of 2019 start of product study for batteries

We choose to focus on tires instead of the other product categories because they are challenging to recycle sustainably and because people experiencing poverty tend to suffer adverse health effects from improper waste management. Additionally, tires are the first priority product category that is being implemented, partially due to the homogeneity of the product ("Ministra Schmidt anuncia que empresas deberán reciclar el 90% de los neumáticos que se consumen en el país," 2018). It is strategic for MMA to begin with tires because it is an easier category to implement than the others and will inform their implementation. Minister of the Environment Schmidt acknowledged that tires are one of the most polluting agents in Chile, thus implying the importance of prioritizing tires in REP implementation ("Ministra Schmidt anuncia que empresas deberán reciclar el 90% de los neumáticos que se consumen en el país," 2018). She also referenced the challenge of illegal tire dumping in Chile, "The tire waste generated annually is equivalent to a Cerro Santa Lucía, generating waste that ends up in clandestine dumps and garbage that invades our country" ("Ministra Schmidt anuncia que empresas deberán reciclar el 90% de los neumáticos que se consumen en el país," 2018).

Those who produce or import priority products will have several obligations including: register in a public registry for business people and/or manufacturers, organize and finance the collection and treatment of products via a management system (known internationally as PROs, called *sistema de gestión* in Chile), ensure that waste treatment is conducted by authorized persons, and meet the collection and valorization goals ("Ley de fomento al reciclaje,"n.d.).

The REP Law establishes that the manufacturers and importers of the products will be responsible for organizing and financing management systems to collect and valorize the waste generated, which will promote the installation of new alternatives. The Superintendency of the Environment is charged with issuing fines and the budget associated with the law allocates approximately 8.7 million dollars, with additional funding for operational costs, the Recycling Fund, and for temporary expenses ("Ley de fomento al reciclaje,"n.d.). Banguera et al. (2018)

states that "costs of the management system are intended to be financed through green taxes to be paid by the consumer, which will be transferred from the producers and importers to the manager, and this in turn will bid the services in the private market for collection and recycling, separately." Financing structures that enable smaller recyclers and tire dealers to compete are still being clarified. One stakeholder, C. Patiño Salas explained that one concern about meeting treatment goals is that it would be difficult to establish a collective system if small and mid-sized tire dealers cannot afford the *instrumento de caución* with recyclers (C. Patiño Salas, personal communication, February 6, 2020). The *instrumento de caución*, or preventive compliance instrument, is a guarantee, a form of insurance, if recyclers are unable to comply with their contract goals, the bank will pay the other parties in the PRO; recyclers must have enough resources to create an *instrumento de caución* with a bank. An unintended consequence could be that REP would privilege large-scale tire manufacturers who can afford a 1 to 1 agreement with a recycling company.

The law differentiates tire recycling goals according to their size, those below 57 inches (Category A) and those equal to and above 57 inches (Category B). Common examples of Category A tires include passenger tires, some truck tires and motorcycle tires. Category B tires include OTR (off-the-road) tires such as mining, agricultural and industrial tires. REP further distinguishes ELT goals with both collection and treatment requirements. There is a collection requirement for the country as a whole as well as regional minimum connection requirements. This duality helps counter the centralized nature of Chile and ensures that all regions of the country execute REP. The national requirements start in 2021 and the region goals must be met beginning in 2023 (Alomar, 2019). The country level collection and treatment levels for ELTs are listed in Table 2 below. Collection Rates are percentages of tires placed on the market in the preceding year that must be collected. Treatment Rates are the minimum percentages of tires placed on the market in the preceding year that must be valorized. It is important to note that there is no treatment method requirement, the thought being that the market would regulate itself and producers would select technologies based on individual financial motivations.

The collection requirements of Category A states that all regions together must collect at least 34.7% of ELTs, compounding to a country level collection rate of 50% starting in 2021. Category A tires will have a national collection rate of 90% by 2028. The treatment of Category A ELTs starts at just 25% in 2021 and more incrementally climbs to 90% by 2028. Category B tires will have a national collection rate of 98% by 2026 (Scott, 2019).

Table 2

Category A Tires Collection and Treatment Rates for Chile via REP

Year	Collection Rate	Treatment Rate

2021	50%	25%
2022	>= 50%	30%
2023	>= 50%	35%
2024	80%	60%
2025	>= 80%	>= 60%
2026	>= 80%	80%
2027	>= 80%	>= 80%
2028	90%	90%

In general, tires were previously subject to a variety of norms and oversight entities. According to a 2008 report prepared for the Ministry of the Environment's predecessor (CONAMA), the SEREMI (regional representative of the Ministry) of Transport was responsible for enforcing compliance with tire standards, but that there was a lack of periodic inspection (CYV Medioambiente LTDA, 2008). As of 2008, Chile lacked an explicit classification for ELTs; instead, they were classified as 'non-dangerous waste' by the SEREMI of Health (CYV Medioambiente LTDA, 2008). The report details that there was no regulation that established criteria for proper ELT management, besides a resolution from the Ministry of Health in 1994 designed to prevent the introduction of the Aedes Albohol mosquito. Additionally, since ELTs were not accepted in landfills, the lack of pertinent legislation incentivized illegal dumping. The Clean Production Agreement: Prevention and Recovery of End of Life Tires in 2009 sought to implement a comprehensive ELT management system, developed by tire producers and coordinated by a trade association, the Chamber of the Tire Industry of Chile A.G. (CINC) (Cámara de la Industria del Neumático de Chile AG, Consejo Nacional de Producción Limpia, & Gobierno de Chile, 2009). The Transport Sub-secretary would also play a role in evaluating tire regulation, with overall program oversight from CONAMA, the National Council for Clean Production (CPL), and CINC. In contrast, under REP, ELTs will be overseen by the Ministry of the Environment (OECD, Ernst & Young, & Gobierno de Chile, 2014).

3. Tires

3.1 Tire Material Background

Material waste has become an extremely important issue due to its negative impacts on the environment. Currently, waste in the form of used tires has become a threat due to environmental pollution, but also due to their effects on the health of the population. Scrap tire piles have been known to catch fire and burn for lengthy periods —sometimes for years — releasing toxins and GHGs. The piles have also proven to be serious breeding grounds for mosquitoes and rodents, which can carry many diseases. Furthermore, disposal of whole tires in landfills creates problems as the tires tend to rise to the surface and take up large amounts of space given their shape (Sienkowicz et al., 2012). Every year, globally over 1.6 billion new tires are generated and around 1 billion of waste tires are generated. However, the recycling industry processed only 100 million tires every year (Goldstein Research, 2020).

Tires are intricately designed with several complex processes which makes it almost indestructible in nature and makes it difficult for the recycling of tires (Goldstein Research, 2020). However, ELTs contain many valuable materials that should be recovered. A tire is made from as many as ten different compounds and is designed specifically to remain intact under high pressure (Moriguch, 2016). While the exact tire compositions are not publicly available due to trade secrets, Table 3 outlines the general composition of passenger and truck tires (Pehlken, 2005, United States Tire Manufacturers Association, 2020). As a result, tires are difficult to disassemble in either a high tech (breaking a tire back down to its initial components) or a relatively low tech (shredding or crumbing) approach.

Table 3

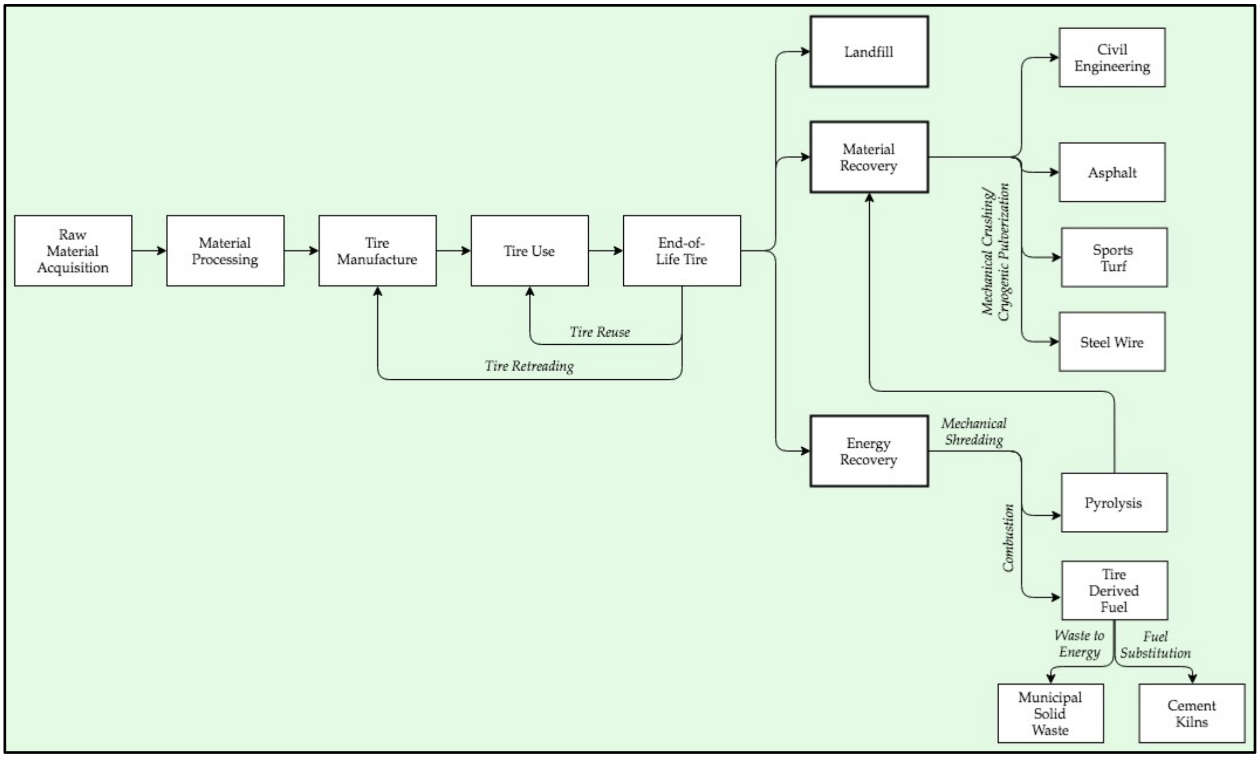
Average Passenger and Truck Tire composition.

Material	Passenger Tire	Truck Tire
Natural Rubber	14 - 19%	27 - 34%
Synthetic Rubber	24 - 27%	11 - 14%
Carbon Black	22 - 28%	25 - 28%
Steel	12 - 15%	14 - 21%
Textile	4 - 6%	0%
Fillers, Accelerators and Antioxidant (Zinc oxide, sulphur, calcium carbonate, clay, stearic acid, phenol and amine antioxidants, wax, thiazole and sulfonic amide accelerators)	16 - 40%	16 - 34%
Average Weight	New 11kg Scrap 9 kg	New 54 kg Scrap 45 kg

Tires are an example of a market sector where the circular economy principles can be applied: they are a clearly identifiable product, designed to last and their collection is unique from all other waste streams. The circular economy for tires starts at the design stage, where raw materials are considered on how they can be best used to create a recyclable product. Next, ensuring the correct pressures and loadings helps to extend the life of tires during the use phase. After the initial use phase, some types of tires are designed for reuse or retreading, mainly OTR, truck and aircraft tires. Finally, the collection and treatment of ELTs can replenish various markets in the circular economy, such as the combustion of tires for energy recovery or the shredding of tires for infrastructure use (Ellen Macarthur Foundation, 2013). The typical life cycle of a tire is further outlined in Figure 2 below (Lutsey, 2006) (Pegg, 2007).

Figure 2

Life Cycle of Tires including End-of Life Treatment Options.



The calculation of used tire statistics is a complex exercise and mainly deals with estimating tire counts (i.e. the quantity of used tires arising in a specific geographic market available for collection and subsequent recovery) and tire treatments (quantity of used tires reused or ELTs sent to material and energy recovery) (ETRMA, 2015).

Originally, scrap tires ended up in landfills, were buried, or burned. Efforts to recover ELTs, and shift away from such applications are being championed by environmentally conscious policies (Díaz-Ferrán et al., 2018). While collection and treatment rates of used tires vary significantly among counties, legislation is driving the tire sector towards recovery and recycling. With collection rates in much of Europe at 100%, the tire industry is on its way to a circular economy. The sustainable ELT market comprises multiple applications with various treatments. One of the markets for scrap tires is through material recovery, where rubber and steel are extracted from the ELT and used as raw material for artificial lawns, industrial models, and asphalt. Another market is through energy recovery, where tires can be used as a fuel alternative. A combination of energy recovery, material recovery, reuse/retreating, and landfilling is how many countries manage and process ELTs.

3.2 Tires in Chile

In Chile, the government estimates that 6.6 million tires are thrown away annually, equivalent to 180,000 tons and a meager 17% collection rate (Alomar, 2019). The tires that are not collected leave the economy through "Open Dumping," brought to a landfill or abandoned outside (Alomar, 2018). Given how prominent the mining industry is in Chile, the majority of the mass of ELTs are Category B tires. Prior to REP, the management of ELTs was a municipal responsibility (Banguera et al., 2018). Two mining regions, Tarapacá and Antofagasta, are the largest producers of ELTs in the country, reaching 70% of the national total, about 140,000 tons of ELTs (Scott, 2019). Chile's large mining industry has led to stockpiles of mining scrap tires that are so enormous, they can be seen from space (Australia's Mining Monthly, 2019).

Chile's tire recycling market is limited to mostly mining and ORT tire recycling. Beginning in 2009, a clean production policy established directions on how to revalue ELTs in the central area of Chile, no bigger than 1.2 meter diameter and no heavier than 100 kg (CINC, 2013). The chosen treatment facilities currently produce crumb rubber that is used in rubberized asphalt, remove scrap steel for steel mills, and have pyrolysis plans in the works (Sheerin, 2018). There are a handful of tire recycling companies in Chile. Polambiente is a pioneer in the grinding and granulation processes of passenger and mining tires in Chile. Their plant can process 2,000 kg/hour of tires with an estimated annual value of approximately 8,000 tons of crumb rubber (Arroyo et al., 2019). There is one cement plant run by Cemento Melón that uses ELTs in cement kilns for fuel. While they have an energy recovery capacity for 15,616 tons of ELTs, in reality they only use 651-918 tons (Coelho, 2018). In northern Chile, there is a pyrolysis plant scheduled to open in 2020 by the tire manufacturing company Kal Tire, which will have the capacity to recycle 7,300 tons of ORT and mining tires annually (Weibold, 2020). While limited to Category B tires, this facility hopes to expand their processing capacity to 25,000 tons.

Currently in the region of Santiago, there are no plants for recycling tires, but there is one company that is planning their installation by REP implementation that already works with the mining sector. The Arrigoni Group also plans to build a tire pyrolysis plant. This plant will be dedicated to Category A tires, and thus is proposed to be no more than 200km from Santiago. This plant will have the capacity to recycle 30 tons of tires per day (Weibold, 2019).

3.3 Tire Case Studies

To better understand which policy interventions to recommend at both the collection and processing level, we researched how other countries manage end of life tires. While Belgium and the United States are not identical to the Chilean context in terms of population or policies, they are similar in their stated ELT collection goals and are regarded as having strong economies in their respective regions (The World Bank, 2019). We also researched Colombia's approach because it is a Latin American country that responded to OECD recommendations for incorporating REP legislation. We did not utilize Colombia in our model, but rather as a means for learning about how a country with a relatively similar GDP (323.803 billion, compared to Chile's 282.318 billion in 2009) utilized specific environmental policies to dramatically increase tire collection rates (The World Bank, "GDP Colombia, Chile, Belgium," 2019). Chile's neoliberal heart necessitates that the ELT solution be economically sound, which both the US and Belgium have managed to achieve. Chile is somewhere in between the US and Belgium in terms of how many tires they will have to manage. When comparing the amount of scrap tires in each county, Belgium has 86,000 tons and the US has 4 million tons, Chile with 180,000 tons ends up being somewhere in the middle when population is taken into account (United Nations Statistics Division, 2019).

The US, Belgium and Colombia represent a juxtaposition in ELT treatment priorities where the former champions energy recovery and the latter two primarily espouse material recovery. Given that Chile is a near blank slate in terms of current ELT treatment infrastructure, both material recovery and energy recovery seem apt endeavors to explore for this report.

3.31 Belgium

Belgium introduced an EPR for tires in 2004 in order to reduce illegal disposal and incentivize eco-design and waste prevention. While waste policy is designed, enforced and reported on a regional level, policies regarding products are handled on a federal level. Most producers collectively outsource their responsibilities under an EPR system to third parties. Belgium's EPR is run by a single third-party entity that has a separate agreement with each region. However, there are no differences in collection and treatment targets among regions (OECD, n.d.).

Their EPR defines the producer as manufacturers and importers of tires including online sellers. They enforce the take-back obligation and advanced disposal fee in the form of a visible fee. The fee for new tires is paid by the consumer at the time of purchase and covers 1) The collection and treatment of tires, 2) Waste tire prevention programs, 3) Communication to the public on the scheme, and 4) The administration of the third-party producer responsibility organization (Winternitz et al., 2019).

The treatment of used tires in Belgium is influenced by coexisting legislation, such as the existence of a tax on incineration, the enabling of the use of rubber granulate as infill material in synthetic sports fields, and the banning of landfilling used tires. This means reuse and recycling are strengthened as most favorable options for waste tires (Winternitz et al., 2019). Today, they are managing an average of 86,000 tonnes of waste tires annually, with recent collection rates above 100%. They have an average material recovery rate of 96% and an energy recovery rate of 4%. They have met their collection target of 100% and exceeded their treatment targets of a minimum of 55% material recovery and maximum of 45% energy recovery as outlined in their EPR (Winternitz et al., 2019).

Belgium is used as a case study because they currently have already met and exceeded the 10-year goal of REP, a 100% collection rate. Moreover, they have also achieved a 100% treatment rate, something Chile strives to do with an ambitious 90% valorization rate by 2028. This country can be used to understand how such noble metrics were achieved and the resources needed to sustain it. Belgium represents a material recovery focused treatment, of which Chile may be more inclined to pursue.

3.32 United States

The US manages used tires through a consumer, which provides insight on a non EPR system for managing scrap tires. In the United States, waste tires are primarily managed at the state level that includes legislation for storage, collection, processing, use and the funding needed to accomplish this programming. In recent years, scrap tire legislation has been a priority in many states. This is an indication that the majority of legislatures recognize that creating viable markets for scrap tires is an essential component of each state's environmental and recycling policies. Currently, 37 states collect fees to fund scrap tire management programs or stockpile cleanup. Tire fees are typically assessed on the sale of new tires or on vehicle registrations. Fees generally range from $0.50 to $2 per passenger car tire, and truck tire fees range from $3 to $5 (US EPA, "Laws and Statutes", 2016). While disparate state programs allow for a range of used tire collection and treatment, collectively, the US collects around 97% of waste tires or 4 million tons but only treats about 81% of this market. This means that only 233 million of the 290 million scrap tires generated are treated. Therefore, landfill disposal makes up around 16% of waste tires nationally (U.S. Tire Manufacturers Association, 2018). Additionally, the US also has an estimated 275 million ELTs in stockpiles which have yet to be treated (US EPA, "Basic Information", 2016).

Tire-derived fuel (TDF) was the first market for scrap tires in the US and from 1979 until 1992, TDF was also the primary market for said tires. Some challenges facing the recycling of tires in the US are the significant capital expenditures stemming from transportation costs, handling and processing equipment and physical space (Sheerin, 2018). Starting in 1992, whole scrape tires were used as feedstock for ground rubber and processed tires were used in civil engineering applications. The US recognized that in order to prevent tires from being stockpiled or disposed of in landfills, diverse markets need to be in place to handle the approximately 290 million scrap tires that are generated annually. TDF remains the largest treatment method for used tires given the viability of this alternative to the use of fossil fuels and its high heating value (US EPA "Markets/Uses", 2016).

The US is used as a case study because they have also met and exceeded REP's ELT collection rate goal, surpassing the 90% by 7%. Furthermore, they represent an important stepping stone in REP's ELT treatment requirements, with an 80% valorization in the US similar to the 80% valorization goal by 2026. The US has embraced an energy recovery method for ELT treatment. This differs greatly from Belgium and provides an alternative path for Chile to consider for valorization treatment. Given these country's similar values of capitalism, economic growth and natural resource extraction, energy recovery may be more attractive to Chile.

3.33 Colombia

Colombia introduced an EPR law in 2007 that covers multiple end-of-life products, including tires (Park et al., 2018). Partially as a means to become an OECD country, Colombia included EPR principles in a national hazardous waste management policy —Prevention and management of hazardous residue and waste: Decree 4741 of 2005—and expanded to include tires in 2010 (Park et al., 2018). Facing increased mobility demand, Colombia imports 5.5 to 6.7 million tires yearly (Park et al., 2018). Additionally, thousands of used tires enter the country unauthorized: 80,000 tires between 2016-2017, which have a short lifespan and are frequently discarded in rivers and public spaces (Alzate, 2019).

In 2015, Bogotá's mayor announced that from June 1st, 2016, all asphalt for road infrastructure must utilize materials from used tires. The following administration reduced the requirement from 100% to 25% of road infrastructure, citing costs (Motoa Franco, 2016). An additional obstacle was the lack of tire pulverization plants in Bogotá, which is necessary to convert tires into materials adept for asphalt (Motoa Franco, 2016). Óscar López, Director of Environmental Control at the Secretary of the Environment explained even using mixed asphalt for all roads would only utilize 10% of the used tires that the city generates (Motoa Franco, 2016).

Resolution 1457 of 2010 outlines requirements for proper end-of-life tire management and prohibits illegal dumping. Producers may establish individual or collective tire collection systems. Article 6 states that the collection systems must allow citizens to return their used tires at accessible collection points, bearing in mind urban population density, not generate costs for consumers when they return the tires, nor require them to purchase new tires, and consider alternative tire usage ("Resolución 1457 de 2010," 2010).

Colombia is used as a case study because it also faces the challenge of illegally discarded tires and is seeking to increase its capacity to process tires once they are collected. In 2012, Colombia met its tire collection goals, but faces the challenge of adequate ELT treatment; the country seems to be prioritizing material recovery (Suárez, 2016). It also has the same 2024 collection goal as Chile—80%, though Chile will have to reach that percentage at a much faster rate (Gobierno de la República de Colombia, 2019).

3.4 Policy Implementation Methods

The OECD identifies four broad categories of EPR instruments, noting that they may be used in combination. They include *product take-back requirements*, e.g. mandatory recycling and collection targets for tires, *regulations and performance standards*, e.g. minimum recycled content for asphalt; notably, the standards can increase product redesign incentives if paired with a tax (OECD, 2016). While recycling content standards are not a prevalent policy instrument globally, we believe they are useful in helping to increase crumb rubber markets and thus achieve compliance with REP treatment goals (OECD, 2016; Product Stewardship Institute, 2015). Based on potential adverse health effects associated with loose fill crumb rubber in playgrounds, we would recommend prioritizing civil engineering applications and/or rubberized asphalt concrete that are less likely to cause environmental damage; rubberized asphalt concrete is advantageous in that it can reduce road lifecycle costs (Wang et al., 2017). *Information-based instruments* increase public awareness and can indirectly help EPR programs, whether through product labeling or reporting requirements (OECD, 2016). While we believe that public awareness is an important aspect of successful REP implementation and visited a *Punto Limpio* in Santiago that had excellent signage and educational material regarding packaging, we think an economic-based instrument that directly affects EPR programs should be prioritized.

The fourth category is *economic and market-based instruments*, which is the category we examine in this section. Market-based instruments include: *Deposit-refund*, *Advanced Disposal Fees*, *Material taxes* in which virgin materials or materials with toxic properties are taxed so that producers are incentivized to use less toxic or recycled materials, and *Upstream combination tax/subsidy* (UCTS) (OECD, 2016). Although material taxes could be earmarked for ELT collection, we had difficulty finding examples of their application to tires; as of 2016, they were used infrequently for any priority product, if at all (OECD, 2016). One argument is that virgin material taxes are best for internalizing extraction damages, whereas taxing waste addresses disposal externalities (Matheson, 2019). UCTS is paid by producers and subsidizes waste treatment, which incentivizes them to change material inputs and product design as well as offering a financing mechanism for recycling and treatment, but they are used infrequently in EPR programs (OECD, 2016).

According to a stakeholder we interviewed in the tire industry, the best policy instrument for collection highly depends on the context: the stakeholders involved, the government, and the technology available for processing the tires once they are collected. One policy instrument is not inherently better suited to a waste-management system and has advantages and disadvantages. However, when deciding which methods to recommend, we considered the potential environmental effectiveness, administrability, e.g. how feasible it would be to operate via *sistemas de gestión* (PROs) or manage at varying governmental levels, and political acceptability. As such, we are suggesting two potential methods: an advanced deposit fee (ADF) and a deposit-refund system (DRS). The benefits and drawbacks to ADF and DRS are outlined in Table 4 below.

Simply put, an advanced deposit fee is a policy method that puts a charge on all consumption of the final material or product, thus increasing the price of the final product to consumers. This method can be leveraged for the collection of ELTs through a fee on tire purchases. An ADF method is employed in the US and in many parts of Europe including Belgium for the collection and treatment of waste tires. The US chose to enact an ADF in order to raise funds to address the stockpile problem and to prevent future problems by increasing recycling and proper disposal (Walls, 2011). Generally, the revenues collected through fees are used to subsidize scrap tire processors or sales of products made from used tires. This system ensures the payment goes directly to the actual recycler.

There are many benefits to this upstream fee method as opposed to the deposit-refund method. First, this avoids the transaction and administrative costs associated with collection and sorting of postconsumer recyclables. Second, paying refunds to processors (recyclers) rather than consumers means fewer transactions, which also reduces administrative costs. Third, incentivizing processing rather than collection may help avoid situations in which materials are collected for recycling but are not actually recycled (Walls, 2011). This arises because processors are paid the subsidy (refund) only when they purchase materials to process and sell for use as an input to the manufacture of a new product. Ensuring a financial stimulus to the treatment phase of ELTs assures that these tires will not be stockpiled or illegally dumped (Ino, 2011). Another important note is that an ADF indirectly affects the market for the recycled material because it reduces the amount of the good available to be recycled (Palmer et al., 1997, Ferguson and Souza, 2010).

An alternative policy instrument that could be applied to facilitate collection is a deposit-refund system. Other countries have used Deposit-Refund systems as a first phase of Extended Producer Responsibility laws or as a precursor, e.g. in Singapore and South Korea, respectively (NEA, 2020; Hong & Park, 2019). Reasons for implementing DRS early-on could include the ability to achieve high recycling rates with low monitoring costs, which may be preferable if the nascent EPR program lacks a robust budget (Gupt & Sahay, 2015). While the MMA does have a budget for REP implementation, if a DRS is well-designed, it could reduce the financial burden on both the government and producers. Another reason for early implementation is that it may be more politically palatable because it does not appear as a tax and thus may reduce initial reluctance to participate (Mrozek, 2000). Policymakers need to decide how to address unclaimed refunds since net revenues could accrue to the regulator and enter a general budget, or policymakers could choose to have a "revenue neutral" implementation, which supposedly does not maximize social welfare, but could more politically appealing because remaining deposits are funneled back into EPR programming (Mrozek, 2000). DRS should include the ability to adjust the fund for refunds if deposits are less than anticipated and thus require additional funding or transfer excess funds if deposits are higher than expected (Mrozek, 200).

DRS have been implemented across the globe and are perhaps the most well known in association with packaging waste, including glass, plastic, and aluminum. It is also well-suited to tires and hazardous materials, such as batteries. One advantage of a DRS for encouraging product take-back is that it reduces the likelihood of 'midnight dumping' in which consumers choose alternative disposal options such as tire burning or illegal dumping instead of paying a tax for legal disposal (Walls, 2013). By receiving a refund, they are incentivized to recycle. Historically, Santiago has experienced illegal tire dumping, so we wanted to choose a policy instrument that would reduce its occurrence. A DRS is also advantageous compared to a Pigovian tax because there are fewer opportunities for tax evasion; a customer pays the deposit when purchasing the tire (Walls, 2013). One caveat is that while a DRS does not reduce waste generation, it typically reduces litter volume because it encourages collection by waste pickers (Gupt & Sahay, 2015).

Table 4

Pros and Cons of ADF and DRS

	ADF	**DRS**
Pros	● Increased Recycling ● No collection costs ● No sorting costs ● Few transactions ● Ensures materials are recycled ● Production decrease ● Consumption decrease	● Increased Recycling ● Production decrease ● Refund incentivizes consumer to return product ● Reduced likelihood of 'midnight dumping' ● Boost urban employment
Cons	● Consumer bears cost ● Good prices are raised unequivocally, regardless if	● Collection costs ● Sorting costs ● Multiple transactions

	consumer recycles	- Does not ensure materials are recycled (illegal dumping)

4. Objectives

4.1 General Objective

To assess the impact of potential strategies for implementing REP for tires on Santiago's urban metabolism using both the framework outlined by Sahely et al. 2003 for Urban Metabolism Studies (Section 1.1) and comparative political analysis. The scope boundary for this study are the 52 comunas that comprise the Región Metropolitana region and the "metabolic" flows assessed are Category A tires, as defined by REP (non-mining use, under 57 inches).

4.2 Specific Objectives

1. Quantify future tire flows in Santiago through Material Flow Analysis (MFA) modeling to help stakeholders understand the potential for outflows to feed different material-recovery and energy recovery markets and budget for implementation costs

2. Select environmental, social, and economic indicators to help the Ministry of the Environment (*Ministerio del Medioambiente* or "MMA") track progress towards broader circularity goals

3. Compare the relative impacts of potential ELT management strategies prioritizing material-recovery and energy-recovery, as well as a hypothetical "business as usual" baseline scenario to further facilitate decision making about potential REP implementation pathways.

4. Consider two types of economic incentive policy methods to promote ELT collection in Chile: advance disposal fee and deposit refunds.

5. Methodology

Section 5.1 outlines the methodology for calculating the annual mass of ELTs year at the end of the REP implementation timeline. We use a material flow analysis framework (MFA) to determine the mass balance of tire outflows from Santiago (Section 5.11). Section 5.12 details how the inflows of tires were calculated, the existing stock of tires in use within the Santiago society/economy, and the predicted quantity in the future. We use this information to calculate annual replacement rates and the consequent mass of tire "outflows."

In section 5.2 we detail calculations for assessing the overall impact of different ELT strategies that will be necessary for successful implementation of REP. We look at three scenarios, a baseline assuming a continued 17% ELT recycling rate, REP implementation prioritizing material recovery, and REP implementation prioritizing energy recovery, and compare their relative impacts from a material circularity, environmental sustainability, human health, and financial perspective. We use the literature to inform our choice of appropriate indicators of these categories and to develop conversion factors and use the information calculated in our MFA to quantify the magnitude of impacts.

This information can help the Chilean MMA and regional local governments understand the tradeoffs inherent in different implementation pathways, balance competing environmental policy priorities, and assess the costs associated with REP.

In order to assess the scope and reach of REP we conducted 9 interviews with stakeholders from government, academia, and industry. These meetings also helped amplify our understanding of current environmental policy in Chile and innovative initiatives to increase recycling at local levels. Summaries of the interviews can be found in Appendix D.

5.1 Tire Material Flow Analysis (MFA)

5.11 Overview

To understand the quantity and mass of ELTs in Santiago at the end of the REP implementation period, our team conducted a Material Flow Analysis (MFA). As noted in Section 1.1, an MFA facilitates analysis of the flows of materials through the economy and environment (McLaren et al. 2000). Hodson et al. (2012) establish the applicability of MFAs to an urban city environment and to the implementation of environmental "interventions." The subsequent sections will detail the elements and calculations of the Santiago ELT MFA.

Having knowledge of the quantity and mass of tires exiting the Santiago economy each year is critical for determining successful REP implementation. Producers can use the predicted quantity of tires to budget for a Deposit-Refund program each year. Third party PROs can use the potential mass of tires for logistics planning; procuring adequate equipment and transportation can require significant capital investment and successful capacity planning is critical for cost reduction. Finally, the MMA can use information about the mass of tire outflows from Santiago to assess the ability of ELTs to provide feedstock for new construction, energy for different sectors, and subsequently collaborate with other government agencies to develop policies and amend regulations required to promote potential new markets. For example, the MMA should promote the development of a competitive crumb rubber market; if the cost of high-quality crumb rubber was more competitive with virgin rubber, then tire manufacturers and other molded product manufacturers might utilize greater quantities of crumb rubber (Product Stewardship Institute, 2015).

Stakeholders that the Product Stewardship Institute (2015) interviewed identified four challenges to strengthening the crumb rubber market: competition with TDF, negative public perception regarding health concerns about crumb rubber on playgrounds, access to scrap tires, and ability to obtain product approval for government procurement. There are a variety of means that the Chilean government could employ, from increasing government purchase of products made from ELTs, investing in R&D to address technical barriers to crumb rubber usage, and support independent studies on public health impacts of residential usage of crumb rubber (Product Stewardship Institute, 2015). Lastly, developing requirements for minimum rubber content in roads would contribute to meeting national goals of reducing greenhouse gas emissions; Wang et al. (2018) found that the usage of combined warm mix asphalt and rubberized asphalt concrete not only improves road performance but also reduces emissions and energy consumption.

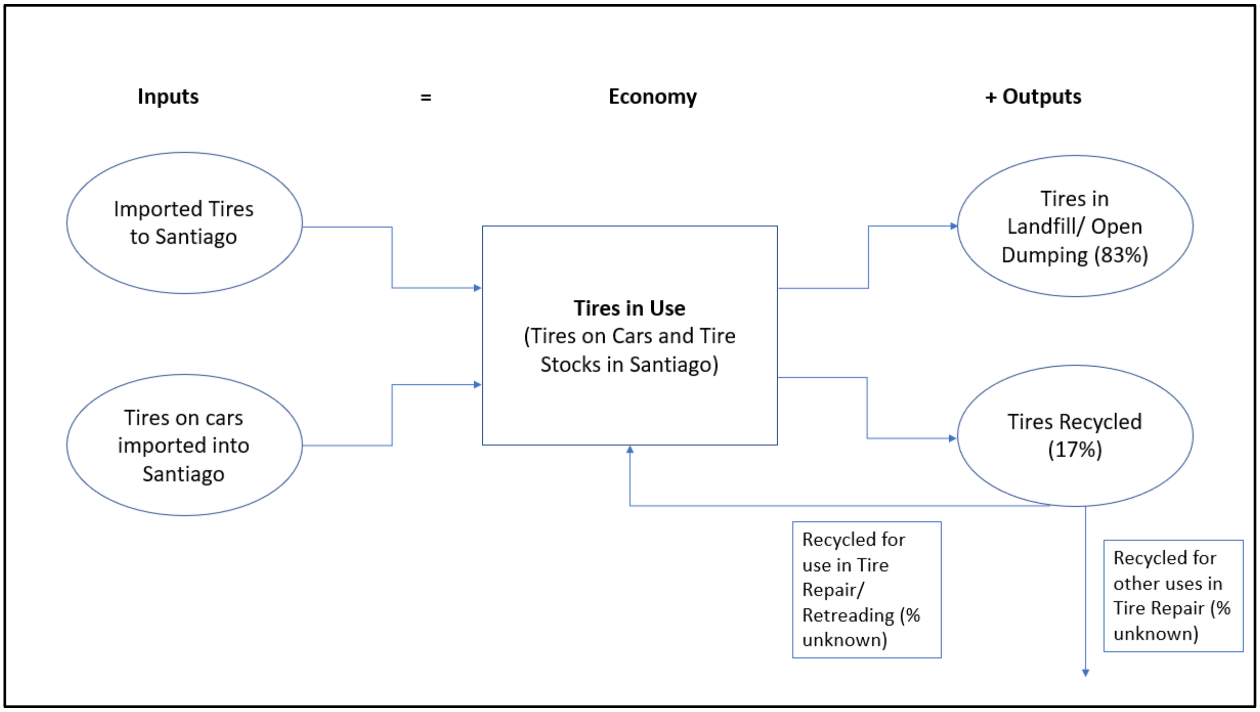
5.12 Mass Balance Calculation

As per the MFA framework, the conceptual mass balance of tires in Santiago RM can be defined by the equation *Input* = *Society/Economy* + *Output*. Our team interviewed a former Goodyear employee in Santiago RM who confirmed that no Category A tires are currently manufactured in Santiago. Consequently, all inputs to the system are imported tires from other countries. These tires can enter as inputs in one of two ways – as tires on imported vehicles and tires that are directly imported.

Society/Economy is defined as the number of tires currently on vehicles or part of the stock of a tire distributor in Región Metropolitana. *Output* consists of tires that have reached the end of their lifetime, leaving the economy. In Santiago, only 17% of tires are thought to be recycled while the rest leave the economy through "Open Dumping," brought to a landfill or abandoned outside (Alomar, 2018). Figure 3 below outlines the conceptual flow diagram of our MFA for Santiago.

Figure 3

Current tire stocks and flows of tires in Santiago



Our team followed the methodology outlined by Sarkar et al. (2011) to determine the estimate of accumulated waste tires through the implementation period of REP. The steps to do so were as follows:

1. Determine the proportion of vehicles of equivalent tire sizes in Santiago, RM and the associated annual tire replacement rates for each category.

2. Determine future vehicle quantity using an econometric method modeling vehicle growth as a function of GDP per capita.

3. Calculate the annual waste tire mass flow rate

5.121 Step 1a – Vehicle Category Proportions

To estimate the number of vehicles in the *Society/Economy* of Santiago, RM we obtained the annual motor vehicle registration permit records (Parque de Vehículos en Circulación, 2001-2018) for the years 2001 – 2018 from the National Institute of Statistics (*Instituto Nacional de Estadisticas* or "INE"). The records contained permits by vehicle type for all regions, provincias, and comunas. The INE methodology of categorizing the vehicles changed multiple times over the 17 years analyzed and our team ultimately identified 10 vehicle types that we included in the categories for our study.

The four overarching categories were assigned using the methodology from Sarkar et al., who grouped vehicles by similarities in tire cost, size, and weight (2011). The vehicle categories contained in the Parque de Vehículos en Circulación and their translation into the four types included in this study are outlined in Table 5 below.

Table 5

Parque de Vehiculos en Circulacion vehicle types and category assignments

Category	Description	Parque de Vehiculos Categories
1	Regular Passenger Vehicles	Automovil y station wagon, todo terreno, taxi basico taxi colectivo, taxi turismo
2	Buses and Light-Duty commercial vehicles (lorries)	Furgon, minibus, minibus transporte colectivo, minibus furgon escolar, bus transporte colectivo, bus transporte escolar y trabajadores
3	Heavy duty commercial vehicles (Mack Trucks)	Camioneta
4	Motorcycles	Motocicleta y similares

The proportion of each vehicle type (P) to all cars in Santiago was calculated for each year through the following equation and then averaged over the 17 years of the study. A table containing the calculated average proportions by vehicle category is included in Appendix B, Table B1. These proportions did not deviate too much year to year so we determined the average was an appropriate representation of vehicles in future years.

5.122 Step 1b – Annual Tire Replacement Rates

For each vehicle category, annual tire replacement rate tire can be calculated using the following equation:

$$R_t = T_t / V_t$$

Where *R* is the replacement rate of the tires per vehicle for a given year t, *T* is the total quantity of tires entering the Santiago RM economy for a given year, and *V* is the total quantity of vehicles in the economy for that year.

To determine *T*, the annual input of tires into the system for each of the vehicle categories, we collected annual statistics on imports of new tires and vehicles to the country of Chile from the UN Comtrade database (UN Comtrade, 2020). Our team assumed that each new vehicle would enter the country with four tires, except for motorcycles which entered with two. As we were unable to find data on the import of tires directly to Santiago RM our team assumed the number of tires entering the region each year compared to the entire country in all four categories would be the same as the proportion of vehicles in Santiago RM compared to the rest of the country. A summary of these proportions can be found in Appendix B, Table B2.

We took the minimum, average, and maximum replacement rates for the 17 years in the study to determine the ranges of R_u to use in step 3. These are summarized for each vehicle category in Appendix B, Table B3.

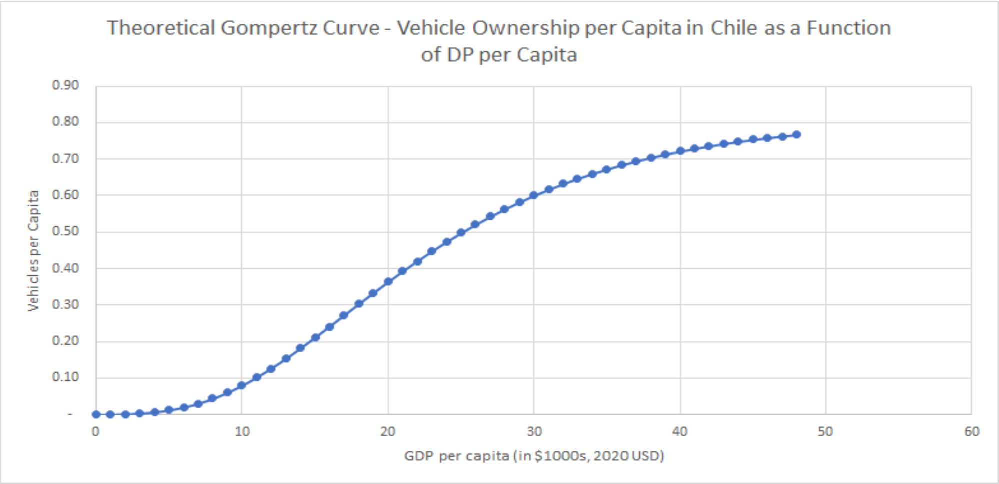
5.123 Step 2 – Anticipated growth in Santiago RM vehicles

Calculation Methodology

Chamon et al. (2008) found that income is one of the determining factors in a country's vehicle ownership rates. In most countries, vehicle elasticity of demand is shown to be high at mid-range GDPs per capita (between $5000 and $10,000 USD). As GDP reaches a range higher than US $10,000 demand becomes steadily more inelastic, meaning vehicle growth slows (Dargay et al., 1997).

One of the econometric approaches to estimating the growth in vehicle ownership is to use a Gompertz Function. Our team used a modified Gompertz function, as outlined in Dargay et al. 1999 to estimate the growth in vehicles growth. A theoretical rendering of a Gompertz curve showing vehicle growth as a function of GDP can be seen in the Figure 4 below:

Figure 4
Gompertz curve of vehicle growth based on GDP



The equation used to predict the vehicle growth as a function of GDP for Chile is given below (Dargay et al., 1997). All constant values used were derived from Dargay et al. (2007).

$$V_t = \theta\gamma^{e^{\alpha e^{\beta GDP_t}}} - (1-\theta)V_{t-1}$$

- **V_t** is defined as vehicles per capita for a given year t. We began vehicle prediction in year 2002 with 2001 calculated vehicles per capita used for year V_{t-1}. For all other years the calculated values were used for V_{t-1}.

- **θ** is the speed of adjustment factor, to capture the speed at which vehicle quantity adjusts to changes in GDP. This value is different depending on whether GDP increases or decreases compared to the previous year. For GDP increases this value was found to be 0.095 and for decreases it was 0.084.

- **γ** is the vehicle saturation level, (the proportion of # of vehicles per 1000 people) at which vehicle ownership will not change. For Chile, this value was found to be 0.81.

- **β** is the high-income elasticity factor (a negative value that captures vehicle ownership growth at high incomes and defines the curvature of the Gompertz curve at high-GDPpp values). For Chile, this value was found to be -0.17 by Dargay, 2007.

- **α** is the low-income elasticity factor (a negative value capturing the speed of vehicle ownership growth at lower incomes that defines the curvature of the curve at low-GDPpp values). For all countries, this value was found to be -5.897 (Dargay, 2007).

- **GDP_t** is the GDP per capita given in USD 2020 dollars.

We then calculated the total number of vehicles in Santiago by using the following equation:

$$\mathbf{C}_t = V_t * Pop_t$$

- C_t = Count of Vehicles in Santiago for year t
- V_t = Vehicles per capita in Chile
- Pop_t = Predicted population of Santiago for year t

Data Collection

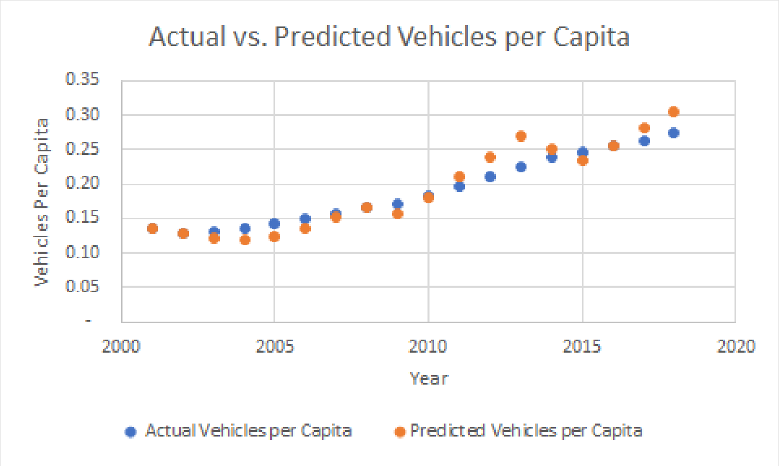
To determine the population of Santiago from 2001 and 2029, our team used population projections for each of the comunas included in la Región Metropolitana (Estadísticas de Demografía y vitales – Proyecciones de Población) provided by INE. Historical GDP per capita values and predictions through 2024 were obtained from the International Monetary Fund (IMF). GDP per capita projections from 2025-2029 were estimated using the predicted future growth rate specified by the OECD for Chile of 3.5% (*OECD, 2020).* All GDPpp values are provided in USD as per the Dargay model.

5.124 Statistical Significance

The prediction power of the model was tested by comparing the calculated values of vehicles to the actual number of vehicles in Santiago RM, as found in the *Parque de Vehiculos* for each year. The model was found to have a strong correlation to the actual historical values, with an R^2 value of 0.95 and a P value of $5.15 * 10^{-12}$.

Figure 5

Actual vs. Predicted Vehicles per Capita



5.125 Step 3. Calculate the annual waste tire mass flow rate

To determine the total number of vehicles in each of the four categories outlined above we used the following equation, as suggested by Sarkar et al. 2011.

$$V_c = PV_t$$

Where P is the proportion of the vehicle category to total vehicles in the category for Santiago that was found in Step 1 and V_t is the total number of vehicles estimated in Santiago for the year in question (t).

Multiplying the annual tire replacement rate for each category by the number of vehicles in each category yields the total number of tires entering the "output" phase of the MFA in each year, meaning the total number of waste tires generated in a given year (N_c) can be defined by the following equation, where R_c is the replacement rate for a given category found in Section 1.

Our team used the values found by Giannouli et al. (2007) for passenger vehicles, light commercial vehicles, heavy commercial vehicles, and motorcycles to approximate the mass of the tires in each category. The estimated mass of tire for each category (M_c) is found in Appendix B, Table B4.

To determine the total mass of tires in kilograms (M) entering the end-of-life phase we used the following equation:

$$M = N_{C1}M_{C1}+N_{C2}M_{C3}+N_{C3}M_{C3}+N_{C4}M_{C4}$$

5.2 Indicators

One of the prevailing critiques of industrial ecology and urban metabolism studies are that the studies frequently seek to understand the material flows without articulating the social, economic, and environmental impact (Hoffman, et al. 2003, Dijst et al. 2018). A common way to articulate this impact is through the use of indicators, or parameters that provide information about the functioning of specific systems that allow for the measurement of change in the system (Science for Environmental Policy, 2018). To that end, we follow the guidance of the Ellen MacArthur Foundation (2015) and translate the MFA of tires in Santiago both into a circularity indicator and additional complementary indicators that assess the impact of strategies on finances, the environment, and human health ("Circularity Indicators", 2015).

Establishing metrics that measure the impact of a policy is an important step for policy decision making, enabling the MMA and other Chilean government actor clusters to balance the tradeoffs inherent in circularity strategies. At the time of our study, there are minimal material and energy-recovery markets in Santiago equipped to handle ELTs diverted from landfill (Alomar, 2020). Further, the country has numerous other environmental priorities, such as Energia 2050 and water conservation, with specific performance targets (See Section 2.2). If certain REP pathways increase material circularity, for example, while compromising one of these other policy objectives then decision makers must be made aware and develop mitigation strategies. We subsequently develop a set of environmental indicators that define these potential tradeoffs.

Quantifying the socioeconomic impacts or policies is also an important step. If recycling processes impact the health of those in the Santiago RM, then the MMA will need to develop new regulations or incentivize different implementation pathways. Understanding the costs associated with these strategies can help producers and the government develop pathways for financing REP (for example, levying an ADF high enough to cover recycling process costs). Finally, indicators can be used tracking progress towards different goals internally, communicating progress to external stakeholders.

To facilitate this type of decision making and understand inherent tradeoffs, our team considered two ELT tire processing scenarios and assessed the relative impact of each. The first was focused on material recovery, using tire materials for use in construction or repairing old tires, the second focused on energy recovery, and the third a baseline comparison. The MMA currently has not established any goals outside of collection and valorization targets for REP; by using the indicators calculated by this model the MMA can develop circularity performance targets and report on progress in other initiatives internally.

5.21 End-of-Life Strategies and Scenarios

There are seven key disposal strategies that this study incorporated into the model:

1. **Landfill or "Open Dumping"** – This method represents the current state of ELT in our study where tires are left in a landfill or out in the open. According to an interview with a former Goodyear employee in Santiago, both methods are currently illegal in the region (C. Patiño Salas, Personal Communication, January 16, 2019).
2. **Waste to Energy (WTE)** – Defined as combustion of tires in a municipal solid waste reactor to recover energy, but not high-quality materials (Sienkowicz et al., 2012)
3. **Fuel Substitution** – The direct substitution of tires for fuel. In this case to be used in the cement industry (Sienkowicz et al., 2012 and Alomar, 2019).
4. **Co-recovery/ Pyrolysis** - The combustion of tires for energy recovery as well as the recovery of potential high-quality materials for resell through pyrolysis (Sienkowicz et al., 2012).
5. **Mechanical crushing** - The crushing or pulverization of scrap tires into crumb rubber or rubber powder for material recovery for use in products such as asphalt or athletic fields, as well as civil engineering (Corti & Lombardi, 2004).
6. **Cryogenic pulverization** – The cooling and chilling materials before fracturing into pieces of crumb rubber or rubber powder for material recovery for use in products such as asphalt or athletic fields, as well as civil engineering (Corti & Lombardi, 2004).
7. **Re-use/retreading** - Using waste tires to repair tires in use and extend their use-phase (Ortiz-Rodriguez et al., 2017).

Our team modeled two potential scenarios for Santiago RM's ELTs; the first based on United States' end of life strategies that prioritize energy recovery (hereafter referred to as

"Energy Recovery Scenario") and the second based on Belgium, emphasizing material recovery ("Material Recovery Scenario"). We also modeled a business as usual strategy that would maintain the current ELT management practices in Chile ("Baseline Scenario"). The proportions of recycled tires undergoing each of the above treatments is outlined in Table 6 below (Recytyre, 2018, US Tire Manufacturers Association, 2018).

Table 6

Three ELT scenarios explored with treatment requirements

	Baseline	**Energy Recovery Scenario**	**Material Recovery Scenario**
Cement Substitution	0%	29.1%	2.9%
Other Waste to Energy	0%	34.1%	0.0%
Pyrolysis	0%	0.0%	0.7%
Salvaged/ Reused	0%	0.0%	7.9%
Mechanical Crushing	100%	36.8%	88.5%
Cryogenic Pulverization	0%	0%	0%

Minimal information was found on baseline tire recycling processes in Santiago. The "chosen treatment" for tires in the northern region of Chile is noted to be "the recycling of rubber and steel materials through mechanical grinding, crushing, and pulverization processes" (Díaz-Ferrán et al., 2018, p. 1). We found that 651 tonnes of tires were used for tire derived fuel in the cement industry in 2014, but were unable to determine whether those tires had originated in Santiago and whether this usage continued through the time of this study (Alomar, 2018). We consequently assumed 100% of recycled tires were processed through material-recovery strategies. We were unable to find information on whether there are cryogenic pulverization plants in Santiago and subsequently assumed all materials would be processed using mechanical methods. That being said, we have constructed the model including cryogenic pulverization as an option if future researchers choose to include this as a pathway.

5.22 Indicator Calculations

Our team selected seven indicators that articulate both the impact of REP on circularity, as well as on the environment, human health, and economics. Details on why each indicator was chosen for Santiago are detailed in the sections below. The magnitude of each indicator for the Baseline, Energy Recovery, and Material Recovery Scenarios were compared to assess which strategy would have the greatest positive impact on circularity.

To calculate each indicator, conversion factors for each of the end-of-life strategies outlined above were established from the literature. All conversion factors incorporate a lifecycle analysis lens, taking into consideration the potential for avoided negative impacts. For example, the climate change indicators for certain strategies appear to be negative representing avoided electricity pulled from the grid and consequent emissions from the combustion of fossil fuels. We selected this approach to account for the first design principle of a circular economy, "design out waste and pollution" ("Circularity Indicators," 2015). Although the positive and negative environmental, health, and resource consumption impacts are often not found within the boundary of a city, these are important considerations in determining whether the urban metabolism of a city is "circular."

The calculation for the Material Circularity Indicator (MCI) is included in Section 5.221. The value of each environmental, human health, and financial indicator was calculated using the following formula:

$$Indicator\ Value = \sum_{d=1}^{7} CF_d * M * P_d$$

- the subscript *d* represents one of the seven disposal strategies outlined above.
- *CF* is the conversion factor of a specific impact category for the disposal strategy *d*.
- *M* is the mass of outflow tires in the year 2029 (the end of the REP implementation time period with a 90% collection and valorization target) which we calculated using the MFA from section 6.1.
- *P* is the proportion of recycled tires allocated to the disposal strategy.

A summary of indicators and metrics that are used in the study, as well as indicators recommended for future consideration, are included in Table 7 and 8 below. Conversion factor values for each ELT disposal strategy are summarized in Appendix B, Table B5.

Table 7

Indicators included in the study

Category	Indicator	Unit
Environmental	Climate Change	kg CO_2 e
	Water Consumption	kg H_20
	Energy Consumption	MJ
Human Health	Carcinogens	g benzo(a)pyrene
	Winter Smog	kg PM
Financial	Processing Cost	$ CLP
	Climate Change Externality	$ CLP

Table 8

Indicators included in the study

Category	Indicator	Unit
Environmental	Ozone Depletion	g CFC_{11}
	Ocean Acidification	kg SO_2
	Eutrophication	g PO_4
Human Health	Heavy Metal Toxicity	g benzo(a)pyrene
Financial	Particulate Matter externality	$ CLP

5.221 Material Circularity Indicator

Since the planet has limited reservoirs of natural materials, the only way to address the degradation of natural resources is to decrease the extraction rate. One of the indicators for assessing this is the Material Circularity Indicator (MCI). According to the Ellen MacArthur Foundation the MCI measures “the extent to which a linear flow has been minimized and a restorative flow maximized for its component materials” (“Circularity Indicators,” 2015). While the MCI is often applied to the material circularity at a product and a company level, our team has extended this framework to look at the stocks and flows of the product (tires) throughout Santiago.

MCI Calculation and Data

To calculate the MCI our team used the methodology and equations outlined by the Ellen MacArthur Foundation ("Circularity Indicators," 2015). The MCI is a unit-less value between 0 and 1 where a perfectly linear flow is below 0.1.

The first step to calculating an MCI is to calculate the Linear Flow Index (LFI), a mass-based indicator that can be derived from an MFA. The LFI also takes a value between 0 and 1 where 0 is a perfectly circular and restorative flow and 1 is completely linear flow. The LFI equation is defined by:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

Where *V* is the mass of virgin materials, *W* is the mass of unrecoverable waste, *M* is the total mass of finished product in the system, W_f is the waste generated to produce recycled content used as raw materials and W_C is the mass of waste generated during the recycling process.

V is calculated using the following equation:

$$V = M(1 - F_R - F_U - F_S)$$

Where F_R is the fraction of feedstock derived from recycled sources, F_U represents the fraction from reused sources, and F_S is the fraction of biological materials used from sustained production. As loop recycling remains a highly experimental practice in the recycling industry, we assumed none of the tires imported to Chile were constructed from recycled materials (Lonca et al., 2018). Consequently F_R, F_U, and F_S are zero.

The equation for calculating unrecovered waste is as follows:

$$W = W_0 + \frac{W_F + W_C}{2}$$

W is the percent of unrecoverable waste, while W_0 is the amount of waste that goes directly to landfill or energy recovery, W_F is the waste generated to produce recycled content used as feedstock, and W_C is the quantity of waste generated in the recycling process.

For waste-to-energy to be considered part of a material-circularity study the material must come from a biological source and be completely uncontaminated by technical materials ("Circularity Indicators," 2015). Since ELTs do not fit these criteria, W_0 consists of all of the waste going to landfill and all of the waste going to waste to energy (conventional waste to energy, pyrolysis, and fuel substitution).

As discussed above, given the lack of closed-loop recycling in tire manufacturing we assumed none of the materials in our scenarios are reused as tire feedstocks. Therefore $W_F = 0$.

W_C is calculated by the following equation:

$$W_C = M(1 - E_C)C_R$$

Where E_C is the efficiency of the recycling process and C_R is the fraction of mass of a product being collected for recycling processes. In this model, C_R represents the fraction of mass going to retreading, material pulverization, or cryogenic pulverization.

E_C for each of the recycling processes was calculated using the following formula:

$$E_c = \frac{Mass\ of\ recycled\ product}{Mass\ of\ ETLs\ entering\ process}$$

Once the linear flow index has been calculated the MCI can be calculated:

$$MCI = 1 - LFI * F(X)$$

F(X) is a utility factor that calibrates the model such that the MCI for products with linear mass flows and a lifetime under the industry average is below 0.1 (Lonca et al., 2018). F(X) is calculated as follows:

$$F(X) = \frac{0.9}{X}$$

$$X = \left(\frac{L}{L_{av}}\right) * \left(\frac{U}{U_{av}}\right)$$

This function considers the lifetime of the assessed product (L) compared to the average product lifetime in the industry (L_{av}), respectively, and the utility of the assessed product (U) compared to the average industry Utility (U_{av}) defined as the number of functional units. Incorporating this into the MCI enables one to differentiate between fully linear products with lifespans and functional units equal to industry-average and one whose lifespan and utility are lower. In this study we were unable to obtain estimates on the serviceable life and number of functional units compared to the industry average for the specific tires entering Santiago, and we consequently assumed (L/L_{av}) and $(U/U_{a}v)$ were both equal to 1, as per the guidance of the Ellen MacArthur foundation.

5.222 Environment

Climate Change

Given the looming threat associated with anthropogenic climate change, CO_2 emissions are a common selection for a key environmental indicator (European Commission, Ellen MacArthur Foundation, 2015). In Chile, climate change is one of the key areas of interest for the Chilean circular economy office ("Cambio Climatico," 2020). Santiago is vulnerable to a variety of impacts associated with increased average temperatures and lower average annual rainfall, which will be felt across socioeconomic classes, with low-income households affected by extreme heat and high-income households subject to a higher risk of floods (Welz & Krellenberg, 2016). The potential negative impacts of climate change on Chile and its urban areas are well documented (Monsalves-Gavilán, 2013) and our team subsequently selected the indicator of "Global Warming Potential" (GWP) expressed as kg of CO_2 equivalent (kg CO_2 e).

GWP for retreading of tires was derived from an LCA conducted by ELTs in Colombia (Ortíz-Rodríguez et al., 2017). The Global Warming Potentials for Material Recovery, Waste to Energy, and Fuel Substitution end-of-life disposal strategies were derived from Corti et al. (2004), a study which conducted a Life Cycle Analysis of different end-of-life disposal strategies in a European context. Emissions from tires in landfills were derived from the US EPA WARM model (ICF, 2019). The global warming potential for material and energy recovery through pyrolysis was derived from a study conducted on mining tires in Chile's Atacama Desert (Díaz-Ferrán et al., 2018).

Resource Consumption - Energy and Water

The Ellen MacArthur Foundation notes that changing the MCI of a product could have consequential impacts on energy usage and water usage ("Circularity Indicators," 2015). While it is expected that implementing circularity strategies would result in a net improvement in energy and water involved in raw material production, given tires aren't produced in Santiago it is important to consider the local impacts on water and fossil fuel stocks of different implementation strategies.

The energy and water consumption for Material Recovery, Waste to Energy, and Fuel Substitution end-of-life disposal strategies were derived from Corti and Lombardi (2004). Conversion factors for retreading were derived from Ortíz-Rodríguez et al. (2017). We were unable to find appropriate conversion metrics for pyrolysis and consequently substituted the conversion factors for direct fuel substitution. While the exact values will of course be different, the tire end-of-life LCA conducted in the Chinese context noted that the overall impact of pyrolysis resulted in negative total values for natural resource consumption (Li et al., 2010). We consequently felt this would provide us with a good relative comparison between different strategies prioritizing energy-recovery and material-recovery.

5.223 Human Health

Winter Smog

Santiago is located in a valley surrounded by the mountains. In the winter months, a phenomenon known as an inversion occurs, and layers of cold air are trapped beneath warm air in the atmosphere preventing air pollution from moving up and out of the metropolitan area (Rose-Pérez, 2015). The link between deteriorating air quality and adverse health effects is well documented within the Santiago RM (Cakmak et al., 2009). Further, air quality has been found to be the worst in areas of increased poverty, making it an issue of environmental justice to address the issue (Rose-Pérez, 2015). Any environmental policies focused on Santiago should consequently consider the impact on winter smog.

Our team chose *Winter Smog* as a key environmental quality indicator, expressed as kg PM. We used conversion factors obtained by Corti and Lombardi to analyze the smog impact mechanical pulverization, cryogenic pulverization, WTE, and fuel substitution (2014). Conversion factors for retreading were obtained from Ortiz-Rodriguez et al. (2017).

No information was available for smog impact of co-recovery of energy and materials through pyrolysis. Li, et al. found that negative respiratory impacts, such as smog, from energy and material recovery pyrolysis from a DALY perspective were comparable to that of mechanical crushing and we subsequently used the value derived for mechanical pulverization for the co-recovery pyrolysis option (2010). More work should be done to determine appropriate winter smog indicators for material and energy recovery through pyrolysis.

Carcinogens

A connection between landfill leachate, emissions, and increased cancer rates amongst people living within 5 km of a landfill was established by Lilycrop et al. (2015). This is often an issue of Environmental Justice; landfills are often located in "sacrifice zones," or fence-line towns that are home to lower-income and minority populations bearing the brunt of negative health impacts (Lerner, 2010). This is particularly true in the Santiago area, where the lower-income comuna housing the Loma de los Colorados landfill, Til Til, has pushed back on the expansion of the landfill citing negative health and environmental impacts (Elgueta et al., 2017, Alvarado & Sherwood, 2018). Consequently, it may be helpful for those developing REP to understand the positive impact of removing tires from the landfill leaching of carcinogenic substances.

Carcinogenic impact is expressed as g of benzo(a)pyrene equivalents and for mechanical pulverization, cryogenic pulverization, conventional waste to energy, fuel substitution, and pyrolysis were derived from the same sources or methodologies as noted under *Winter Smog*.

5.224 Financial Impact Indicators

Processing Costs

Andersen notes that public policy decision makers need to carefully analyze how circular economy principles can provide net benefits from a socio-economic perspective (2007). The Ellen MacArthur Foundation posits that implementing circular economy principles presents an economic opportunity on a macro-level worth billions through both net material savings, mitigation of price volatility and supply risks, creation of employment benefits, and reduced externalities ("Towards the Circular Economy," 2013). We applied this theory to our research by analyzing both the costs that are incurred by the city and how they would be transferred to producers, as well as the potential reduction in negative externalities as a result of different REP implementation pathways.

To estimate the operational costs associated with the energy recovery and co-recovery of energy and materials our team used the life cycle cost analysis conducted by the California Integrated Waste Management Board's (CIWMB) (Peace et al., 2006). Li et al.'s life cycle analysis in a Chinese context provided the life cycle costs of pyrolysis and material grinding and found that per-unit processing costs of grinding was 16% those of pyrolysis. This value was used to scale the CIWMB values and derive a processing cost for material grinding. Our team was unable to find information associated with the retreading of tires and we substituted the processing cost of material pulverization. A review of the literature indicated that retreading was an economically viable and profitable option when available, so we felt comfortable using this cost value. Future work should confirm an appropriate processing cost for retreading one ton of tires.

The cost of bringing one ton of waste tires to landfill was found to be $11.4 USD/ton of municipal solid waste (Grau et al., 2015). It is important to note that waste disposal costs can vary by landfill and by distance required to travel to dump materials. Future work should involve collaboration with regional stakeholders to determine the specific costs of the three regional landfills.

The CIWMB report provided operating costs as a proportion of capital costs (Peace et al., 2006). Consequently, our team used the published purchasing power parity (PPP) of converted USD processing costs to Chilean dollars using the OECD purchasing power parities (PPP) of 288 CLP/USD for the construction to the estimated costs of the local currency ("Conversion Rates - Purchasing Power Parties," 2020).

The processing cost per ton was estimated through the following formula:

Processing Cost/ Ton of Recycled Tires = Annual Depreciation + Operating costs (% of capital costs * total capital costs / ton/year)

Annual depreciation was calculated assuming a 10 year depreciation schedule.

Annual Depreciation = Total capital cost $/ (ton recycled tires/ year) / 10 years

Externalities

Externalities occur when "a transaction between A and B has unwanted, positive or negative, consequences for a third party" (Andersen, 2007). Quantifying the cost of these externalities through the lens of economic activity is critical for assessing the benefits of a circular economy approach.

In 2017, to account for the negative externality of climate change, Chile implemented a carbon tax on all stationary emission sources of over 50 MW of 5 USD/ ton CO_2 equivalent (Elgueta et al., 2017). A green tax is also applied on Particulate Matter (PM) Nitrogen oxide (NO), and Sulfur Dioxide (SO_2). As these latter pollutants are considered "local" the tax per tonne varies according to a formula based upon an annual value provided by the Servicio de Impuesto Internos, population saturation in the local area, and the variable cost of producing electricity.

Our team focused on accounting for CO_2 emissions and global warming in our model. We used the Chilean carbon tax of 5 USD, converted to CLP using an exchange rate of 0.0012 USD/CLP, as the social cost of carbon per t CO_2 emitted to calculate the potential financial benefit/ negative impact from different REP implementation strategies. Future work could involve establishing an externality unit value for emissions of particulate matter through collaboration with the Servicio de Impuesto Internos and the Ministerio del Medioambiente that can be used to further quantify the financial impact of these strategies.

5.225 Indicators for Future Consideration

Environmental Indicators - Ozone Depletion, Ocean Acidification, Eutrophication

Ozone depletion is another area of focus for the Chile Circular Economy office ("Unidad Ozono - Informacíón," n.d.). Chile is a signatory of the Montreal Protocol, and consequently understanding the impact of these different strategies on the emissions of chlorofluorocarbons (CFC's) and other ozone depleting substances is important for the implementation of an environmentally friendly policy. However, Chile has appropriate controls in place to achieve Montreal Protocol targets and consequently, ozone layer depletion is not a high-importance area of impact for consideration for this study.

We considered and decided not to use indicators associated with eutrophication and ocean acidification. Although nutrient flows into and out of the cities are extremely hard to quantify (see Appendix A, Figure A2), and high quality nutrients are critical components of circular urban metabolisms, as of the time of this study Chile does not have significant problems with eutrophication and consequently it is not a high area of focus for the ministry of the environment.

Human Health - Heavy Metal Pollution

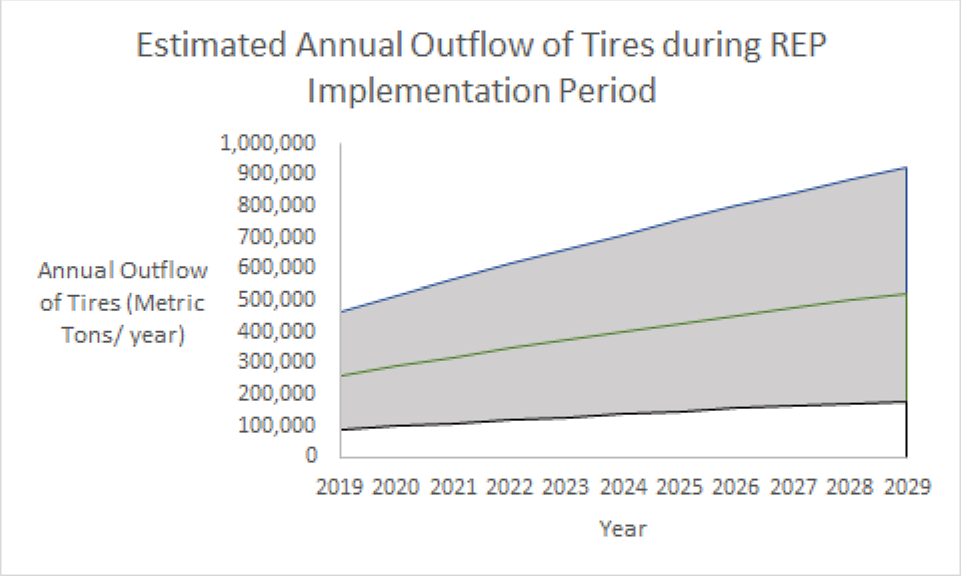
Our team considered assessment of the impact of heavy metal poisoning. Although heavy metal concentrations in Santiago have been found by a team of researchers from Pontificia Universidad Católica, no national monitoring system exists for these metals currently and it was determined to be an area of future exploration (Roldán, n.d.*)*.

6.0 Results and Discussion

6.1 Tire Outflows

Assuming successful collection of tires according to REP targets, the shaded area of the graph in Figure 6 below represents the range of tire outflows in metric tons depending on the replacement rate. The black line represents the minimum replacement rate, the green is the average, and the blue is the highest.

Figure 6
Estimated Tire Outflows



The MMA and la Cámara de la Industria del Neumático del Chile (CINC), the principle organization for tire producers and distributors in Chile, estimate that 100,000 metric tons of ELTs will be produced annually during the REP implementation period (Alomar, 2020). This figure aligns most closely with the values derived from the minimum replacement rate scenarios, albeit is slightly lower. Our team subsequently used this replacement rate for all indicator calculations.

6.12 Calculation Considerations

The methodology used to categorize vehicles by CINC and our study is different. According to a report by CINC published in 2019 it appears as though the number on each vehicle were considered to be different and tires are categorized into two groups, not four (CINC, 2018). Further, the estimated quantities of tires on each vehicle type are 4.99 and 8.75, rather than our estimated value of 4, to account for a replacement tire. The mass of the tire outflows is not given. All of these factors contribute to the differences in the calculated quantity of tires and future work should consider surveys of Santiago drivers and tire distributors to confirm the appropriate tire quantity and mass for the region.

The number of tires in the *Society/Economy* stocks are dependent on the number of vehicles in Santiago, which we estimated based upon GDP. During the course of our study (2019-2020) Chile suffered both political upheaval as well as the global COVID-19 pandemic. The GDP estimates obtained from IMF were calculated prior to both of these events. The long-term impacts of both of these events on country output are unknown as of yet, but it is possible they will negatively impact Chile's GDP growth (Laing, 2020). These GDPpp estimates and associated calculations should be updated as the economic impact of these events are realized.

Replacement rates of tires are influenced by numerous factors, including road conditions, weather, maintenance, and mileage traveled (Sarkar et al., 2011). In comparing the values derived for Santiago to the literature derived values we determined that the replacement rates for Categories 1,2, and 4 were consistent with the literature and our replacement rate range encompassed the values calculated by CINC. Future work to confirm these values should include interviews with key stakeholders and Santiago drivers.

The minimum, average, and maximum replacement rates of vehicle Category 2 are higher than the other categories, but this as well is also consistent with the literature. This could be attributed to two different factors. Passenger vehicles, such as buses, often have dual axle rear wheels meaning they have six tires, rather than four which would increase the replacement rate (Sarkar et al., 2011*)*. Further, public transportation vehicles and light-duty commercial vehicles operate consistently for many hours a day, covering more mileage than the other categories of vehicle and carrying heavier loads requiring more frequent replacement of tires. The replacement rates for vehicle Category 3 are lower than the values given in the literature. It is possible this is due to the assumption that vehicles imported only have four tires, as outlined in Sarkar et al. 2011, while some heavy-duty vehicles may have up to 18. To reconcile this difference, our team recommends conducting additional primary research, including interviewing heavy-duty vehicle drivers in Santiago and other transportation stakeholders.

Our assumptions around tires entering the region is likely a big influencer on our replacement rates. We assumed that the flows of tires into Santiago were the same proportion to the tires entering Chile as vehicles in Santiago to the rest of the country. It is likely that this assumption is flawed and that a smaller proportion of tires entering the country are actually inflows into Santiago RM, instead being held as stocks in a distributor's warehouse. Future work should include determining the actual proportion of imported tires entering Santiago.

6.2 Interpretation of Indicators

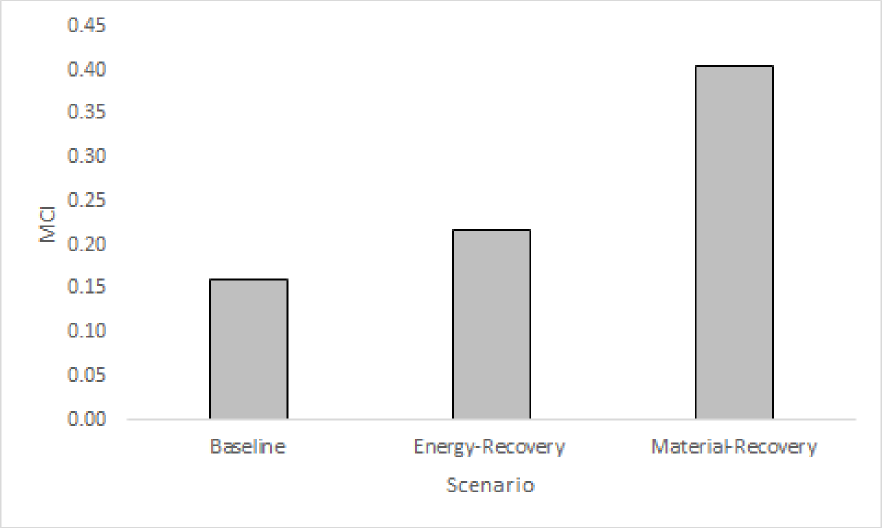
The Energy Recovery Scenario was found to have the greatest positive impact from the perspective of human health (respiratory impact and carcinogens) and natural environment indicators (climate change and resource consumption), while the Material Recovery Scenario is more attractive from the economic and material circularity perspectives. A detailed analysis of each impact indicator category is outlined below.

6.21 MCI

As shown in Figure 7, from a material circularity perspective, the material-recovery scenario had the largest MCI score and thus the greatest positive impact. The Energy Recovery Scenario was only 0.06 points better than the baseline of no REP implementation. This is primarily due to the fact that waste included in energy recovery is considered to be unrecoverable waste, as it cannot be returned to a reservoir or stock of materials.

Figure 7

MCI Scores by Scenario



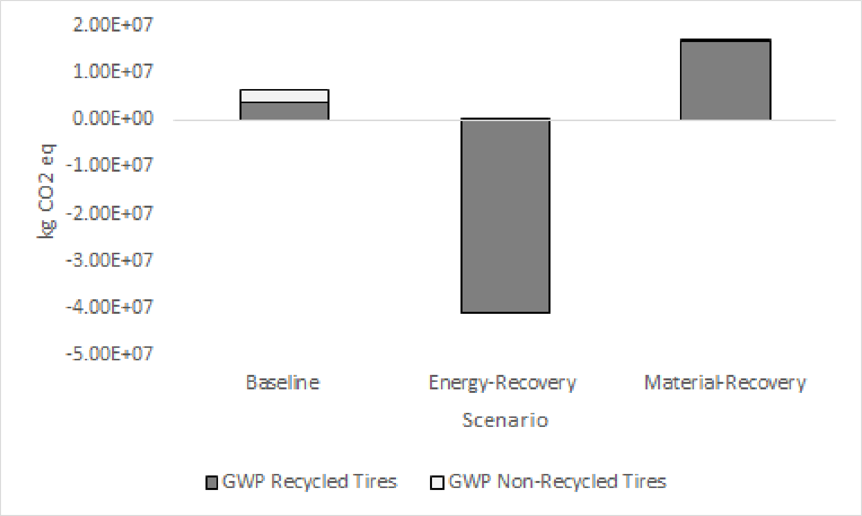
There are a few considerations which might influence the relative impacts of the MCI. First, a large component of W_c (waste generated from recycling activities) comes from retreading, an option which is less viable in Chile than in the country in which the material-recovery scenario was based upon (Alomar, 2018). Secondly, we assumed that 100% of the finished product was derived from virgin feedstocks and not recyclable material. An analysis of tire MCI scores in a Brazilian and European context found that introducing retreading and promoting re-use had a larger positive impact on MCI scores than incorporating more recycled material into the finished product (Lonca et al., 2018). If the MMA were to prioritize the improvement of Santiago's MCI then policies aimed at promoting retreading should be prioritized over policies incentivizing more recycled materials in imported tires.

6.22 Global Warming Impact

The Global Warming Potential for the three scenarios are outlined below in Figure 8.

Figure 8

Global Warming Potentials for Baseline, Energy Recovery, and Material Recovery Scenarios



Between the three different scenarios the United States aligned one had the greatest positive impact on Global Warming Potential. Implementing a high-energy recovery strategy similarly to the United State would result in an estimated 40,411 t CO_2 E avoided greenhouse gas emissions in one year, a 46,876 t CO_2 E improvement over the Baseline Scenario. The positive benefit from waste-to-energy and co-recovery strategies are largely realized due to avoiding emissions normally associated with fossil fuel combustion for electricity and heat generation, as well as avoided energy consumption in the mining and production of fossil fuels for energy generation.

The Material Recovery Scenario had the greatest *negative* impact on Global Warming Potential, representing a 10,627 t CO_2 E *increase* over the continuation of the Baseline Scenario in 2019. This is primarily due to the energy intensive nature of pulverising tires and the grinding and treatment processes for use in retreading (Corti & Lombardi, 2004). This issue, however, should not be considered a deterrent in REP implementation given the heavy risks associated with tires and landfills and the potential Global Warming Potential of these "open dumping"' tires catching on fire, which our modelling does not account for.

There are areas where the impact indicators can be improved through future research. The true impact conversion factors for Santiago are likely to vary slightly from the values provided in our study. The co-recovery through pyrolysis factors were derived from an LCA conducted in the northern part of Chile using electricity drawn from the SING grid, while Santiago RM is on SIC. The central and northern grids produce energy from a different mix of fossil fuel resources, and consequently the emissions factors of these two grids are likely to vary (IEA, 2018). Further, the LCA's conducted for material pulverization, cryogenic pulverization, conventional waste-to-energy, and cement kiln fuel substitution were conducted in Italy, which has an average emissions factor of 382 g CO_2 E/ kWh of electricity produced while Chile's average is 435 g CO_2 E/kwh (Sienkiewicz et al., 2012).

Despite these considerations, the model provides an appropriate relative comparison between the three scenarios and helps identify opportunities for improving circularity. With a higher emissions factor than Italy, the magnitude of impacts of both scenarios will likely be amplified in the Chilean context. Further, while the SING electricity grid has a higher mix of fossil fuels than SIC, the emissions factors of the pyrolysis energy recovery process is likely still less than conventional fuel substitution due to the energy intensive nature of treating pyrolysis liquid for material recovery (Díaz-Ferrán, 2018). Further, pyrolysis represents the end-of-life process for only a small portion of ELTs in the Energy Recovery Scenario and no proportion of the Material Recovery Scenario. If Santiago were to pursue higher levels of material recovery the regenerative nature and global warming impact of processing tires for use in asphalt production or civil engineering could be improved by using on-site renewable distributed energy generation at processing facilities

Finally, it's important to note that CO_2 is a global pollutant, not a localized one. Thus, the positive impacts of Santiago's efforts will not be realized within the boundaries of our study. However, given the role of Chile as a signatory in the Paris Climate Agreement and the unique threats of climate change on the nation, policy makers should consider the impact of global warming potential to be a priority. If making decisions purely based on global warming potential, the energy-recovery scenario would prove to have the highest positive impact.

6.23 Human Health Impacts

The impacts of localized pollutants, carcinogens and PM, *are* felt within the boundaries of the city. Figures 9 and 10 show the impacts of the different scenarios on the human health indicators of smog and carcinogens.

Figure 9

Smog Impact of Each Scenario

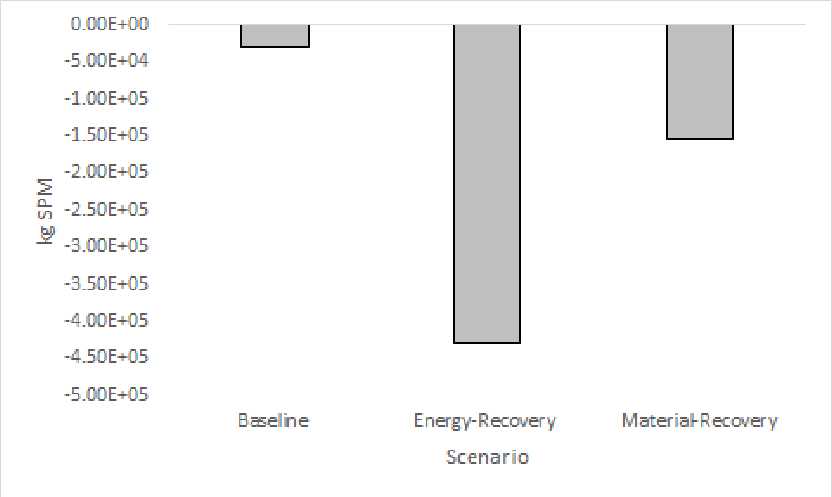
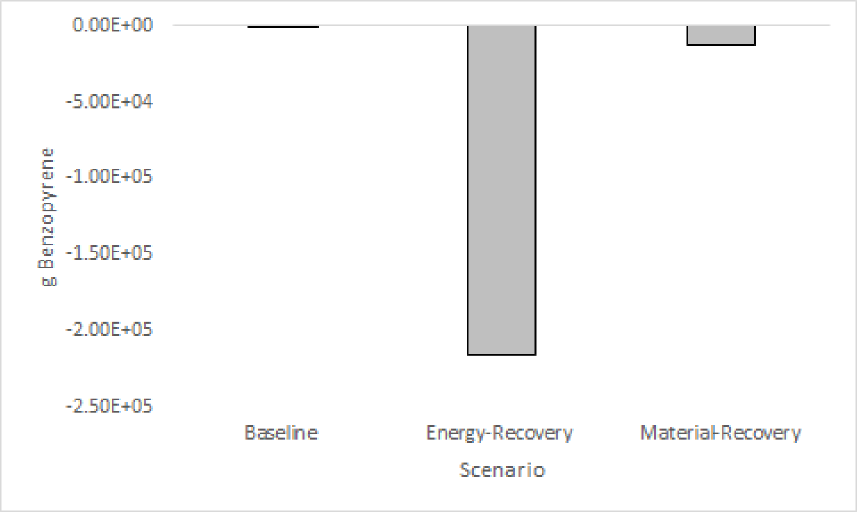


Figure 10

Carcinogenic Impact of each Scenario



The Baseline Scenario performed the worst, even before considering the potential risk of this category. The model assumes that tires in the landfill are undisturbed. If tires were to incinerate this would dramatically increase the concentration of airborne particulate matter, highlighting the importance of implementing REP (Downard et al., 2015*).*

The greatest positive human health impacts would be realized from the energy recovery scenario. That being said, the overall impact on Santiago would be limited. It is estimated that particulate emissions from transportation, estimated to be about 40% of overall city emissions, will be approximately 0.5 kton/year by 2029 (Gallardo et al., 2018). Consequently, waste to energy recovery strategies would be akin to a <0.001% improvement in particulate matter emissions and consequently should not be a key factor in choosing an implementation strategy.

6.24 Resource Consumption

As seen in Figures 11 and 12, the Energy Recovery Scenario had the greatest positive impact on both water and energy consumption. This scenario avoids the water consumption required in fossil fuel energy production, as well as the substitution of tire waste in the direct production of energy. The Material Recovery Scenario, on the other hand, requires a significant amount of water for the grinding and pulverization, and retreading processes as well as energy.

With water availability to Santiago predicted to fall 40% by 2070, there is interest in improving the efficiency of this sector (Gallagher, 2016). Currently, Chilean water companies' average annual non-revenue water (water leakages) of 31%, with 15% considered to be "efficient" (Molinos-Senante et al., 2015). Around 96% of the current Chilean water supply and sanitation sector is privately owned, with the Superintendencia de Servicios Sanitarios (SISS) acting as the financial governance and quality regulating body (Orphanópoulos, 2005). While there are over 53 water and sanitation entities, Santiago's services are mainly provided by Aguas Andinas, the largest water utility in Chile and a foreign owned company (Molinos-Senante et al., 2015). Chile will most certainly be faced with a water deficit and given their strong agricultural and hydro power markets, it will be important to properly account for the needs of all sectors.

Figure 11

Water Consumption of each Scenario

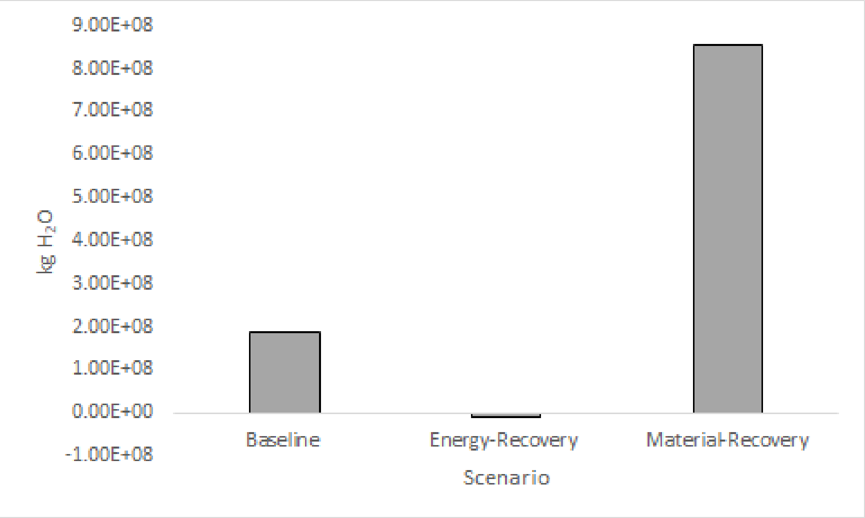
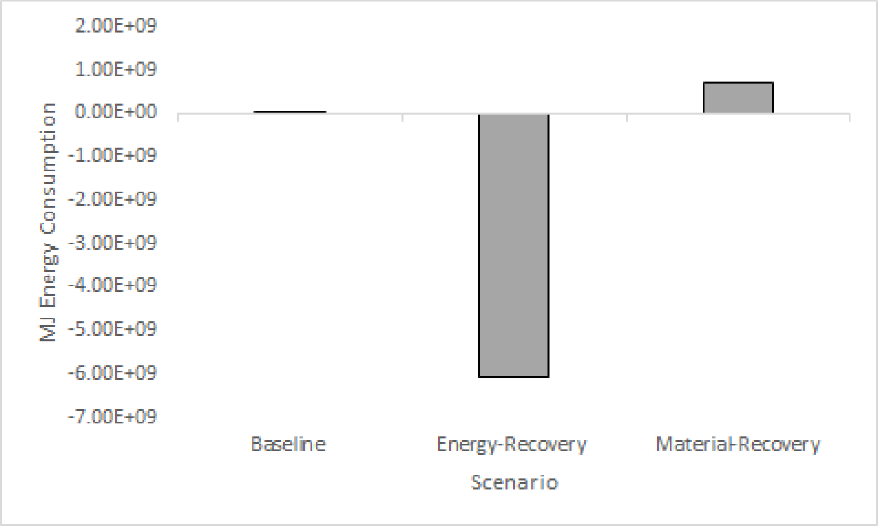


Figure 12

Energy Consumption of each Scenario

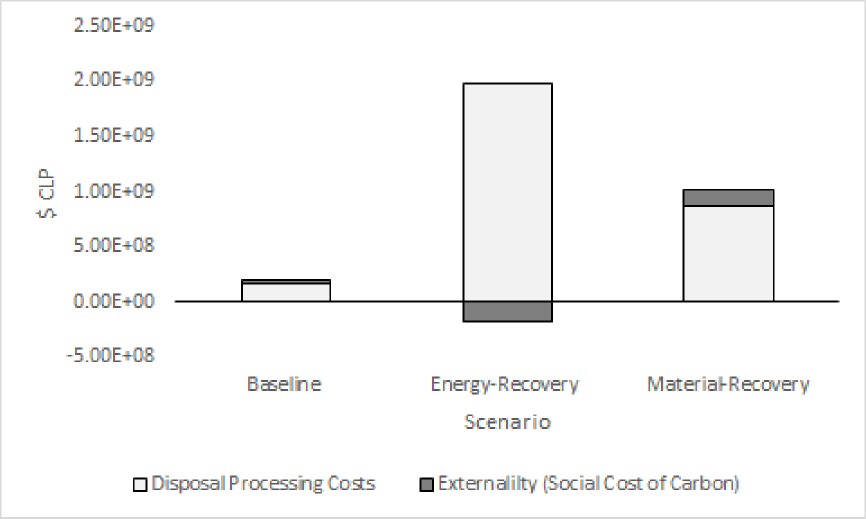


6.25 Disposal Cost and Externalities

Figure 13 highlights the financial impact of each scenario, both the processing costs and the climate change externality.

Figure 13

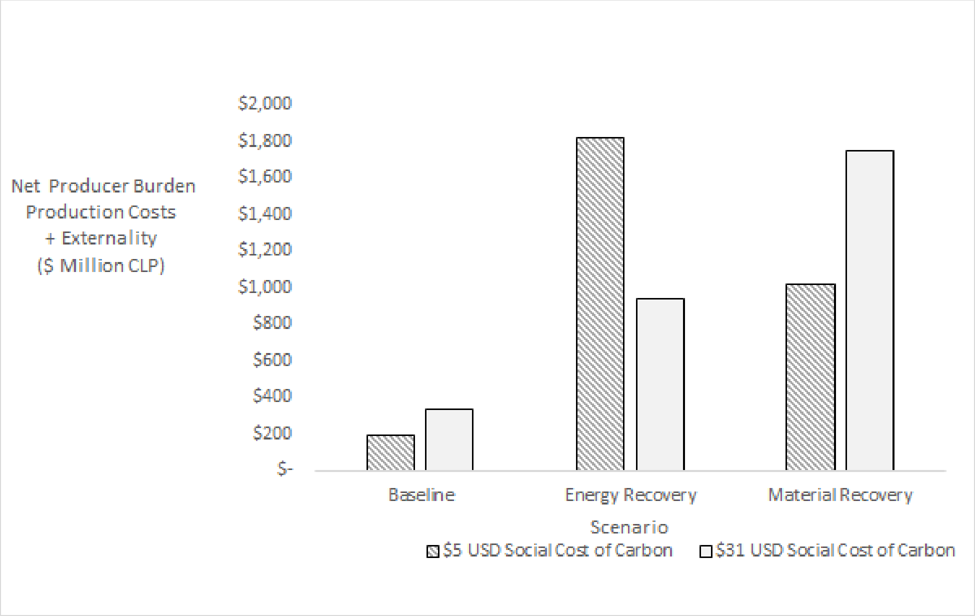
Processing and externality costs associated with each scenario



The Energy Recovery Scenario had the highest processing costs and the $5 USD / t CO_2 social cost of carbon did not improve the cost-competitiveness. Increasing the social cost of carbon would alter this. Nordhaus found that the Social Cost of Carbon for the United States in 2015 is $31/ t CO_2 (2017). With the 2015 U.S. value, instead of the current Chilean Carbon tax, the Material Recovery Scenario becomes more expensive than energy-recovery. This is highlighted in Figure 14 below:

Figure 14

Comparison of net costs under different social costs of carbon



Our study did not consider the potential revenues associated with the different implementation strategies as there are currently few markets for the products obtained from ETLs in Chile (Alomar, 2020). Currently, tire retreading is illegal for private vehicles as well as the front wheels of lightweight commercial vehicles and any public transportation vehicle that can carry more than 17 people (GESCAM, 2017). Only one cement company uses fuel substitution and there has been minimal demand for shredded and pulverized tire rubber for use in other products, resulting in an accumulated stock of about 2,000 tons (Alomar, 2018). Without a resale market an item-based ADF of $82.38 CLP for the Energy Recovery Scenario and $46.15 CLP for the Material Recovery Scenario ($0.10 and $0.06 USD, respectively given 2020 exchange rate) would be required to cover the processing costs and $5 USD Social Cost of Carbon. Calculations are detailed in Appendix C, Table C1. Future work should also consider the collection and transportation costs incurred by PROs.

6.3 Tradeoffs and Application to Chile

While the Energy Recovery Scenario would have the greatest positive impact from the perspective of climate change, resource consumption, and human health indicators, the Material Recovery Scenario performed better in terms of improving material circularity and finances (even considering the current MMA prescribed social cost of carbon). If the objective is to prioritize positive impact across most indicators, the clear recommendation is to focus on policies and partnerships that maximize energy-recovery. These results, however, highlight the tradeoffs inherent in environmental policy implementation and further consideration must be given to how these competing priorities should be balanced.

One strategy is the development of an impact score. Rather than comparing the relative impact of different strategies across the same indicator, an impact score would normalize all categories, weighting them according to importance, and/or provide a single score to facilitate comparison between the two categories. Although there are many existing life cycle impact assessment methodologies that could be modified to apply to this study, they were developed using the social, environmental, and economic priorities of different regions and thus do not represent the priorities of Santiago, Chile. Further, these impact assessment methodologies are not directly applicable to a dynamic model focused on urban metabolism.

While additional research is required to develop an official weighting scheme, analyzing the model results through the lens of existing environmental policy in Chile leads our team to recommend more focus on policies and economic incentives that prioritize the positive impacts on resource consumption and climate change. The World Bank notes that Chile has the highest energy consumption in South America and that energy consumption is expected to have an annual growth of 4.1% between 2015 and 2030 (Nasirov et al., 2018). As shown in section 6.22, investing in energy-recovery can result in net reduction of greenhouse gas emissions, enabling progress towards the GHG reduction targets outlined in Energía 2020 and the Paris Climate Accords. Further, avoiding water consumption through conventional energy production is essential given the impending water scarcity issues noted in Section 6.24.

The interviews conducted with public and private sector stakeholders corroborate this issue. Recycling rates of plastic packaging greatly increased as consumer education and demand for responsible packaging grew (A. Correa, personal communication, August 26, 2019). While this stakeholder was referring to packaging and not tires, he did acknowledge that the market for returnables is huge in Chile; perhaps if there is already a culture of returning products that require high amounts of energy to produce, there will be a willingness to return tires. Another stakeholder in the private sector pointed out that Chile lacks technical and material requirements, e.g. that a road has to have 10 or 30% recycled rubber and that there is not a well-developed tire recycling industry (C. Patiño Salas, personal communication, February 6, 2020).

Prioritizing material circularity in an impact score becomes even less attractive when considering the demand for crumb rubber. The MCI is calculated assuming there is demand for recycled tire products; circularity is not improved if ELTs become stocks of scraps within the economy (Alomar, 2018). According to Chile Neumáticos, an association of 22 companies representing the majority of Class A tire sales in Chile, the current capacity for recycling tires in Chile is just over 32,000 tons/year – insufficient to cover the expected outflows calculated in

Section 6.1 (Alomar, 2020). Chile needs to foster a demand for products containing recycled tires as well as invest in improved tire recycling facilities. Manufacturers and industries that utilize ELTs need to have the confidence that they will be able to obtain a steady supply of waste tires before making investments; the Chilean cement industry could process between 25,000 to 30,000 tons of waste tires as TDF after investing in the appropriate technology (Alomar, 2018). As such, energy recovery is a viable possibility, assuming investment and supply issues are addressed.

While the focus of our study is on the end of the REP implementation period, and indicators discussed above were calculated using projected 2029 tire outflows, the model can be used to assess tire outflows and the impact throughout the implementation time period. This is useful for calculating the quantity and mass of accumulated ELTs as the markets for crumb rubber and capacity for waste-to-energy are expanded.

6.31 Policy Implementation Interventions

The COVID-19 pandemic has taught us that the dependency on one sector makes us vulnerable. Coupling the waste tire market to one particular treatment would be unwise. A mixed treatment market would be more resilient and could be included in REP legislation via treatment minimums, to ensure its application. For example, we are encouraged by the efforts by the MMA and the Ministry of Public Works to incorporate sustainability standards in the 2021 highway manual and incentivize the use of recycled rubber in public highways (Alomar, 2020). The Ministry of Housing is also updating standards for recycled rubber in urban public spaces and we are eager to see other forms of collaboration that normalize the use of recycled rubber (Alomar, 2020).

Implementing REP for ELTs will require a management system that will be composed of a network of local suppliers or collectors, collection points, reprocessing plants, a final disposal and a market, where the products derived from the separated and recycled waste is negotiated. All of these actor clusters will have to be considered and engaged in the implementation on continuation of REP.

There are many facets of REP that can be customized to best fit the case of Chilean ELTs. One of the important decisions Chilean producers will have to make is whether to organize themselves individually or collectively (through a PRO). Multiple PROs can lead to gaps in data so it is important that if this approach is pursued, penalties for incomplete reporting are enacted. Moreover, whether or not to employ a free market system or a traditional EPR system to collect tires needs to be determined. The former would mean that collectors contract individually with specific collection points, giving collectors control over the price of their service. The latter would mean that the PROs contract with the collectors, not the collection points. This changes the influence and power individual collectors have during negotiation.

REP will have to determine collection points. These areas could be garages, tire retailers or municipalities. Furthermore, these collection points must specify if they will have a "1-for-0" principle (waste tires must be accepted even if no new tires are purchased) or a "1-for-1" principle (only accept waste tires in return for a sold tire). Clarity as to when exactly a tire becomes waste will be important so that all collectors are on the same page for determining reusable and retreadable tires. Chile will also have to decide whether or not to include tire stocks into the legislation, where part of the ADF's profit could be allotted to clean up historical stocks of waste tires. If Chile pursues the DRS route, policymakers and stakeholders will need to recognize that DRS is not self-financing and will require continued investment; recycling of priority products does not generate money, but can save municipalities money (Deloitte, 2019; G. González & T. Saieg, personal communication, August 30, 2019).

Regarding implementing a DRS, policymakers would need to calculate the marginal social cost of solid waste disposal to achieve an optimal deposit-refund rate (Matheson, 2019). There are high compliance costs associated with DRS and deposit rates would need to increase as income levels rise to compensate customers for their effort (Matheson, 2019). Utilizing DRS for collection is an excellent means for stimulating urban employment, incorporating and formalizing waste picker labor, and engaging the public in promoting circular economic activities.

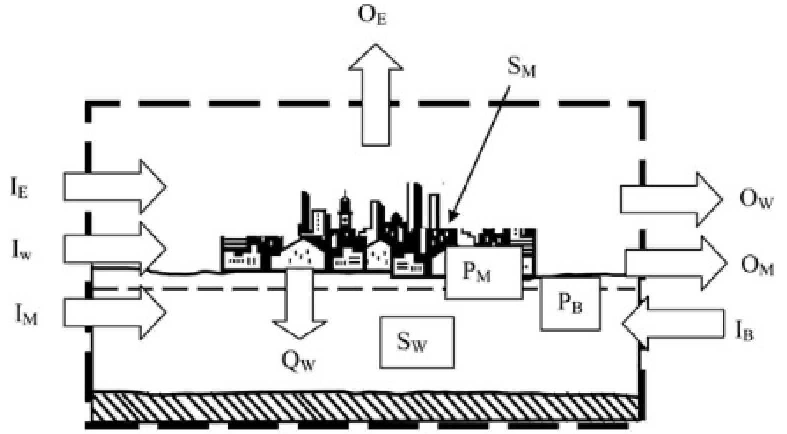
Banguera et al. (2018) uses a reverse logistics network to model the optimal sets of service centers, collection centers and reprocessing plants in RM, given a maximum benefit/minimum investment for an ELT management system under REP. In this system, they utilized the current 13 local suppliers of recyclable separated waste and outlined a set of potential collection centers and a set of potential reprocessing plants. This study may be useful for determining the financial viability of ELT waste treatments and ELT collection ratios scenarios.

In summary, the tire collection and treatment cases were studied for Santiago de Chile, as it pertains to the implementation of the REP law. Through data collection and stakeholder interviewing, two scenarios were modeled, alongside a business as usual model, with the main findings being that the energy recovery has the greatest positive impact in terms of human health, climate change, and resource consumption indicators, whereas material recovery is better in terms of finances and improving material circularity. These results provide a tool that can guide the MMA, stakeholders, and researchers in developing the best pathway to implement an effective tire recovery and treatment market that not only meets REP's goals but minimizes environmental, social, and economic impacts, both in Santiago and in Chile.

Appendix A

Figure A1

Proposed Standard Urban Metabolism Framework by Kennedy and Hoornweg (2011).



Inflows
- Biomass [t & J]
  - food
  - wood
- Fossil Fuel [t & J]
  - transport
  - heating/industrial
- Minerals [t]
  - metals
  - construction materials
- Electricity [kWh]
- Natural energy [J]
- Water [t]
  - Drinking (surface & groundwater)
  - Precipitation
- Substances [t]
  - e.g. nutrients
- Produced goods [t]

Production
- Biomass [t & J]
- Minerals [t]

Outflows
- Waste Emissions [t]
  - gases
  - solid
  - wastewater
  - other liquids
- Heat [J]
- Substances [t]
- Produced goods [t]

Stocks
- Infrastructure / Buildings [t]
  - construction materials
  - metals
  - wood
  - other materials
- Other (machinery, durable) [t]
  - metals
  - other materials
- Substances [t]

Figure 1 Urban systems boundary broadly showing inflows (I), outflows (O), internal flows (Q), storage (S), and production (P) of biomass (B), minerals (M), water (W), and energy (E). t = tonnes; J = joules; kWh = kilowatt-hours.

Figure A2

Water, Nutrient and Energy Flows

Water Flows:

Water is considered to be one of the most significant flows into and out of an urban environment. The first, water, is a critical input and serves as the basis for many purification processes and as a means to remove wastes from the system. Equated to the blood of an organism by Warren Rhodes and Koenig (2001), it is also generally the largest input into an urban environment by mass (Kennedy et al., 2007). Most water is discharged from the system as waste.

The development of a city can have a significant impact on water flows. One study compared Hong Kong's metabolism between 1970 and 1997, a time period where the small city's population grew by over one million people each decade (Kennedy et al., 2007). Additionally, the study found that domestic and industrial water consumption increased by 30% and 60% respectively and Hong Kong needed to increase the amount of freshwater imported from 23% to 75% as it exceeded the supply that was locally available in 1979. Increased wastewater inputs by nature lead to an increased volume of wastewater discharge, and pollute the surrounding areas (Warren Rhodes and Koenig, 2001). Kennedy et al. 2007 notes that this trend is ubiquitous and that the six urban metabolism studies conducted after 1990, an era of relatively high economic activity, almost all have higher water consumption and wastewater outputs than the studies of Sydney and Brussels conducted in the 1970's (Warren Rhodes and Koenig, 2001).

The direct relationship between the increased development of a city and increased freshwater demand can engender negative ecological impacts, such as depleted groundwater tables and aquifer contamination. Understanding the metabolic processes of a city that influence its water demand can help urban planners and city engineers develop integrated water-supply management and wastewater management policies.

Energy Flows:

Cities account for nearly 70% of greenhouse gas emissions in the energy sector (IEA, 2016). Consequently, energy balances are an important component of an urban metabolism study, although one that is less consistently analyzed. The reasons for this are further discussed below.

Douglas (1983) devised the following theoretical equation to quantify a city's surface energy balance (Sahely et al., 2003).

$$\mathbf{Q_S+Q_F+Q_I = Q_L+Q_G+Q_E}$$

With inputs into the system defined as follows:
Q_S = rate of arrival of the sun's radiant energy
Q_F =the rate of generation of heat due to combustion
Q_I = rate of heat arrival from the Earth's interior

And outputs of the system defined as follows:
Q_L is the rate of heat loss due to evapotranspiration
Q_G is the rate of heat loss by conduction to soil, buildings, roads

$Q_E$is the rate of heat loss by radiation.

This is an aspirational equation, as it needs to be driven by data that is not easily accessible data. With the exception of the study of Brussels conducted by Duvigneaud and Denaeyer-De Smet (1977), most urban metabolism studies only focus on anthropogenic energy sources and consumption, ignoring natural sources of heat and radiation from inputs as well as all heat and radiation losses from evapotranspiration, soil conduction, and any natural advection (Kennedy et al., 2007).[1] This approach, however, leaves out environmental considerations that influence energy demand and climate change, such as the urban heat island effect where the temperature in metropolitan cities is several degrees higher than that of other natural areas (Barles, 2010).

There are several factors that have been shown to influence the energy demand of a city. Changing the industry trends of a city has been shown to influence the per capita energy demand, with increased industrial processes requiring increased energy inputs (Warren Rhodes and Koenig, 2001). The temperature of the city will also influence energy demand, as warmer winters and cooler summers require less energy inputs to maintain population comfort (Kennedy et al., 2007). A city's population density has been shown to have a negative relationship with the energy consumption per capita of the transportation sector.

As noted above, one of the major challenges with quantifying the urban energy balance is the availability of data. A study by Voskamp et al. (2018) noted that in general energy data incorporated into urban metabolism studies is insufficient to inform detailed policy interventions and data is required on a temporal spatial scale of hourly data by neighborhood or higher.

Nutrient Flows:

Nutrients are another important input and output to the field or urban metabolism, and one of the hardest due to the diffuse nature of commercial food systems. It is estimated that 90% of nitrogen and phosphorus flows are associated with food production and consumption (Kennedy 2007). Other nitrogen flows are associated with combustion processes releasing NO_X. Nutrients typically exit the system through municipal wastewater flows or as food waste. Nutrient overloading in a system can lead to environmental problems, such as ground water pollution and eutrophication (Kennedy et al., 2001).

It is extremely challenging to estimate the balance of food consumption and production in a specific region due to the widespread and dispersed nature of commercial food systems (Sahely et al., 2003). Consequently, urban metabolism studies that attempt to quantify nutrients keep this focus extremely narrow (Kennedy et al., 2001). Two UM studies have been conducted since the 2000's focused on quantifying nitrogen flows in and out Bangkok and Toronto. Both studies found that their respective city's rates of nutrient re-uptake were less than 10%, making this resource flow a particularly exciting focus area for proposed policy and technical interventions (Færge et al., 2001, Forkes, 2007).

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[1] Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The changing metabolism of cities. *Journal of industrial ecology*, *11*(2), 43-59.

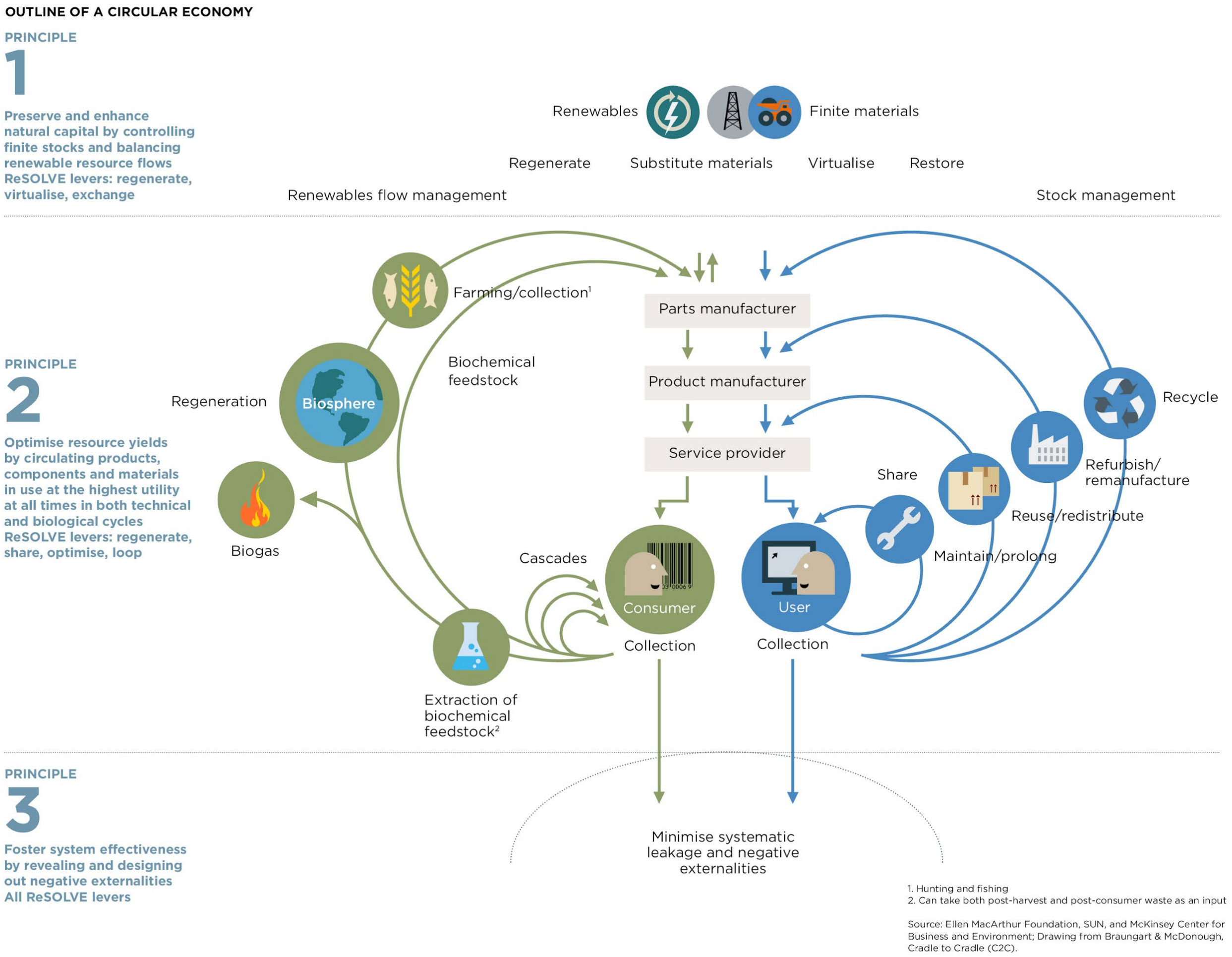
Figure A3

Proposed definition by Korhonen et al. (2018)

> “Circular economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows. Successful circular economy contributes to all three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates” (Korhonen et al., 2018, Page 39).

Figure A4

Circular Economy System Diagram, with the goal of rebuilding capital (Ellen MacArthur Foundation, n.d.)



OUTLINE OF A CIRCULAR ECONOMY

PRINCIPLE

1

Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
ReSOLVE levers: regenerate, virtualise, exchange

PRINCIPLE

2

Optimise resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles
ReSOLVE levers: regenerate, share, optimise, loop

PRINCIPLE

3

Foster system effectiveness by revealing and designing out negative externalities
All ReSOLVE levers

1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

[2]

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[2] Ellen Macarthur Foundation. (n.d.) Circular Economy System Diagram. (n.d.). Retrieved from https://www.ellenmacarthurfoundation.org/circula r-economy/infographic

Appendix B

Table B1

Santiago RM Average Proportion of Vehicle Category to Total Vehicles (P)

Vehicle Category	P (%)
Category 1	74
Category 2	8
Category 3	14
Category 4	4

Table B2

Santiago RM to entire country vehicle proportions by category

Year	Category 1	Category 2	Category 3	Category 4
2001	43%	45%	32%	51%
2002	46%	44%	33%	48%
2003	46%	45%	32%	52%
2004	47%	45%	32%	56%
2005	47%	45%	31%	57%
2006	47%	44%	31%	62%
2007	47%	45%	31%	65%

2008	47%	45%	30%	62%
2009	46%	44%	30%	60%
2010	45%	44%	30%	57%
2011	45%	43%	29%	55%
2012	45%	43%	29%	53%
2013	44%	43%	28%	51%
2014	44%	43%	29%	51%
2015	44%	43%	28%	50%
2016	43%	43%	28%	50%
2017	43%	43%	28%	50%
2018	42%	43%	28%	52%

Table B3

Minimum, Average, and Maximum Tire Replacement Rates by Vehicle Category

Vehicle Category	Minimum Tire Replacement Rates	Average Tire Replacement Rates	Maximum Tire Replacement Rates
Category 1	0.64	1.01	1.25
Category 2	2.11	6.99	12.71

Category 3	0.63	2.08	3.51
Category 4	1.52	2.89	6.37

Table B4

Predicted mass of tire in each vehicle category

Vehicle Category	**Predicted Mass per Tire (kg)**
Category 1	7.26
Category 2	8.16
Category 3	19.96
Category 4	3.63

Table B5

Summary of Conversion Factors for every 1000 kg of ELTs

	Environment/ Resource Consumption			**Human Health**		**Circularity**	**Finance**
Disposal Strategy	**Greenhouse Effect (kg CO2)**	**Water Consumption (kg Water)**	**Energy Consumption (MJ)**	**Carcinogens (g Benzo-a-pyrene)**	**Winter Smog (kg PM)**	**Efficiency Rating (with Tire Pieces)**	**Processing Cost ($ CLP)**
Retreading	1318.1	16.69	19571	-0.05	0.054	0.279	5,552.61
Mechanical pulverisation	122.0	6087	4968	-0.05	-1	0.768	5,552.61

Cryogenic pulverisation	455.0	93,503	10,641	31	1	0.771	7,128.00
Conventional Waste-to-energy	-870.0	-4538	-94,258	-3	-5	0	21,384.00
Fuel substitution	1.0	-2585	-24,109	-1	-2	0	10,044.00
Pyrolysis	-609.3	-2585		-1	-1	0.430	28,512.00
Landfill	18.1						9,525.00

Appendix C

Table C1

ADF Calculation of Energy Recovery and Material Recovery processing and externality costs.

	Energy Recovery Scenario	**Material Recovery Scenario**
Estimated disposal costs incurred by producer ($CLP)	1,984,528,486.84	875,983,468.81
Estimated quantity of ELTs in 2029 (using minimum replacement rate estimates) (#)	22,043,949P	22,043,949
ADF required to cover processing costs (disposal costs / ELTs) ($ CLP)	**90.03**	**39.74**
Estimated externality ($5 USD social cost of carbon) ($ CLP)	(168,505,065.82)	141,294,847.60
Net producer burden (disposal costs + externality) ($ CLP)	1,816,023,421.02	1,017,278,316.41
ADF required to cover processing costs & externality (net producer burden / ELTs) ($ CLP)	**82.38**	**46.15**

This rudimentary calculation of an ADF is an example of how the model can be used for planning and budgeting purposes, although future financial analysis on ADFs should be conducted with updated transportation and processing costs.

Appendix D

Government
Municipalities face huge deficits, approximately $340 million/year, on waste management, three-quarters of which is spent on collection. Increasingly, people want to be involved in recycling; politically it is attractive to provide neighbors with ability to recycle and compost. Municipalities will not make money with REP, but it will alleviate some of the costs associated with collection. REP does not allow a fixed price per ton, e.g. of plastic, and instead is more similar to how Belgium operates in that there are three options: 1) the municipality does the collection with their own trucks and personnel, 2) PROs do a tender and the best collector gets the contract, which sets the price, and 3) the municipality decides to do the tender and contract with public providers; the PRO states the competitive collection standard.

Industry
A key differential of their recycling model is the education that happens at the recycling stations. They are studying and implementing 'nudges' to see if it changes human behavior, e.g. where information is posted at the recycling centers, the height of the glass station, etc. If people become better at recycling, the post sorting phase will be easier for the operators. Chile is a good market for pilots; companies feel pressure from consumers and from legislation on packaging solutions and REP helps to accelerate these changes. Chile is a huge market for returnables and lots of clients are interested in developing refillable systems.

Industry
Tires are one of the most critical pollutants in Chile; there is a lot of illegal dumping in fields next to highways. The EPR law was inspired by the European Union, but there is a lack of recycling industry in Chile. There are a lot of initiatives on the web on using materials that come from tire waste, in different civil engineering applications, but Chile does not have technical manuals that require a certain percentage of rubber in roads or bricks. The main use of waste tires in Chile is as an energy source for the cement industry, which is not environmentally friendly. It is not that some kind of waste management system is better than the other, it is which is better than the other depending on the context, the stakeholders involved, the government, and the different policies. In REP, there are financial questions that need to be clarified, particularly surrounding the *instrumento de caución*; if a recycler cannot afford that amount of money, then it would be very difficult to establish a collective system.

Government
Waste evaluation showed that 50% of waste was organic matter; if wanted to have a large impact on the budget, would need to address this fraction. Informal waste pickers tend to work with plastic, metal, and paper in the municipality, which is less than 5% of waste in some cases. As such, the waste pickers were already organized; it did not make sense for the municipality to

focus on that fraction. The culture change did not come out of thin air, it came because collecting and processing organic waste was a means to reduce pressure on the municipal budget. It's a complete cycle: trucks collect household food waste, bring it to the treatment plant, it becomes compost and humus, and it is used in the municipal nursery. Many municipalities do not have the land necessary for this scale of composting and vermiculture. Not all municipalities have the same reality – they need to evaluate their situation so they can apply policies that are tailored to their context.

Government
Provided valuable suggestions on where we could find data and which entities to contact, e.g. SISS, CNE, SEC, CONAF, SECTRA. Santiago has challenges with air being trapped, due to the geographic situation. There are good norms related to particulate matter, but Santiago will always face these challenges. Santiago is growing very fast due to people relocating for work. The government is trying to implement policies related to electromobility, metro lines are being added and public buses are electric. The government is interested in developing public infrastructure and transport. REP is going to facilitate more waste moving to recycling. Another recent policy to address waste is the No More Bags law.

Government
There has been an increase in citizen participation, but it could improve in regards to local issues. Chile is a super consumerist society, which affects people's awareness of issues and engagement. More interaction among people would be better for the city. Community development plans are participatory, with workshops at schools and neighborhood meetings. REP is super important, but there is still a lot that needs to be clarified and the implementation period will require a lot of adjustments. The municipality will have to decide which management model it wants for its territory. Mayoral continuity has been key here because environmental programs were able to be continued instead of falling through when political will changes. One issue that needs to be solved is the inequality in municipality revenues; some municipalities have to seek outside funding for environmental projects, not that they are unable to implement the programs, but it is more challenging.

Academia
Circular economy, as an issue, is transversal and applies to a wide number of areas, from energy, to agriculture, to tourism. Addressing the challenges in natural resource usage is fundamental for saving humanity. Latin America has a lot of the world's biodiversity and natural resources, as such, it is very important for humanity. Chile has very low levels of recycling compared to those in Europe; Europe announced in 2015 that it is transitioning to a circular economy. The transition to a circular city in Santiago is a dream and it is far from becoming a reality. One aspect of the REP law has to do with the growth of recycling, but from the public perspective, the environmental initiatives are slow. Mayors do not have the

jurisdiction to limit what types of cars, for example, are allowed in their municipalities. Instead, they are able to make changes on a micro-scale, typically on issues pertaining to recycling.

Academia

The public is very sensitive to price increases. The government tried to push for the installation of smart meters, with units paid for by the consumers, which was a huge failure. Think if you now impose a true carbon tax, there would be a pass through of those costs. People use the Chilean regulator as a springboard, to then go to the private companies, which was a principal-agent problem. It does not happen as frequently as it did in the 1990s because salaries in the public sector are now closer to that of the private sector. The wholesale energy market today is only open for generation firms, not for demand. If one is a demand aggregator, or a big mining company, one cannot participate in the wholesale market. It is hard to get the distribution company to offer an electric savings program, they do not have an incentive for people to consume less power.

Nonprofit/thinktank

In Chile, a lot of municipalities are composting, but at a very small scale and more for environmental education purposes. There is only one plant operating at an industrial scale. Only 0.5% of organic waste is composted. The REP law is a big step because the private sector is going to collaborate with the municipalities and people will begin separating their waste at the point of origin. Up until now, there has been a lack of national interest in addressing organic waste. The main barrier is that there is a lack of awareness that waste is a problem, but this is changing. Another barrier is that those who pollute do not pay; 80% of Chilean households do not have to pay a waste fee. Regarding anaerobic digestion, one of the barriers is economic – the price of energy is decreasing in Chile because of the incorporation of solar energy. Projects that have co-generation, that generate both heat and electricity, perform better economically.

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