

## ABSTRACT

HERRERA DIAZ, MARIA ALEJANDRA. Analytical Approaches of Sustainability Characterization for Bio-based Systems. (Under the direction of Dr. Stephen S. Kelley).

The worldwide motivation to reduce environmental emissions through the inclusion and creations of renewable products and process has made that woody biomass play an important part in this change due to it is considered one of the most plentiful and low-cost reserve for biofuels and carbon based materials. The estimation of the environmental, social and economic aspect in bio-based product and companies is a critical and unclear topic. Currently, producers are struggling with the challenges and trade-offs related to different materials that traditionally have been primarily made from fossil fuel. Inquires about the real sustainability performance and conversion economics of bio-products and processes require to be addressed. On the other hand, one of the major challenges faced by bio-based companies is their own estimation of sustainable impacts in accordance to the governmental regulations. To do so, the Environmental, Social and Governance (ESG) attributes are considered as the most suitable indicators of how companies could describe a sustainable research or project development, and how they play a key in the business strategies and economics. Thus, this study intended to evaluate different analytical approaches of sustainability characterization for bio-based systems.

The global growth in energy demand with the combination of the existing cumulative levels of environmental pollution, is actually determined to the transition for alternative and renewable energy sources. Torrefied biomass is considered as an alternative material to substitute coal without the need for costly renovations to the current coal operating plant. Hence, the **first chapter** of this study delivers an economics and environmental life cycle analysis (LCA) of the torrefied

biomass at different operational conditions. To do so, this methodology uses an integrated process model to obtain the key parameters for the potential environmental and economic benefits of the product compared with coal and natural gas. Results suggest that as initial view, by torrefaction process with other sources, this is highly affected for the GHG emissions, which are controlled by the combustion process for power generation. Opposite outcomes are presented if biogenic carbon is considered in the analysis. On the other hand, according to the tornado analysis, operational temperature is one of the important parameter that make impact either on the greenhouse gas emissions than variable cost and net present value. This will determine the extra utility fuel and feedstock required.

The use of wood for railroad ties has been historically attractive in the United States over the past. Benefits such as their precise toughness and springiness, comparative lightweight, and ease on the manufacturing and installation are the reason for that. Opposite to this, concerns as a natural resource, dimensional instability due to moisture changes, susceptibility to biodegradation, weathering, and fire resistance make the use of wood still challenging. Consequently, wood modifications attempts have been applied over the years in order to overcome these obstacles. On the other hand, the use of concrete material is currently debated due to the high CO<sub>2</sub> impacts present during the production process but longer life time and carbonation effect make this material also attractive to use. The application of technical changes is highly dependent on both the features of the technologies themselves and the characteristics of the sustainability context including the environmental, social and economic assessment. Therefore, a complete analysis is required for decision-making process. Environmental full-cost accounting (FCA) is a novel analytical framework that describes ecological and human health impacts of products and processes using financial measures. The main goal of the **second chapter** was the application of the FCA

methodology for the comparison of a series of chemically treated wooden and concrete railroad crossties. For all product, production of the treatment chemicals and the crosstie, use, and disposal phases were involved along with amount of emissions generated, and associated health and environment costs. Two alternative end of life (EOL) scenarios were analyzed energy recovery and disposal in a landfill. Results shows that the EOL scenario for treated crossties govern when environmental and social costs were defined. In contrast to this, concrete crossties, where the production stage is the main contributor. Wood treatment utilizing copper-chrome-arsenic (CCA) signifies a worst case EOL scenario due to the high costs associated with atmospheric emissions of arsenic and CO<sub>2</sub>. Finally, depending on how biogenic CO<sub>2</sub> is treated, concrete or furfuryl alcohol treated wood had the lowest environmental price.

Nowadays, it is common that profitable corporations display stronger incentives to disclose their information on the social performance to improve their social image. At the same time, companies might also face the fear of costs rising due to Corporate Social Responsibility activities. The interaction between corporate social and financial performance is still uncertain for most companies all over the market, here the forest-based industry is not an exception. Therefore, **the third chapter** evaluate the relationship between the ESG and the financial performance of individual pulp and paper, and wood product companies. To do so, different statistical tools will be applied to identify the potential correlation and causation existing between the economic performances, social and environmental attributes. The assessment exposes a positive causality relationship among the total ESG score and market capitalization, net sales, and return on equity. Also, it was found that the environmental score alone exhibited the same trends as total ESG reveal.

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Analytical Approaches of Sustainability Characterization for Bio-based Systems

by

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## **DEDICATION**

First, to the honor of God for always accompanying me and giving me the gifts of wisdom and understanding at all times.

To my beautiful son Mathias for giving me the strength to be better every day.

To my life companion Eliezer, to my parents Melba y Jesus and siblings Maria Carolina, Jesus Miguel and Andrea Isabella, who have always given me their support, advice and love.

I LOVE you all.

A Dios todopoderoso, por acompañarme siempre y darme los dones de la sabiduría y el entendimiento en todo momento.

A mi hermoso hijo Mathias, quien me da la fuerza para ser mejor cada día.

A mi compañero de vida Eliezer, a mis padres Melba y Jesus y a mis hermanos Carolina, Jesus y Andrea, quienes siempre me han dado su apoyo, consejo y amor.

A todos ustedes, los AMO.

## **BIOGRAPHY**

Maria Alejandra Herrera Diaz was born in Caracas and raised in the beautiful city of Merida. She graduated from the Universidad de Los Andes in 2014 with a B.Sc. degree in Chemical Engineer. At the beginning of 2016, Maria enjoyed the trainee program in Kraft-Heinz Company. In Fall 2016, she moved to Raleigh, North Carolina, USA. There, she spent one year as Visiting Scholar in North Carolina State University under the direction of Dr. Steve S. Kelley and Dr. Yuan Yao. Followed by his research interest, Maria successfully started her Ph.D. studies in the spring of 2018 in the Department of Forest Biomaterials at North Carolina State University by the guidance of Dr. Steve S. Kelley and Dr. Yuan Yao. Her research project includes different analysis related with the sustainability assessment for the bio-based process and products.

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## **CHAPTER I**

### **1. INTRODUCTION**

#### **1.1. Overview of the sustainability assessment**

The idea of “sustainability” was presented due to uncontrollable factors such as climate change, natural resource depletion, energy deficiencies, waste management, population growth, and increased product demands that disrespect the environment. This concept is considered one of the most complex evaluation methodologies. Several ideas are available in the literature to provide an accurate definition, but the scope and purposes highly variate. Some focus more on environmental issues, while others cover social and ethical values. Pope et al. in 2004, reviewed the evolving conception of sustainability assessment by providing some clarification on different approaches described in the literature for sustainability assessment (Pope et al., 2004). The conclusions propose that an integrated assessment-based environmental impact assessment (EIA) and strategic environmental assessment (SEA) are the main precursors of this concept. In addition, some incorporate social and economic considerations as well as ecological. Ness in 2007, suggests that this appears to be defined as an integrated valuation of nature and society systems in short and long-term perceptions to support and define actions that should or should not be taken to promote a society sustainable (Ness et al., 2007). Bond et al. in 2012, summarize sustainability assessment and propose this concept can be defined as any procedure that directs decision-making through a sustainability scheme (Bond et al., 2012). Thus, even though a standard idea is still in progress, an assessment of the combination of the main attributes, such as environmental, social, and economic, summarizes the concept.

The necessity of sustainability valuation starts with awareness to resolve social, economic, and environmental concerns. For this last one, different events have been remarkable in his evolutions.

For example, environmental awareness was first introduced in Stockholm (Sweden) titled United Nations Conference on Human Environment in 1972, where the ecological deterioration throughout the world was the main focus of the meeting (UN, 1972; Nautiyal & Goel, 2021). In 1992 during the United Nations Framework Conventions on Climate Change, the environmental consciousness increased with the emphasis on sustainable development (UN, 1992). In 1997, the Kyoto Protocol was known as the primary stage in the procedure to battle against the global warming due to it was considered as the first time that some exact guidelines were shaped for all nations to reduce the emissions targets and achieve them in a certain period (Crooks., 2022; Encyclopedia Britannica., 2021). Regarding this, environmental assessment has converted into an effective practice to make an equilibrium among the social and economic aspects (Nautiyal & Goel., 2021; USEPA, 2021). In 2009, the United States Environmental Protection Agency was the pioneer in regulating greenhouse gas emissions by engaging some economic and social sustainability activities such as the inclusion of regulatory policy tools such as emissions trading, greenhouse gas reduction benefits evaluation, emissions taxes, and the display of the economic impacts of ocean acidification (USEPA, 2021). These were presented with the target to diminish social costs while emissions are also reduced. Finally, during the Paris Climate Agreement in 2016, several countries were in accordance to reduce global greenhouse gas emissions to limit the worldwide temperature rise in this century to 2 °C (United Nations, 2022). The treaty offers a pathway for developed countries to help other nations in climate mitigation and transition achievement by producing several tools for the transparent monitoring and reporting (Denchak, 2021; United Nations, 2022).

On the other hand, it is well known that practically all human actions require a massive quantity of energy and natural resources that produce different products and services (Nautiyal & Goel,

2021). Currently, numerous countries and corporations are motivated to establish carbon neutrality targets. These solutions are becoming ambitious across economic sectors by investing in new technologies and impacting society to achieve the goals. Hence, sustainability assessment is a persuasive exercise in making all human activities more careful from an all different point of view.

## **1.2. Sustainability Impacts**

### **1.2.1. Environmental Impact**

Environmental impact is any alteration to the environment that might be adverse or favorable to them. These are the results generated from a facility's activities, products, or services (Boechler et al., 2021). Thus, it is the consequence that human activities have on the environment. Pollution or damage resulting from an accomplishment might have short-term or long-term ramifications that are directly connected to public health and quality of life issues (Abdallah, 2017).

The most significant environmental impacts comes from the energy dependence of the society which has an effect on the climate change. Currently in the US, around 80% of the energy comes from fossil fuel (U.S Energy Information Administration. EIA, 2021). Burning hydrocarbons derived from this source to provide useful energy will be affected in the emission of carbon dioxide (CO<sub>2</sub>) (Abdallah, 2017; Boechler et al., 2021; Zelinger, 2021). Other actions that cause destruction to the environment embrace inappropriate waste disposal to either of water and soil. The fundamental environmental impacts is based on the five following aspects:

- ✓ Climate change (GWP)
- ✓ Ozone depletion
- ✓ Acidification
- ✓ Photochemical smog
- ✓ Eutrophication

- ✓ Environmental Human Health
- ✓ Biodiversity
- ✓ Land-use change (Bolin & Smith, 2011; Erlandsson & Almemark, 2009; Garcia-Rey & Yepes, 2012; “ISO14040,” 2006; Kutnar & Hill, 2017).

### **1.2.2. Social Impacts**

The inclusion of the social measurement is still challenging to be incorporated in the analysis. This is due to the complexity finding the appropriate indicator to disclose the right value. Even though of this, companies and researchers have found some ways to face these difficulties presented. Social impact assessment is a method and tool for measuring and ascribing positive social change to on a specific direct actions (Brightest, 2020). A good framework should provide good indicators, easy data collection and capacities, and impact analysis.

Explanation of social impact could be defined as any substantial or positive alterations that resolve or address social injustice and defies (Mitchell, 2021). These are considered several frameworks that represent the assessment of all impacts on humans and includes how people and societies interact with their socio-cultural aspect. A social impact might be conceptualized by seeing people, culture, community, political systems, health, safety, wellbeing, and personal and property rights (International Association for Impact Assessment, 2009).

### **1.2.3. Economic Impacts**

Economic sustainability is a wide set of decision-making values and business habits that pretend to reach economic growth without appealing to the damaging environmental tradeoff (Krugman, 2022) . This involves evaluating the ecological impact of economic activities and developing sustainability goals that generate a more future world.

Economic impacts happen anytime when money passes from consumer to company or business to business. These economic impacts are usually measured by employment or jobs, regional revenue, household earnings, value-added and overall profits which might measure the success of a project commonly related to environmental and social effects (Krugman, 2022). Employment and household earnings are the most meaningful measures in a regular economic development impact assessment for a new business established or expanding in a community. Creating a new company that significantly affects the environmental aspect will provide a value added to the communities by generating several employments.

### **1.3. Sustainability Tools**

Sustainability assessment is treated as a multidisciplinary activity that manages various objectives. Researchers have used multiple methods for sustainability assessment. Each method has its peculiarity, constraints, and complexity. The progress and success of sustainable development involve conclusions of different criteria, standard approaches, descriptions, and appropriate application of methods to generate effective outcomes (Bohr, 2020). As a consequence of the evolution of sustainable development, several procedures have also been matured to impose the appropriate sustainability goals. Various methodologies are currently available for sustainability assessment, as Table 1.1 summarizes. According to the literature, the most prominent is Life Cycle Thinking, but also integrated tools based on a mathematical and statistical model that is getting attraction due to those allows for the integration of the primary precursor (Arantza López, Lara Mabe, Beatriz Sanchez, 2015; Ness et al., 2007; Taisch et al., 2017). All of them uses numerous qualitative approaches, a compilation of data, and quantitative procedures to produce valuable outcomes.

**Table 1.1.** Summarization of common sustainability tools

<b>Metric/Tool</b>	<b>Sustainability Dimension</b>	<b>Summary</b>	<b>Reference</b>
<b>LCA</b>	<b>Environmental</b>	<b>Life Cycle Assessment (LCA)</b> is a structured, comprehensive method based on ISO 14040 standard. This quantifies the environmental impacts, such as all relevant emissions and resources consumed. Also, it includes the related environmental and health impacts and resource depletion issues of a product or a service throughout its life cycle.	(Arantza López, Lara Mabe, Beatriz Sanchez, 2015; “ISO14040,” 2006; Myllyviita et al., 2017; Ness et al., 2007; Taisch et al., 2017)
<b>(LCC)</b>	<b>Economic</b>	Life cycle costing (LCC) is an approach that measures the total cost of an asset over its life cycle, including initial capital costs, operating costs, maintenance costs, and the asset’s residual value at the end of its life. Also, the analysis includes environmental costs such as Life Cycle Cost Assessment and Full Cost Environmental Accounting.	(Myllyviita et al., 2017; Ness et al., 2007)

**Table 1.1** (continued).

<b>EEA</b>	Environmental and Economic	Eco-Efficiency Analysis (EEA) combine the examination of economic and ecological aspects of goods and service systems, without the use of monetization or any another harmonization technique. Indicators are generally expressing the ratio between an environmental and an economic/financial variable.	(Arantza López, Lara Mabe, Beatriz Sanchez, 2015)
<b>CBA</b>	Economic	<b>Cost Benefit Analysis (CBA)</b> is used to evaluate public or private investment proposals by weighing the project's costs against the expected benefits. For sustainability assessment, CBA can be an effective tool for weighing different alternatives' social costs and benefits.	Myllyviita et al., 2017)
<b>S-LCA</b>	Social	<b>Social Life Cycle Assessment (SLCA)</b> can be defined as a tool that assesses the social impacts that belong to the domain of human and social sciences quantifying the social impacts on the complete life cycle. This approach is based on the same principles as LCA; however, the technique are not well-established yet. This method has only been applied in a limited number of cases, but the topic is greatly discussed in the field of LCA.	(Falcone & Imbert, 2018; Mattioda et al., 2020; Rafiaani et al., 2016; Siebert et al., 2018)

**Table 1.1** (continued).

<b>TSA</b>	Environmental, Social, and Economic	Techno-Sustainability Assessment is a novel framework incorporating an inclusive indicator selection that combines a specific product or technology's environmental, economic, and social impacts and their entire value chain.	(Van Schoubroeck et al., 2021)
<b>MFA</b>	Environmental and Economic	<b>Material Flow Analysis (MFA)</b> quantifies the inputs and outputs of materials or substances related to the processes, which involves a simple model of the interrelation between the economy and the environment. The method consists of all the materials required for the complete production process minus the actual weight of the product represented as the actual material intensity of a given product.	(Myllyviita et al., 2017; Prokofieva et al., 2011)
<b>CF</b>	Environmental	<b>Carbon Footprint (CF)</b> represents net emissions of CO <sub>2</sub> and other greenhouse gases over the full life cycle of a product or process. Typically, it is expressed as a CO <sub>2</sub> equivalent (kilograms or tones per functional unit).	(Arantza López, Lara Mabe, Beatriz Sanchez, 2015)
<b>E-LCA</b>	Economic and Social	<b>Exegetic Life Cycle Assessment (E-LCA)</b> is based on the first and second law of thermodynamics. This includes all quality losses of materials and energy, allowing for a wide range of applications to identify opportunities to save costs and assess societal sustainability.	(Arantza López, Lara Mabe, Beatriz Sanchez, 2015)

**Table 1.1** (continued).

<b>EEIO Model</b>	Environmental and Economic	The environmentally extended IO (EEIO) analysis is a technique for appraising the linkages between economic consumption activities and environmental impacts. The original IO model is a quantitative method that describes the interdependencies between different branches of the economy. Compared to the original this is an extensively utilized method for measuring the consumption-based drivers of environmental impacts.	(Myllyviita et al., 2017)
<b>FCA</b>	Social	<b>Full Cost Accounting (FCA):</b> in an analytical framework that combines the environmental impacts measured by LCA with the social and financial implications. It considers both direct and indirect costs, including external costs (damages) and adverse effects of an activity or decision, and assigns these direct and indirect costs to the process or product.	(Bruyn et al., 2018)
<b>LCSA</b>	Environmental, Social and Economic	<b>Life Cycle Sustainability Assessment</b> denotes the valuation of all environmental, social and economic negative influences and benefits in decision-making practices for sustainable products throughout their life cycle by combining the LCA, LCC and SLCA tools.	(Ciroth et al., 2011)

**Table 1.1** (continued).

<b>Optimization Method</b>	Environmental, Social and Economic	Optimization methods are used to seek an optimal alternative among a potentially infinite number of alternatives. Optimization methods are a versatile group of methods, ranging from the simplest linear programming to more complex multi-objective optimization methods. This tool will generate a pareto graph optimal solutions, which will be presented to show the tradeoffs between the objectives and shed light on best scenarios.	(Myllyviita et al., 2017)
<b>PROSA</b>	Environmental, Social and Economic	<b>Product Sustainability Assessment (PROSA)</b> is a method for the strategic analysis and evaluation of product portfolios, products and services. The goal of PROSA is to identify system innovations and options for action towards sustainable development.	Myllyviita et al., 2017)

#### **1.4. Corporate Social Responsibility Overview**

Corporate Social Responsibility (CSR) is a complex concept that is still argued. Some authors suggest that is the ongoing guarantee that corporations perform their work ethically and add value in economic development while enhancing the quality of life of the employees and families as well as of the local community (Barauskaite & Streimikiene, 2021; Hinze & Sump, 2019; Linnea & Bråtenius, 2015; Mughal et al., 2021). In other words, that means that this allows the companies to measure the impact of their activities on the environment, society, and the economy. Hence, this is the way in how business could monitor their sustainability activities. In this way, firms can get accurate and intuitive data which will help them improve their processes and have a more positive impact on society and the world allowing them to communicate with their stakeholders their goals regarding sustainable development, and to get to know better how the company is managed.

Nowadays, various companies consider CSR as a basic part of their brand reputation due to it is believed that new customer's generations will be more engaged to do business with the brand that identify to have more ethical values (Awaysheh et al., 2020; Muñoz-Torres et al., 2019; NASDAQ, 2019). Therefore, companies are encouraged to involve in CSR because on their principles. Common CSR goals covers the improvement and minimization of the environmental externalities over measures such as implementation of renewable energy sources for the carbon offsets (Kammoun et al., 2021). Also, some social activities such as stimulation of the volunteerism among the companies and employees, the remove of unethical labor practice and donations make that CSR accomplishments create a robust bond among employees and corporations.

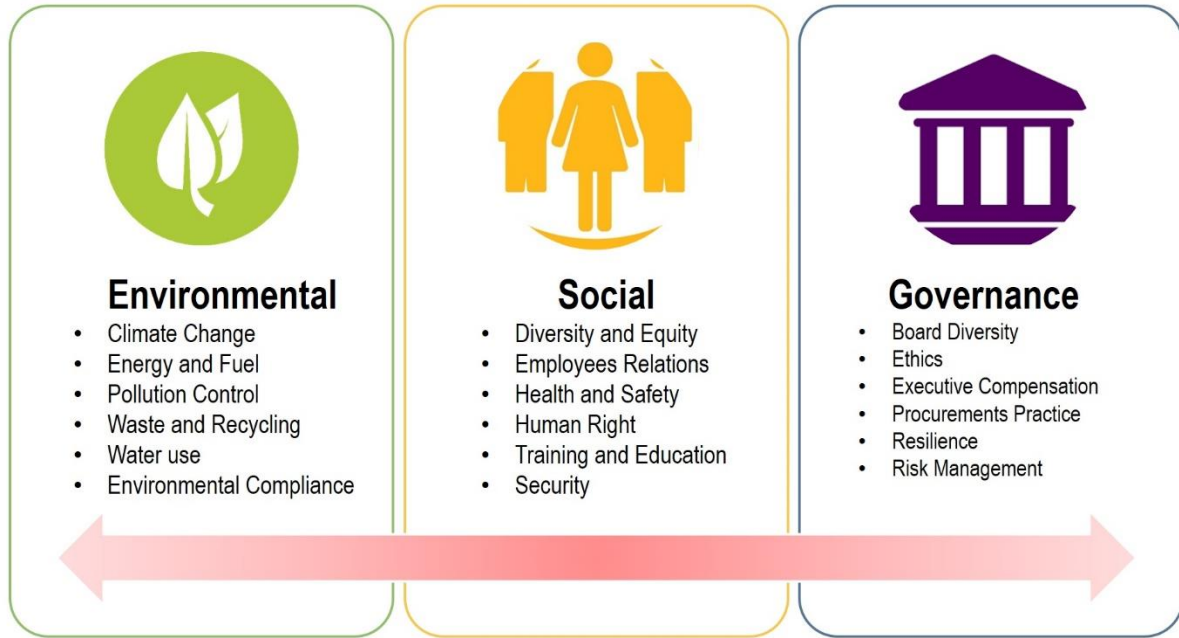
#### **1.5. ESG Overview**

Over the past years, economic performance was the only way to measure the success of a company. Nevertheless, nowadays this is no longer the only factor that is taking into account, because it has

been extended to environmental impacts and social benefits. Hence, not only factors such as financials measurements is considered in the corporation risk analysis, materials and energy use, industrial emissions, employee satisfaction, compensations, employee training, etc. are examples of factors that has been included.

Environmental, social, and governance (ESG) principles are a set of criteria's for corporation's performance used by socially mindful investors to screen potential investments (Arnold et al., 2012; Minutolo et al., 2019; Tempero, 2019). ESG criteria make emphasis on the assessable outcomes that support investors in make better decisions in their risks and ethics of particular companies.

All of the ESG criteria's are based on the sustainable development goals presented by the United Nations on 2016 (ONU, 2020). Figure 1.1 summarize the common features that each parameter acknowledge. For instance, environmental values includes in how a business is aware of the environmental considerations. Social criteria evaluate relationship management with workers, customers, and the communities where it operates. Governance deals with leadership, internal controls, director's payments, and shareholder rights (Kocmanová & Šimberová, 2014; Valente & Atkinson, 2019).



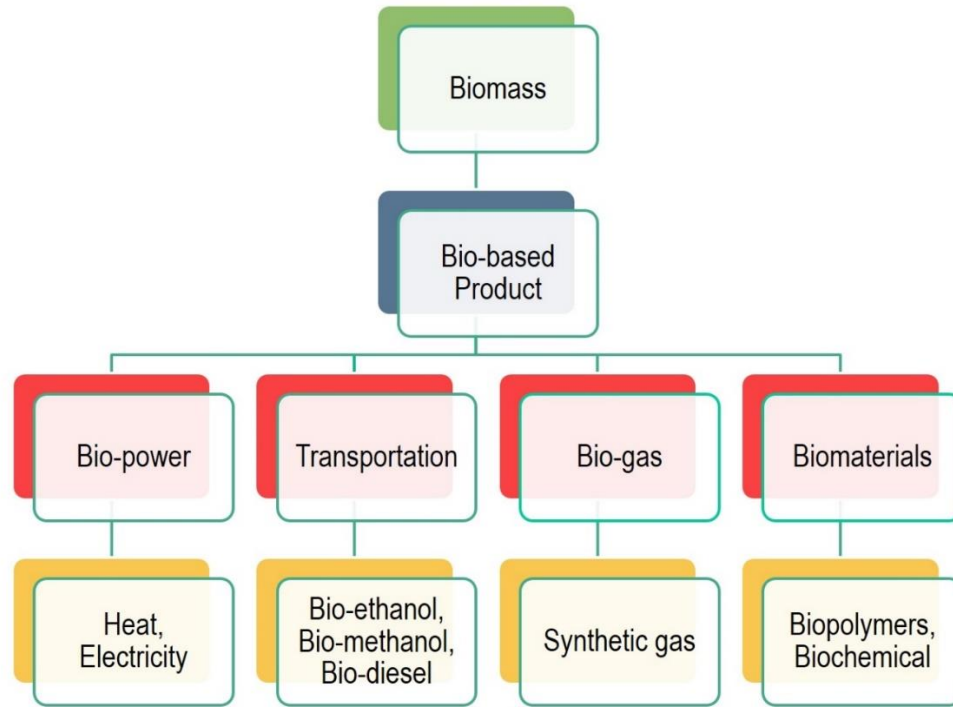
**Figure 1.1.** Environmental, Social and Governance Criteria's (Barman, 2018a; Henisz et al., 2019)

The connection between CSR and ESG is strong, but still is not the equivalent (Polley, 2022). CSR is the model and bounces background about sustainability outlines and corporate responsibility philosophy. ESG is the action and quantifiable result. ESG habit is commonly used to assess how well a company follows the sustainability and corporate responsibility target (B. Townsend, 2020). To clarify, CSR might be assumed as the qualitative part and ESG is consider as the quantitative section.

### **1.6. Sustainability Assessment and ESG concept in Bio-based Product and Processes**

Bio-based materials acquired from underutilized biomass, such as agricultural and forest residues, represent an important part of this movement. Some advantages of using these sources are their global availability, has low energy production and possible alternative waste strategies, like biodegradation, which is in contrast of oil and gas product. In addition, bio-based materials offer opportunities for rural areas, such as employment increase and added value generation for biomass

producers. Different forms of bio-based products could be manufactured or extracted from biomass through chemical, mechanical, thermal, or biological treatments and be used for electricity, heat, biochemical, and biomaterials as Figure 1.2 shows (Tong et al., 2021).



**Figure 1.2.** Classification of bio-based products from biomass (Tong et al., 2021)

The demand of renewable materials has been rapidly increasing over time due to need to decrease the environmental impact in the world due to the biogenic carbon effect (DeCicco, 2018; DeCicco et al., 2016). Moreover, investment levels are a significant consideration as trillions of dollars in new electricity sector investment, which will be needed to meet the global targets in the Paris Climate Agreement. Still, even though fossil fuels such as coal or natural gas contribute to the possibility of easy access to electricity, nowadays, different governments, such as UE and USA have started changing their approaches on how to produce this type of product.

Bio-based products have great prospective to solve the existing energy and environmental emergencies. Nonetheless, the selection to use biomass back on a variety of reasons, such as accessibility, public policy, feedstock price, investment process equipment and facilities. Hence, the evolution of innovative conversion technologies suitable for this raw material is expected to make bio-based products competitive with oil-based products.

The high demand of investors and customers on less carbon intensive energy on the electricity sector is transitioning to pollution-free renewable power, making the bio-based material more attractive for this market. Therefore, driving the sustainability assessment and ESG investment unto companies that are doing the best to mitigate the long-term damages due to climate change, a full accounting of renewable material use and investment in ESG scoring will achieve this objective. On the same way, renewable materials from bio-based product such as biomass, is a prospective better scoring on environmental, social and economic criteria compared to fossil fuel.

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## CHAPTER II

### 2. OBJECTIVES

The main objective of this study is to understand the systematic methodologies of sustainability assessment for bio-based products and processes. This work includes three different analyses 1) Life cycle assessment and techno economic analysis, 2) social evaluations through the external cost estimation, and 3) influence on the Environmental, Social and Governance aspect in the financial performance. Bio-based products and processes were analyzing in different ways. First and second steps were focus on use of three different tools to evaluate the environmental, economic and social assessment. The third part was most related in how companies manage their sustainability concept and how this impacts their financial performance.

#### 2.1. TORREFACTION PROCESS

##### **Integrated Process Model, Life Cycle and Techno-Economic for Torrefied Biomass to Displace the Coal in Electricity Generation.**

The overall goal of this study was to develop an understanding of the Life Cycle Analysis (LCA) and Techno-economic implications of an integrated system that uses woody biomass to produce torrefied wood product that can be used to replace coal in power generation. To do so, a mathematical model highlights the ability to combine the results from the mass and energy modeling with the financial and life cycle assessment models. Thus, output from the mass and energy model is used as inputs for modeling both.

The integrated system includes the LCA implications of systems for 1) the sustainable production of the woody biomass, e.g., growing, harvesting and replanting the wood biomass, and 2) the torrefaction process used to convert the woody biomass into a coal-like torrefied wood that can be

used for power generation. Also, with this combined systems a robust financial analysis tool of the torrefaction process was created. The input for this work is woody biomass, with user-defined moisture content, caloric value, and price, while the output is a densified torrefied product, with a defined moisture content and caloric value. The final densified product will have a higher energy density and a lower moisture content than the starting woody biomass, which will reduce transportation costs. The torrefied product will also be relatively hydrophobic, and should be relatively durable, and allow for low cost, year round, outside storage.

## **2.2. RAILROAD TIES FROM WOOD AND CONCRETE**

### **Environmental Full Cost Accounting of Alternative Materials Used for Railroad Ties: Treated-Wood and Concrete Case Study**

Full-Cost Accounting (FCA) is an innovative tool that associate the environmental impacts resulted from Life Cycle Assessment with the social and financial aspects of alternative products or processes due to it includes both direct and indirect costs, with external costs well known as damages cost. The main objective of this chapter was to use the full cost accounting procedure to estimate the costs of wood railroad ties and concrete. Five types of treated wooden railroad ties were investigated: CCA, Copper-Boron-Arzone (CBA), Creosote, Pentachlorophenol (Penta), and Furfuryl Alcohol. The examination involved cradle-to-grave emissions with the considerations of two alternative end of life (EOL) scenarios: energy recovery and disposal in a landfill. Finally, sensitivity analysis was used to identify the largest sources of emission uncertainty influencing total costs estimates, and the natural variation of emissions outputs.

## **2.3. ENVIRONMENTAL, SOCIAL AND GOVERNANCE WITH THE FINANCIAL PERFORMANCE**

### **Relationship between Environmental, Social and Governance (ESG) Ratings and the Financial Performance of Pulp and Paper, and Wood Product Companies.**

Sustainability metrics are classically measured into environmental, economic and social features. Nowadays, investors and stakeholders have gotten interest on Environmental, Social, and Governance (ESG) attributes. This type of thinking could be added to financial performance and impact decision-making. Bio-based materials and industry are particularly sensitive to the ecological harm, social forces, and reputational risks. This study assesses the causal relationship between several measures of a company's financial performance, and their total ESG scores, and the score for each of the individual ESG attributes. The original features of the work embrace 1) the use of a single data source (Bloomberg), and 2) evaluation of the strength of relationships using the granger causality analysis. The idea is to demonstrate that by improved each ESG parameter, companies will be benefited in terms of economic growth.

## **CHAPTER III**

### **3. INTEGRATED PROCESS MODEL, LIFE CYCLE AND TECHNO-ECONOMIC FOR TORREFIED BIOMASS TO DISPLACE THE COAL IN ELECTRICITY GENERATION**

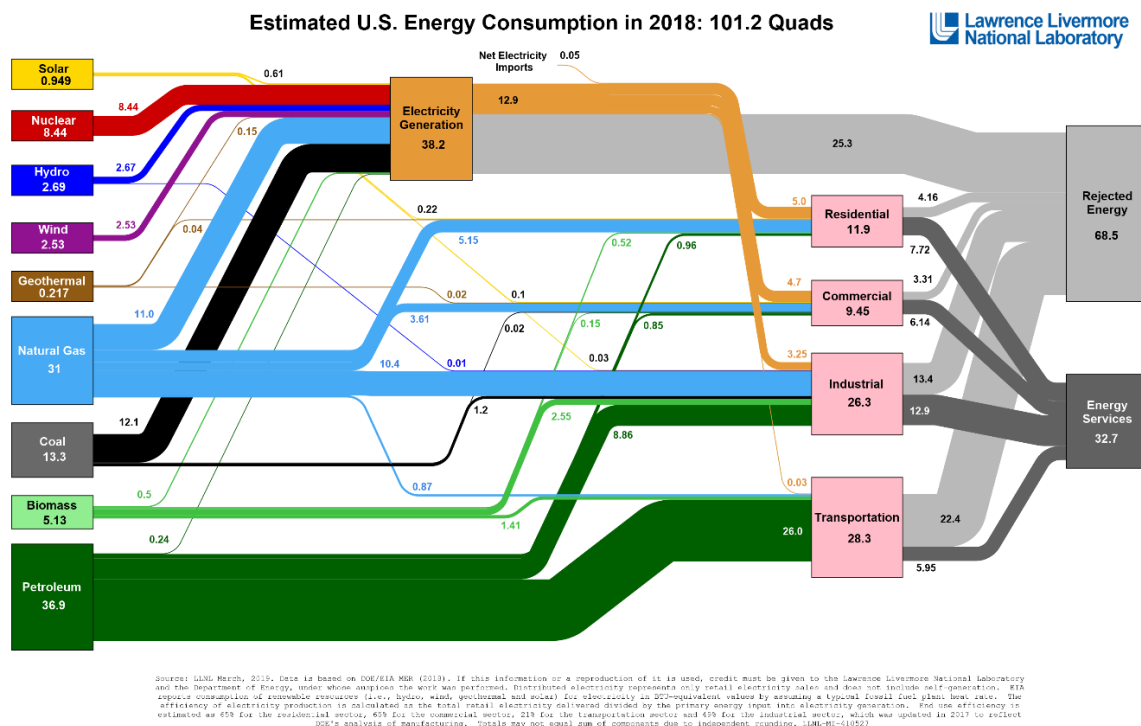
#### **3.1. Abstract**

The demand for renewable energy has been rapidly increasing over time due to the need to decrease the environmental impact in the world. Torrefaction is a process that 'roasts' biomass resulting in a material with a higher energy density, more easily ground, and much lower hydrophobicity. This torrefied solid has the potential to replace coal without requiring costly upgrades to the current coal operating plant. This process is a simple thermochemical treatment of biomass conducted at temperatures between 200-300 °C in the absence of oxygen at atmospheric pressure and is considered as a renewable, on demand source of renewable energy. This study aims to provide an economics and environmental life cycle analysis (LCA) for the torrefaction process. This approach uses an integrated engineering process model to document the potential environmental and economic benefits of biopower generated with torrefied biomass instead of coal. This engineering process model can be used to evaluate the trade-offs between environmental and economic impacts between alternative production scenarios (e.g., torrefaction process conditions, transportation modes, feedstock production, etc.). The process model shows that if the moisture content of the incoming biomass was high (40-50%), and the final torrefied product's caloric value was low, there may be a need for supplemental fuel. This is due to the relatively small volume of torrefaction gases and vapors used for the process heat. Conversely, if the moisture content of the incoming biomass was low (20-30%), and the caloric value of the final torrefied product was high, then there was excess process heat. However, the torrefied biomass with high caloric value also has a

relatively low mass yield requiring a larger volume of starting woody biomass, and thus higher feedstock costs. In all cases, torrefied biomass had lower fossil carbon emissions than coal or natural gas.

### 3.2. Introduction

The use of energy in its different forms has become crucial for human life. Heat or power are instances of that. Electricity production can be accomplished with a wide variety of renewable and non-renewable technologies. Figure 3.1 shows the total energy production and consumption patterns in the U.S. (Stark, 2019; U.S Energy Information Administration. eia, 2021b).



**Figure 3.1.** U.S. primary energy consumption by energy source, 2018 (Stark, 2019)

Renewable electricity generation is growing rapidly but from a low starting point. Biomass provides about 5% of the total U.S. energy mix, but only a tiny (0.5%) fraction of the electrical energy (U.S Energy Information Administration. eia, 2021b). The major contribution to renewable

energy is based on corn ethanol, which is problematic since this compete with corn used, directly or indirectly, as a food sources. More recently technology advancement have made less expensive than many fossil fuel alternatives. One major limitation for solar and wind is they do not provide power 'on-demand (Portland General Electric, 2018). In addition fossil fuel sources have emissions of greenhouse gases (GHG) that drive climate change, which is showing increasing damage in both financial and environmental terms.

The European Union is considering bioenergy as a fundamental part of its transition to a low carbon economy, importing more than 15 million tons of biomass pellets to replace coal-fired electrical generation (Scarlat et al., 2015). The very recent disruption with the war in Ukraine and the UE and US boycott of Russian fossil fuels have also highlighted the costs of these energy sources. Their goal is to increase renewable energy production for primary energy consumption by 2030 to reduce GHG, and also provide more energy security. Bioenergy obtained from underutilized biomass, such as forest or agricultural residues, or dedicated energy crops can support this transition away from fossil energy. Biomass is widely dispersed and, when sustainability managed, can contribute to a low carbon economy. However, biomass also presents unique challenges when competing against fossil fuel sources. High moisture content, low heating value, and relatively high costs are critical limitations that make biomass less attractive relative to coal (Svetlana et al., 2016). Consequently, new technologies are needed to overcome these limitations.

Wood pellets were developed as a biomass pretreatment, and they were established as a modern form of bioenergy during the beginning of the 21st century (Svetlana et al., 2016; Telmo & Lousada, 2011). Pelletization increases the energy density, while decreasing moisture and ash

content, making pellet more attractive as a replacement for coal. In addition, with their increase energy density pellets reduces transportation and handling costs (Harper et al., 2009).

A typical palletization process consists of three unit operations, drying, pelletizer, and combustion unit (Oberberger, 2010). Due to the high moisture content of the initial biomass, additional fuel is required to generate the necessary energy for the drier, which creates additional cost and GHG emissions. Even with densification, the hydrophilic nature of biomass, potential for dust formation and biological degradation, remain as challenge. The drier and associated combustion system, and pelletizer require a capital investment, and ongoing operating costs. To avoid very expensive retrofits to the power plant, biomass is usually co-fired at a ratio of 15-20 % of biomass which limits the impact of biomass power (Bhuiyan et al., 2018; Wang et al., 2021).

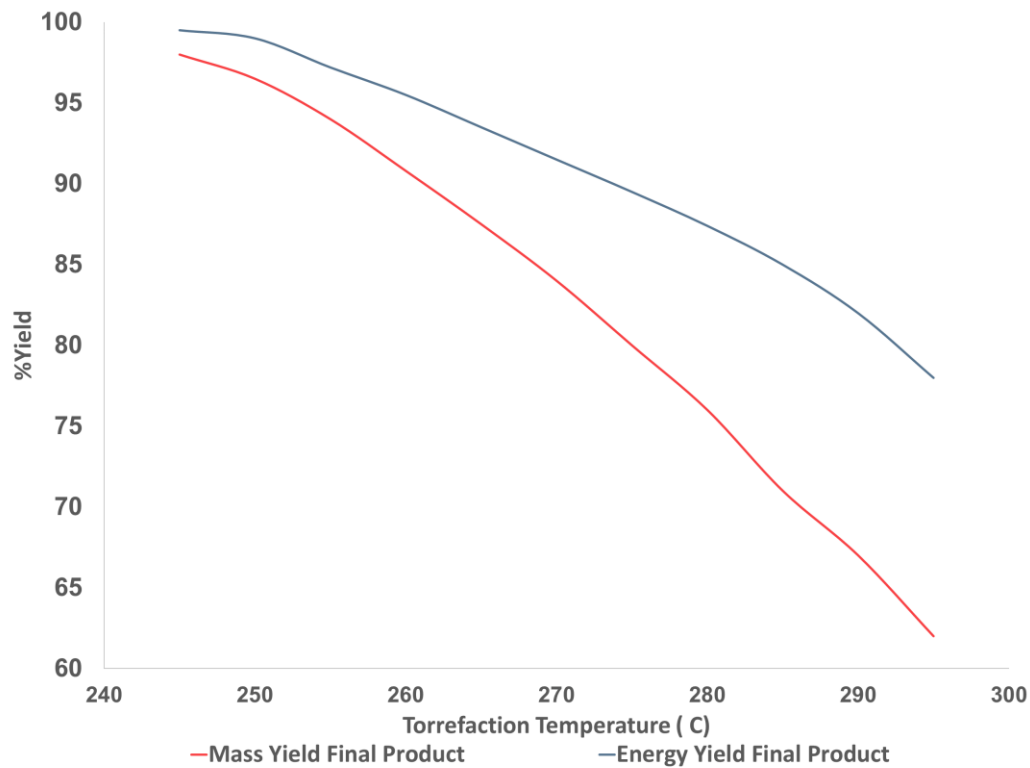
Torrefaction is an old concept but attracted renewed interest in the past few years (Chen et al., 2015; Kosov et al., 2016; Schipfer et al., 2017). Most commonly it involves a simple thermochemical treatment of biomass at temperatures between 200° and 300° C without oxygen, under atmospheric pressure conditions (Bates & Ghoniem, 2014; Chen et al., 2015). This process produces a higher BTU, more easily ground, and less hydrophilic material. This torrefied biomass can then be converted to torrefied pellet (TP) using processes similar of biomass pelletization. Importantly, depending on the biomass properties, and the detailed process conditions the torrefaction gases can be burned for the process heat needed to dry and conduct the torrefaction reactions. Typical mass and energy conversions are 70% and 90%, respectively. However, the thermal reactions and resulting mass and energy yield are heavily dependent on operational and physical conditions, such as temperature, time, and particle size (Bates & Ghoniem, 2012, 2013, 2014).

Looking at the details of the biomass reactions the hemicelluloses are this first component to decompose during the torrefaction process, followed by partial decomposition of lignin and cellulose at higher temperature or longer times. The decomposition processes involves a series of dehydration reactions which makes the biomass more hydrophobic. Secondary decomposition reactions of all three wood components increase the energy density, and increase the ease of grinding, but also limit some the viscoelastic processes that allow for pellet formation. (Bates & Ghoniem, 2012). The combination of hydrophobic character and the pellet density allows the finished product to be stored outdoors, avoiding the costs associated with the construction of storage buildings.

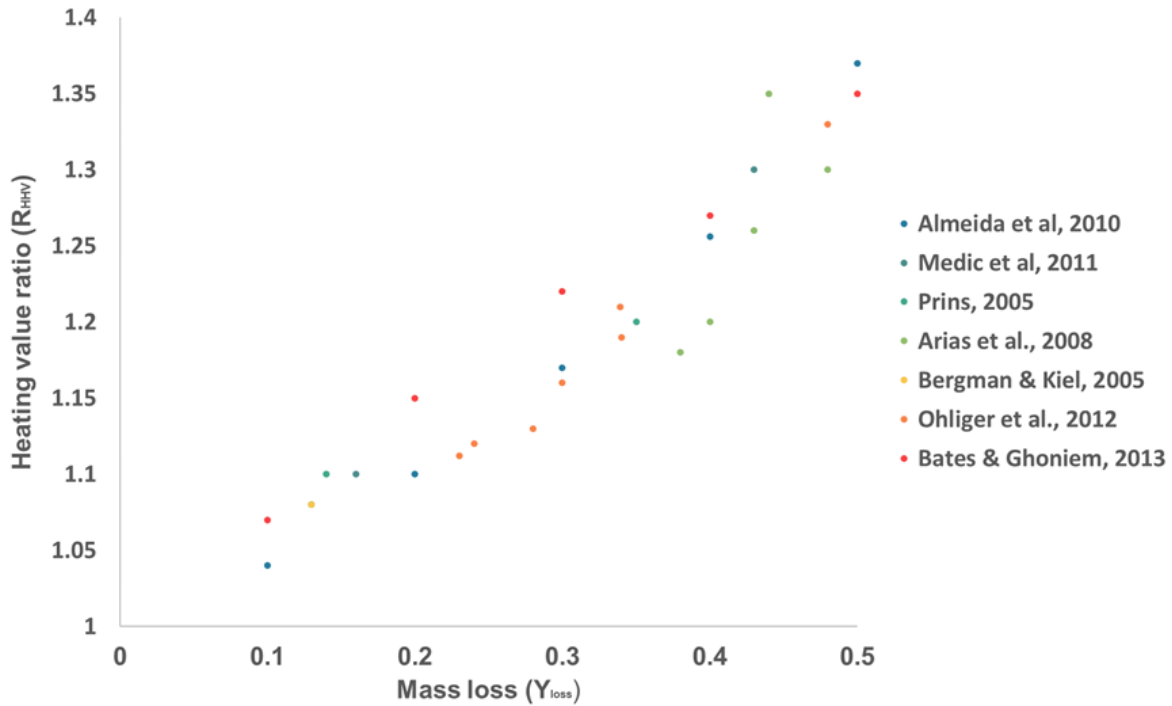
In regards, to the torrefaction process itself, the gases and vapors generated during biomass degradation can be burned, and recirculated dry the biomass and run the torrefaction process. Under many operating conditions, no external fuel sources are needed, decreasing costs and environmental burdens. According to Bach (2017), optimal conditions for the process are 30 min for residence time, and a temperature of 275-300°C (Bach et al., 2017).

It is essential to highlight the general relationship between the mass and energy yield across several studies, as illustrated in Figure 3.2 and Figure 3.3. These show the effects of torrefaction temperature on the mass and energy yield. Together these two figures show the same overall trends, in which the energy yield is always higher than the mass yield. Figure 3.2 also emphasize the rapid decomposition of the biomass, and the associated the loss of mass, as the reaction temperature is increased Figure 3.2 also highlights the non-linear effects of higher torrefaction temperatures, which are required to produce torrefied materials with a higher caloric value. In practical terms, this means that as the energy content of the final product increases and there is a corresponding mass yield decrease, more biomass has to be purchased to satisfy the plant capacity

targeted. Depending on the manufacturing plant's size, this means an increase in transportation costs. If biomass is not readily available, there could be an increase in producer/landowner payments (Gonzales et al., 2013). Trucking is the standard shipping method for green biomass and its costs can vary widely.



**Figure 3.2.** General relationship between torrefaction temperature and the mass and energy yield for the torrefied product (Prins et al., 2006b)



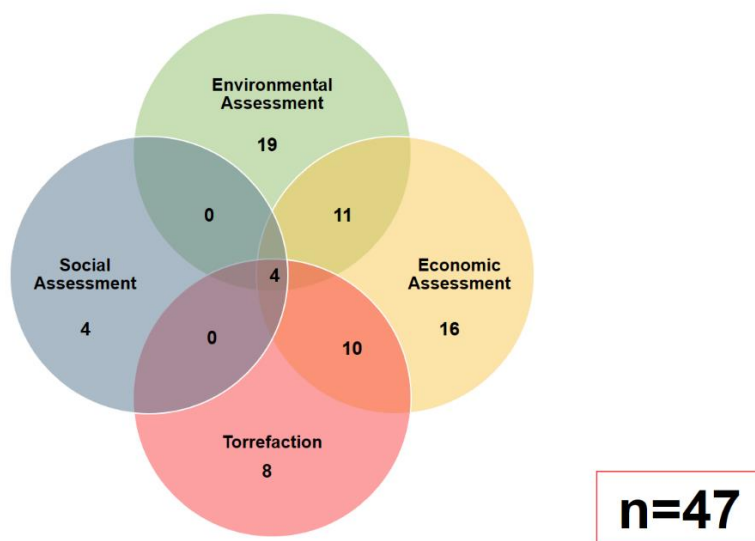
**Figure 3.3.** General relationship between mass yield and heating value (increase in caloric content) derived from published literature (Bates & Ghoniem, 2013)

Compared to wood pellets, this torrefied solid has the potential to increase the co-firing ratio above 15%, and even replace coal without requiring costly upgrades to a currently operating coal plant (Bhuiyan et al., 2018; NREL, 2000; Thraon et al., 2015; Tsalidis et al., 2014; Wang et al., 2021).

The biomass supply chains are critical for both standard pellet production (white pellets) and torrefied pellets (black pellets). Some economic studies have suggested a cost-saving of around 23% when using black pellets compared with standard white wood pellets (Koppejan et al., 2015). This reduction is due to lower freight costs due to higher energy density, lower grinding energy needs, reduced extra utility fuel required, and no additional cost at the power plant. Furthermore, the final torrefied pellets have low sulfur and mercury content, lower CO<sub>2</sub>, and other environmental burdens lower grinding energy needs, better hydrophobicity, and in some regions, the use of a

biomass fuel may even be required for maintaining permission to operate a power plant or boiler. (Thraon et al., 2015).

Judging the change of alternative materials is complex and involves attention to environmental, social, and economic aspects (Cardon et al., 2011; Thomassen et al., 2019). Life Cycle Assessment (LCA) is commonly used to evaluate the environmental burdens associated with manufacturing a product, from the extraction of the raw materials to disposal at the end of life (Erlandsson & Almemark, 2009; Garcia-Rey & Yepes, 2012; “ISO14040,” 2006; Puettmann & Oneil, 2013). Previous studies have presented the environmental assessment for torrefied biomass, as Figure 3.4 shows. According to this, around 40% of these works give information regarding this information. Global warming potential is the most common factor evaluated in most studies. Major conclusions suggest that torrefaction offers a considerable reduction of 15-40% of the CO<sub>2</sub> emissions compared with another alternative (Adams et al., 2015; Akbari et al., 2021; Arteaga-Pérez et al., 2015; Christoforou & Fokaides, 2016; Homagain et al., 2016).



**Figure 3.4.** Summary of Torrefaction Studies

With all these trade-offs biomass remains an attractive fuel for power product due to its biogenic nature. (Hammar & Levihn, 2020; Montre, 2010). Previous work has concluded that in some cases increasing the harvest from forest for energy actually increases global warming since biogenic CO<sub>2</sub> is released before the slower process of biomass growth (Hammar & Levihn, 2020; Ortiz et al., 2016; Sterman et al., 2018). These works highlight the impact of growth rate for the trees. These researchers also highlight the purpose of the harvest, logs for lumber used in durable wood products, and the use of harvest or mill residues or thinning for biopower. While the supposition that carbon neutrality matches climate neutrality may be rational when the bioenergy product results from fast to slow-growing biomass feedstocks (i.e., annuals) and it becomes questionable for bioenergy. Thus, to account for the biogenic carbon dynamic, a time-dependent LCA can be achieved at yearly fluxes of greenhouse gases (Giuntoli et al., 2020; Prisley et al., 2018).

Torrefaction technology has been developing for more than two decades with most of the interest coming from small entrepreneurs (Wild & Calderón, 2021). One exception was the joint venture between Solvay Chemical and a Mississippi-based torrefaction company (*Solvay, Mississippi Torrefaction Company Announce JV to Produce Biomass*, 2014).

A great deal of work has been devoted to understanding the process per se such as raw material, operational conditions, properties on the final product, etc. Several issue for safe operation have also be identified and documented. For ease of handling the torrefied biomass was most commonly compressed into pellets or briquettes, which specifications are presented in (ISO, 2021).

As a new product with a limited production history, there is an extensive range in projected production costs (\$ per annual ton or BTU) for torrefied materials. A key conclusion from the systematic literature review is Table 3.1 (Radics et al., 2017), which shows the variations in the estimated costs of the final torrefied product. According to this study, feedstock costs and

depreciation are the most significant factors that impact the cost of the finished product. However, while the final costs vary 15% from the high to the low, the differences in the costs for capital and labor varies by 300-500%. These wide differences highlight the relatively early stages of the technology and the need for caution in estimating costs. It should be noted that biomass feedstock is one of the major contribution of operational cost. Studies reveal that it could represent around 50% of variable cost (Deutmeyer et al., 2012).

**Table 3.1.** Cost Components by Studies (Radics et al., 2017)

<b>Literature Source</b>	<b>Feedstock (\$/BDMT)</b>	<b>Labor (\$/MT)</b>	<b>Energy (\$/MT)</b>	<b>Depreciation (\$/MT)</b>	<b>Other (\$/MT)</b>	<b>Total (\$/MT)</b>	<b>\$/GJ</b>
<b>(Koppejan et al., 2012)</b>	35.1	10.4	16.3	32.8	54.0	163.3	7.4
<b>(Radics et al., 2016)</b>	49.6	22.3	10.3	49.8	39.7	171.7	7.8
<b>(Walton &amp; Bommel, 2010)</b>	76.6	5.2	5.2	17.4	69.6	174.2	7.9
<b>(Ochoco Lumber Company, 2015)</b>	55.1	26.5	11.0	45.9	45.2	183.9	8.3
<b>Mean of Studies</b>	54.1	16.1	10.7	36.5	52.1	173.3	7.9

Also, based on the experience of the white pellet (WP) industry, where many producers had protracted start-up times before reaching near-nameplate production, which were at least in part

due to problems with dust handling and fires, and explosions, it is very likely that the initial torrefaction plants will face similar challenges. The prudent investor will plan for a slow ramping up to full-scale production.

Nevertheless, torrefaction operations can use much of the experience derived from wood pellet operations. The exception is the costs, and operations for the torrefaction reactor. It is essential to note the lack of information about the capital and operating costs of a torrefaction reactor. Some studies have suggested a 15 year lifetime, based on pellet plant lifetime (Batidzirai et al., 2013). Several torrefaction reactors are being introduced to the market (Acharya et al., 2012; Koppejan et al., 2015). Still, the limited scalability in some reactors, companies have used different production layouts, although rotary drum and moving bed reactors appear to be most common for the torrefaction reactor (Koppejan et al., 2012).

Table 3.2 highlights the economic outcomes based on variations in the plant scale in 2012 (Batidzirai et al., 2013). The equipment units analyzed were chipper, dryer (rotary drum), reactor (moving bed), hammer mill, pelletizing, pellet mill, cooler, and Bio-CHP Boiler. The authors used scale-independent learning applied to second-generation biomass processing. The results show a significant non-linear relationship between scale and specific sub-operations. There is an increasing value for capital expenditure, operational expenditure, and electricity cost per year but a decrease of 23%, 38%, and 50% in the overall production cost (\$/GJ) when the plant scale grows.

**Table 3.2.** Economics attributes of torrefaction plant by the different scale at 2012 (Batidzirai et al., 2013)

Cost item	Plant Scale (thousands of ton TPD)				Units
	50	100	250	500	
<b>CAPEX</b>	23.4	38.1	72.3	117.5	M\$
<b>CAPEX/yr.</b>	2.7	4.4	8.4	13.7	M\$/yr.
<b>OPEX/yr.</b>	1.9	3.0	5.8	9.4	M\$/yr.
<b>Electricity cost</b>	0.3	0.5	1.4	2.7	M\$/yr.
<b>Production Cost</b>	97.7	80.4	66.2	51.7	\$/ton
<b>Production Cost excluding feedstock</b>	4.8	4	3.3	2.6	\$/G.J.

Principal end-users, such as power plants, are clearly interested in direct coal replacement, especially if the replacement does not need an additional boiler upgrade and investments. Still, the absence of standards for the final torrefied product has made market introduction difficult (Koppejan et al., 2012, 2015; Thraon et al., 2015). Increasing the market for torrefied pellets, end-users should get assurance in the quality of the final product procured. Still, the advancement in the transparency of product standards challenges the gain in market acceptance. Deficiencies in market standardization and immaturity of a new company have complicated the market price establishment. In other words, are torrefied pellets competing with coal or white pellets on a dollar per G.J., or are there other attributes to justify a higher price for black pellets. The biomass torrefaction industry is still in its infancy and scale-up experience is missing. However, there has been at least one successful demonstration, where Portland General Electric ran the Boardman coal plant on torrefied wood (Board, 2018). Existing coal-fired power plants have clear interest in

torrefied wood as a drop-in replacement since it does not need additional boiler modification and investment.

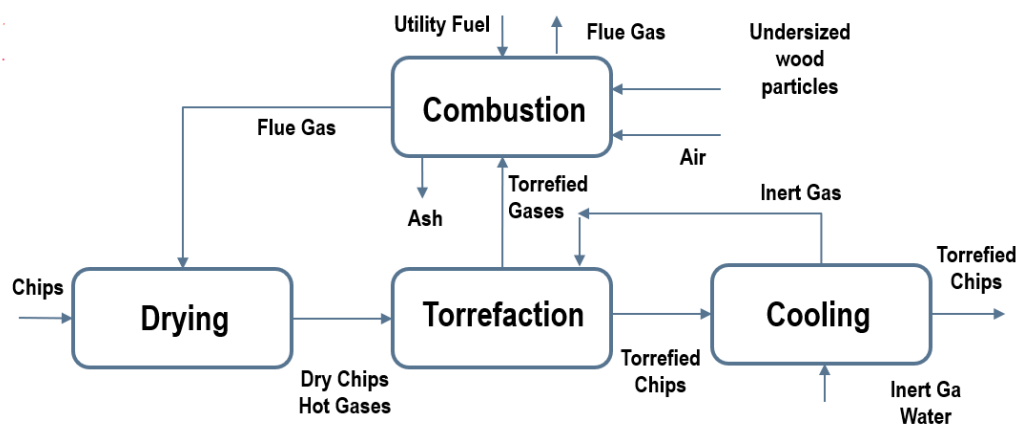
This study provides a robust tool that allows a financial Technoeconomic Analysis (TEA) and environmental life cycle analysis (LCA) for the torrefaction process. This model combines the mass and energy modeling of the torrefaction process, with the financial and life cycle assessment models. Thus, output from the mass and energy model is used as inputs for modeling both.

### 3.3. Materials and Method

#### 3.3.1. Process Description

The process flow used in the model is presented in Figure 3.5. The general torrefaction process can be distributed into several phases: sizing and separation, drying and torrefaction, pelletization, and cooling. However, three main stages have been defined in this process:

- ✓ **Biomass sizing and separation:** To control the quality of the final product and enhance heat transfer through increasing contact area, raw material is reduced in size using a chopper. Undersize particles produced in the chopping are used in energy production units. Oversized particles are feed back into the chopper.



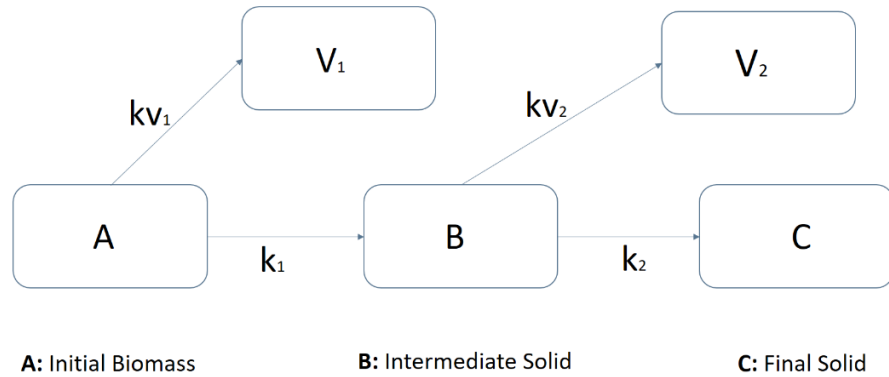
**Figure 3.5.** Torrefaction Flowchart

- ✓ **Torrefaction:** Chips are fed into a dryer, and heated to 150°C. At this point, accessible water is evaporated at a constant temperature. Next, dry chips are sent into the torrefaction reactor. In this step, the actual torrefaction chemical reactions take place. Extractive components are volatilized. Biomass degradation starts when the temperature reaches 200°C. For the modeling, two products are tracked, the torrefaction solid and the torrefaction vapors and gases. Torrefied biomass is then densified, although this process is more complex than for white pellets due to the brittle nature of the torrefied intermediate. In addition, the torrefaction process requires a combustion unit such as boiler or furnace to generate the heat needed for drying and torrefaction. Undersized particles along with torrefaction gases may have sufficient energy depending on the moisture content of initial biomass and extent of torrefaction. Extra biomass fuel, e.g., bark, may be added in the system to meet the heat demand.
- ✓ **Densification process:** For practical handling the torrefied biomass is compacted into pellets, and cooled. Moisture may be added to assist with compaction, and to minimize exothermic reactions and ensure safe storage.

### 3.3.2. Mass and Energy Balance

The kinetic model shown in Figure 3.6 uses a two-step reaction as a first-order mechanism to define the solid mass loss. Several studies have shown that the a two-step decomposition mechanism satisfactorily describes the mass loss during the process (Bates & Ghoniem, 2012, 2013, 2014; Prins et al., 2006a). In this model, torrefaction products are represented by five pseudo-components. Solid-phase (A, B, C) represent: raw biomass (A), an intermediate solid (B), and the final torrefied product (C),  $V_1$ , and  $V_2$  are volatiles compounds generated. The first reaction

relates to hemicellulose and some lignin decomposition, forming light volatiles ( $V_1$ ). The second reaction is related to cellulose decomposition and secondary charring reactions of hemicellulose reaction products by catalytic degradation resulting in the formation of CO and CO<sub>2</sub> ( $V_2$ ).



**Figure 3.6.** Biomass Kinetic Model (Bates & Ghoniem, 2012, 2013, 2014; Prins et al., 2006a)

The kinetics that illustrates the evolution of these pseudo components used in this study is proposed by Di Blasi and Lanzetta (Di Blasi & Lanzetta, 1997) and described by Bates and Ghoniem (Bates & Ghoniem, 2012, 2013, 2014). The equations that define the evolution of these pseudo components are the following:



**Mass Balance:**

$$\gamma_A = \frac{d[A]}{dt} = -(k_1 + kv_1) \times [A]^{n_A} \quad \text{Equation 3}$$

$$\gamma_B = \frac{d[B]}{dt} = (k_1) \times [A]^{n_A} - (k_2 + kv_2) \times [B]^{n_B} \quad \text{Equation 4}$$

$$\gamma_C = \frac{d[C]}{dt} = k_2 \times [B]^{n_B} \quad \text{Equation 5}$$

$$M = [A] + [B] + [C] \quad \text{Equation 6}$$

$$\beta = \frac{k_1}{k_1 + k_{V_1}} \quad \text{Equation 7}$$

$$v = \frac{k_{V_1}}{k_1 + k_{V_1}} \quad \text{Equation 8}$$

$$\gamma = \frac{k_2}{k_2 + k_{V_2}} \quad \text{Equation 9}$$

$$\varepsilon = \frac{k_{V_2}}{k_2 + k_{V_2}} \quad \text{Equation 10}$$

where

$$k_1 = 2.48 \times 10^4 e^{\left(\frac{-75976}{RT}\right)} \quad \text{Equation 11}$$

$$kv_1 = 3.23 \times 10^7 e^{\left(\frac{-114214}{RT}\right)} \quad \text{Equation 12}$$

$$k_2 = 1.10 \times 10^{10} e^{\left(\frac{-151711}{RT}\right)} \quad \text{Equation 13}$$

$$kv_2 = 1.45k_2 \quad \text{Equation 14}$$

## Energy Balance

$$H_i(T) = H_{f,i}^o + \int_{T_0}^T Cp_i(T) dT \quad \text{Equation 15}$$

$$\frac{dq_r}{dt} + \sum_{x=1}^5 \frac{d(H_x m_x)}{dt} = 0 \quad \text{Equation 16}$$

$$\Delta H_{r,1} = \beta H_B + \nu H_{V_1} - H_A \quad \text{Equation 17}$$

$$\Delta H_{r,2} = \gamma H_C + \varepsilon H_{V_2} - H_B \quad \text{Equation 18}$$

$$\Delta H_{r,final} = \beta \gamma H_C + \nu H_{V_1} + \beta \varepsilon H_{V_2} - H_A \quad \text{Equation 19}$$

The literature shows that biomass degradation reactions are highly dependent on operating conditions. When biomass is exposed to higher temperatures, solid mass (C) yield decreases and torrefaction gases/vapors increase ( $V_1$ ,  $V_2$ ). The maximum yield of B is presented when  $V_2$  is minimized; meanwhile, more volatiles ( $V_2$ ) are formed at the higher temperature. Figure 3.3 illustrates the energy content of the solid and volatile products. The cumulative volatile products' energy yield and average heating value are expressed as a function of mass loss or volatile mass ( $Y_{\text{loss}}$ ). Commonly, operating conditions provide a decrease in mass and energy yield, with a corresponding increase in the volatile yield.

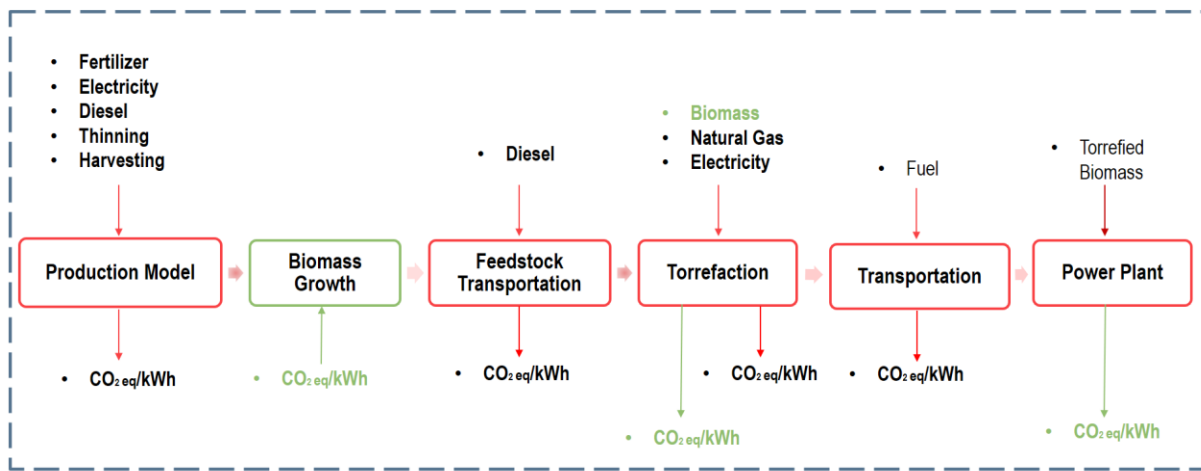
Studies by Bates and Ghoniem in 2013 showed that a combustion unit using the fines and torrgas commonly has sufficient energy for drying and torrefaction operations (Bates & Ghoniem, 2013). If the moisture content of the incoming biomass is high or the torrefied product caloric value is low, natural gas or additional biomass may be required.

The cost of the initial biomass, and any supplemental fuel, have a significant impact on the overall economics. There is a complex relationship between the incoming moisture content, the mass yield and energy yield of the torrefied product, and the sales prices of the resulting product. It is supposed that a higher energy product would command a higher price but have a lower mass yield; thus, additional raw biomass must be employed to reach a constant mass of torrefied product. However, a lower mass yield product will also have more torrefaction gases/vapors, which can be used for process heat and reduce the need for extra utility fuel, depending on the moisture content of the incoming biomass.

### **3.3.3. Life Cycle Assessment**

An environmental assessment of a process can be measured using Life Cycle Assessment (LCA) by following ISO14040 ("ISO14040," 2006). The stages of LCA include 1) goal and scope

definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. The system boundary for this cradle-to-gate is shown schematically in Figure 3.7 using 1kWh as the functional unit. This boundary conditions for this process do not include the growth and management of the forest's biomass, biomass preparation, torrefaction process, combustion at the power plant, and the individual transportation steps. The coal and natural gas data are taken for the databases supplied with SimaPro, a commercial LCA software package.



**Figure 3.7.** System Boundary of Torrefaction Process

Figure 3.7 highlights the heat, mass flows, and transportation dominating the overall energy demands and emissions. In this process, the harvested and delivered biomass is ground, screened, and fed into a dryer run on the torrefaction gases, fine particles from the screens, and additional natural gas as needed. The dryer and torrefaction unit are both identified for the sake of clarity, but in a real commercial operation will likely be a single unit operation. A single combustion block is used to generate the heat needed for the dryer and torrefaction and eliminate any VOC emissions from the process. Thus, the overall process emissions were limited to CO<sub>2</sub> and moisture from the dryer, and combustion system.

### **3.3.4. Financial Assessment**

With the additional goal of understanding the GHG emission and incentives that might be used to support commercial deployment, financial implications of this process were evaluated. A discounted cash flow model was used to screen a wide variety of process alternatives. Important elements of the model include the installed capital costs of the torrefaction plant and the costs of the biomass.

It is important to note that for this financial model the mass and energy balance information is critical. Modeling a biomass torrefaction production process has been difficult since these theoretical models appear to under-estimate the process heat generated by the torrefaction operations, and thus the need for supplemental natural gas. The operating experience of several partners suggests that there is no need for supplemental natural gas, which will improve the process economics, and will also reduce the net greenhouse gas emissions from the process.

With these financial inputs the model can then be used to calculate the before and after-tax annual cash flows and annual incomes, the net present values (NPVs) and internal rates of return (IRRs), and the minimum selling prices that would be required to achieve the specified rates of return (i.e., where  $NPV=\$0$ ) for the torrefaction operation. NPVs and IRRs are commonly calculated three ways: before finance and tax, before tax, and after tax. In this write-up we will focus on the NPV after tax results.

One key aspect of the ‘financial’ model is that it requires the user to input the mass yield of the torrefied product and amount of supplemental heat, e.g. natural gas, if any needed to conduct the overall operation. For this base case analysis, we have assumed torrefied product similar to the low grade coal used by Portland G&E in Boardman OR (Portland General Electric, 2018). This product has a relatively low energy content, 9,800 Btu/lb. and thus allowed as relatively high mass

yield of the torrefied product, estimated at 86%. Table 3.3 shows the other assumptions for this initial TEA model.

**Table 3.3.** Base assumptions in TEA model

<b>Parameter</b>	<b>Unit</b>	<b>Value</b>
<b>Project Planning Period</b>	year	25
<b>Plant Size</b>	BDT/yr.	200,000
<b>Plant total Installed Capital cost</b>	\$ (1,000)	14,610
<b>Nominal discount rates used to calculate NPVs After Tax</b>	%	5.54
<b>Revenue Inflation Rate</b>	%	1
<b>Standard Operating days per year</b>	days/yr.	357
<b>Terminal Asset value</b>	%	5
<b>Cost inflation rate</b>	%	2
<b>Plant Operators</b>	#	25
<b>Variable labor cost</b>	(\$/worker/scheduled hour)	9.19
<b>Feedstock Specification</b>		
<b>%MC</b>	%	40
<b>Initial HHV</b>	MJ/kg	20.58
<b>Cost</b>	\$/green ton	25
<b>Final Product Value</b>	\$/ton delivered	250

Costs were taken from the prior literature (Gresham, 2013). The pellet industry has similar equipment as the torrefaction industry, and thus operations such as dryers, boilers, hammer mills, pelletizer, and coolers can be used for capital expenditure estimation. One operation unique to the torrefaction process is the torrefaction reactor itself. Capital investment for equipment with a different capacity a scale-up was estimated using Equation 20 using a scaling factor of 0.7. Indirect

and contingency costs were calculated using the method that was proposed by Chemical Engineering Economics (Garret, 2012).

$$\frac{Costs_{size2}}{Costs_{size1}} = \left( \frac{Size_2}{Size_1} \right)^\alpha \quad \text{Equation 20}$$

### 3.3.5. Sensitivity Analysis

Defining a base case with average input values allows for further exploration of the profitability of a potential torrefied pellets plant by observing how alterations in these average values affect the overall financial performance and GHG emissions. Tornado analysis is a tool that compare the significance of variables. Each uncertainty treated needs to evaluate the low, base, and high results would be. The sensitive measure is displayed as an uncertain value while all other one are considered at reference point values. By doing this, allows testing the sensitivity linked with one variable.

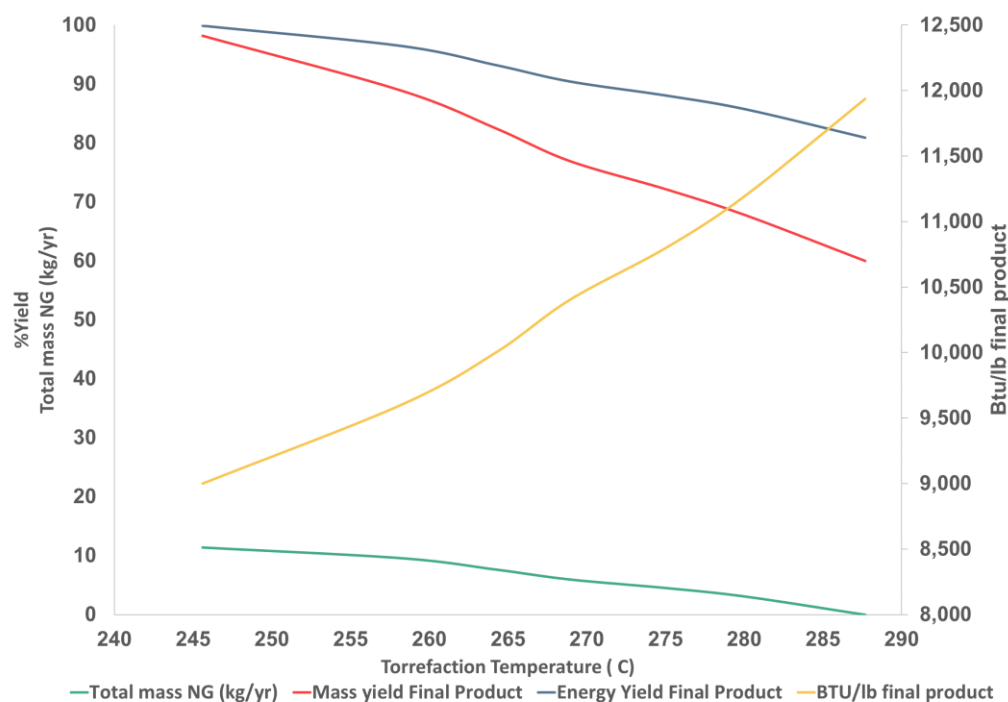
### 3.4. Results and Discussions

The torrefaction modeling highlights the relationship between the mass and energy model and the overall process of GHG emissions. Inclusion of the financial parameters can be used to evaluate the trade-offs between environmental and economic performance. The study shows how the mass and energy model has a complicated combination of variables including the caloric value of the incoming woody biomass and the final torrefied product, the moisture content of the incoming biomass, the torrefaction temperature, and the efficiency of the torrefaction process, which all impact of the heat balance and carbon emissions. This work shows how a financial model based on the process model can be used to identify the parameters that significantly impact the financial outcome.

## Process Modeling Results

Based on the process models and literature data, there is a general relationship between torrefaction time and temperatures, and the final torrefied product's mass yield and energy content. Longer reaction times and higher temperatures create a torrefied product with a higher caloric value, but lower mass yields. A higher caloric content product will have higher financial value but also requires the purchase of more feedstock to produce the same mass of final product. The torrefied product with higher caloric values, also produces more GHG/kg of final product from the torrefaction process. The product gases can be used to process energy, reducing or eliminating the need for supplemental heat.

Figure 3.8 shows the effects of increasing torrefaction temperatures on the mass yield, HHV and the potential requirement of supplemental natural gas. At lower torrefaction temperatures, the mass yield is higher, but there will likely be a need for supplemental fuel due to the relatively low amount of total gases available for both the drying and torrefaction processes. However, as the torrefaction temperature increases, the mass loss increases, resulting in the production of more torrefied gases, reducing the need for supplemental fuel. At torrefaction temperatures above 290 °C, this model project that no supplemental fuel is needed. It is worth noting that the operational practices of some pilot systems suggest that combustion of the torrefied gases and vapors can produce sufficient heat for both the drying and the torrefaction process. Thus, the kinetic model and operational experience are not entirely aligned.

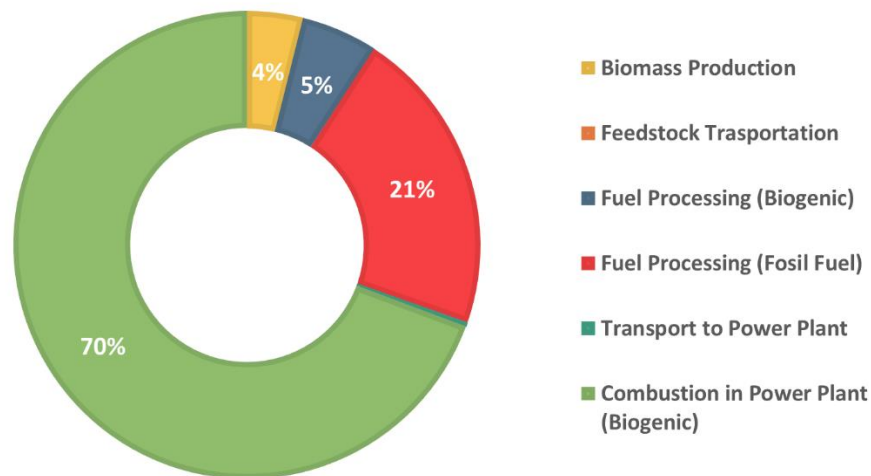


**Figure 3.8.** Relationship between the mass, the HHV of torrefied product, and supplemental natural gas, as a function of torrefaction process temperature

## Life Cycle Assessment

The GHG emissions for the different process steps are shown in Figure 3.9 for biomass feedstock with an initial moisture content of 50% and final energy content the same as PRB coal (21,630 J/g or 9,300 Btu/lb.). Consistent with prior work, the GHG emissions from the combustion process dominate the LCA footprint. For biomass with a 50% moisture content and a starting caloric value of 19,770 J/g (8,850 Btu/lb.), the modeling shows that the process heat will be a significant source of GHG emissions. These emissions can come from two potential sources, combustion of the torrefaction gases will be the most apparent source of process heat and GHG emissions, and if needed supplemental fuel from either natural gas or additional biomass. While natural gas may be the most straightforward supplemental fuel system from an operational point of view, it will also

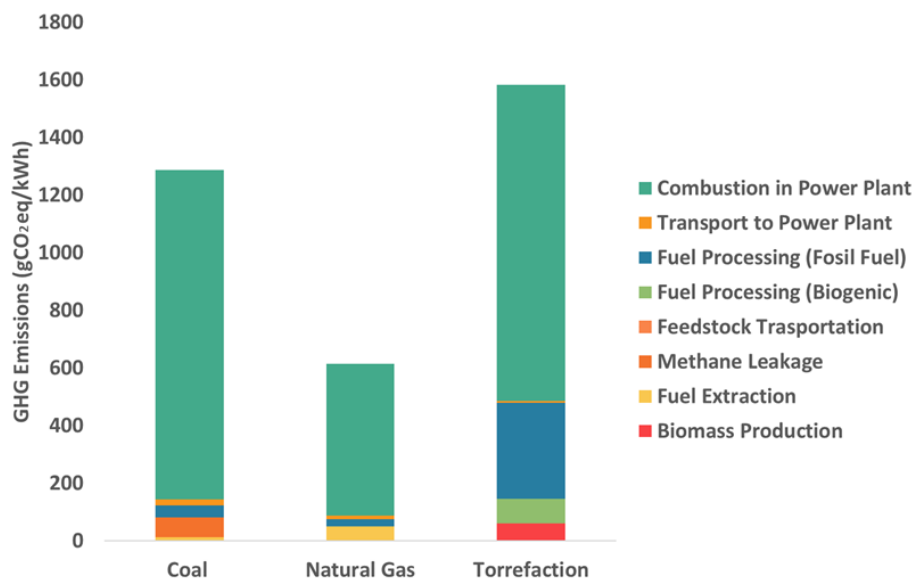
be a significant source of fossil GHG. Supplemental biomass added to the biomass solid fuel boiler is also a viable option and will only produce biogenic emissions. Even though the power plant combustion process is the major contributor of GHG emissions, these are biogenic emission so over time these can be recaptured by the growth of new biomass.



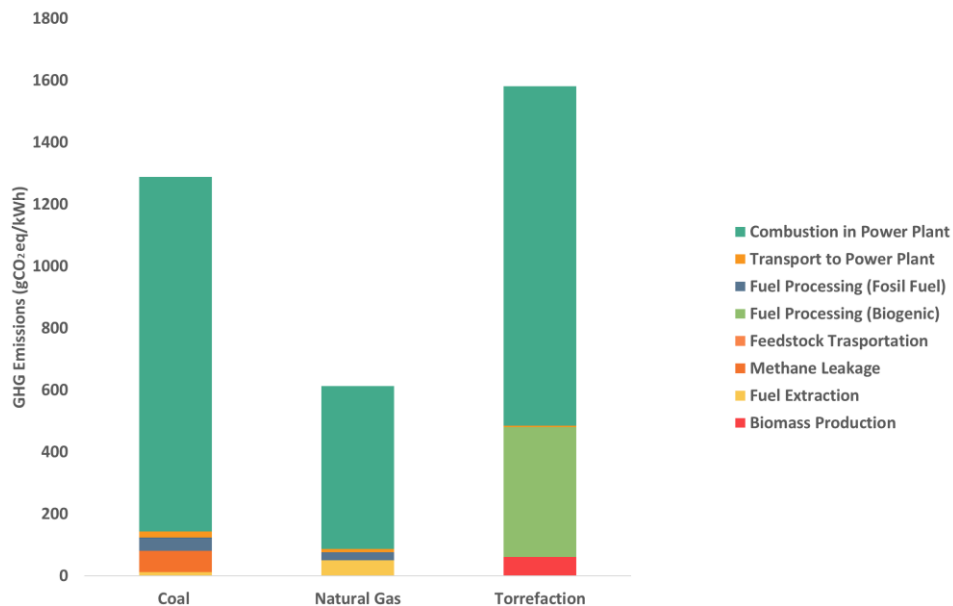
**Figure 3.9.** GHG emissions torrefaction process

To better understand the LCA of alternative power production options, coal, natural gas, and torrefaction biomass were compared over a single year. The total GHG emissions, biogenic and non-biogenic, for the three power production alternatives, coal, natural gas, and torrefied biomass, are shown in Figure 3.10.

A



B



**Figure 3.10.** Life cycle inventory of the GHG produced by the combustion of three alternative fuels. a) with natural gas b) without natural gas

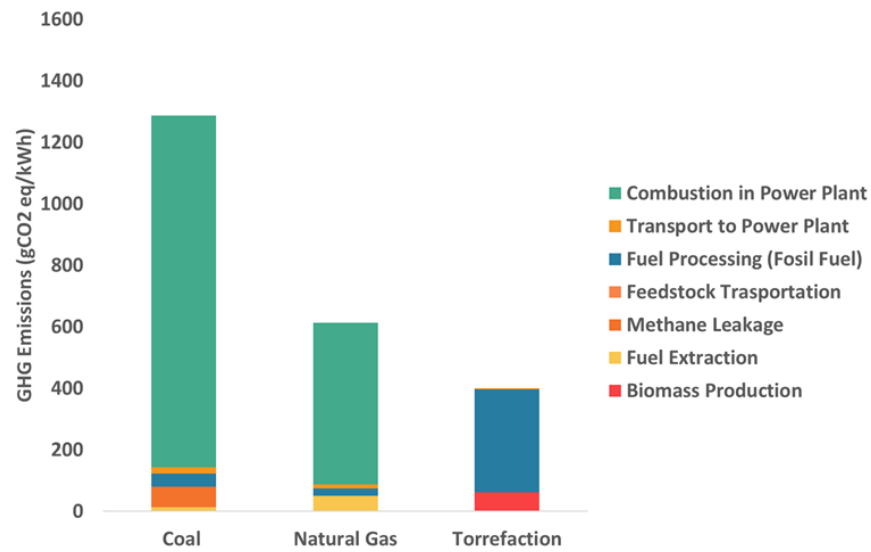
Most significantly these results highlight the advantages of power generation with natural gas relative to a solid fuel such as coal or torrefied biomass. This analysis includes the GHG generated by fugitive methane emissions, although these emissions are complex and not completely understood. But, some recent reports suggested that the fugitive emissions from natural gas have been under counted (Sahoo et al., 2018, 2019; Tumuluru et al., 2021). This analysis includes the GHG generated by methane emissions, although these emissions are complex and not completely understood.

These results highlight several other important points. First, the total direct emissions from the torrefied biomass are more significant than coal. This is primarily due to the additional heat demand needed to dry and torrefied the woody biomass and the loss of mass in the torrefied product.

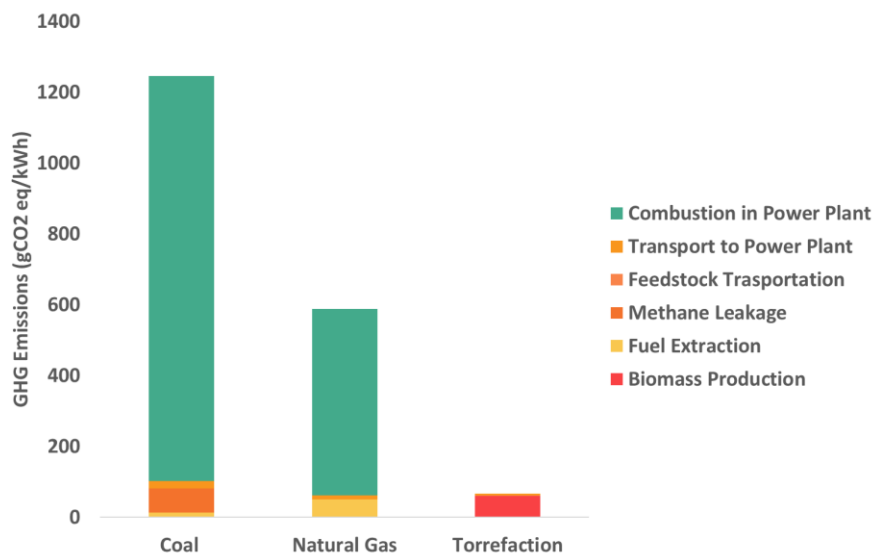
Second, the emissions for the torrefaction process are significant. This is due to both the need for drying the biomass, and the torrefaction reactions themselves. Third, the GHG emissions associated with the transportation of the biomass are small. This includes both ‘in woods’ operations, and the transportation of the wet wood for 50 miles. This presentation shows results that are consistent with the modeling work presented in Figure 3.3 that has both recycled torrefaction gas and added natural gas. The GHG emissions are dominated by the combustion process, where the emissions for the coal and torrefied biomass are the same due to their identical caloric values. Secondary, unit operations in the coal plant such as scrubbers for sulfur and mercury are not included on this LCA analysis.

While the gross emissions are shown in Figure 3.10 the more appropriate way to view the torrefaction process emissions over the long term is to differentiate the biogenic and non-biogenic emissions. The emissions from fossil fuel sources alone are shown in Figure 3.11.

A

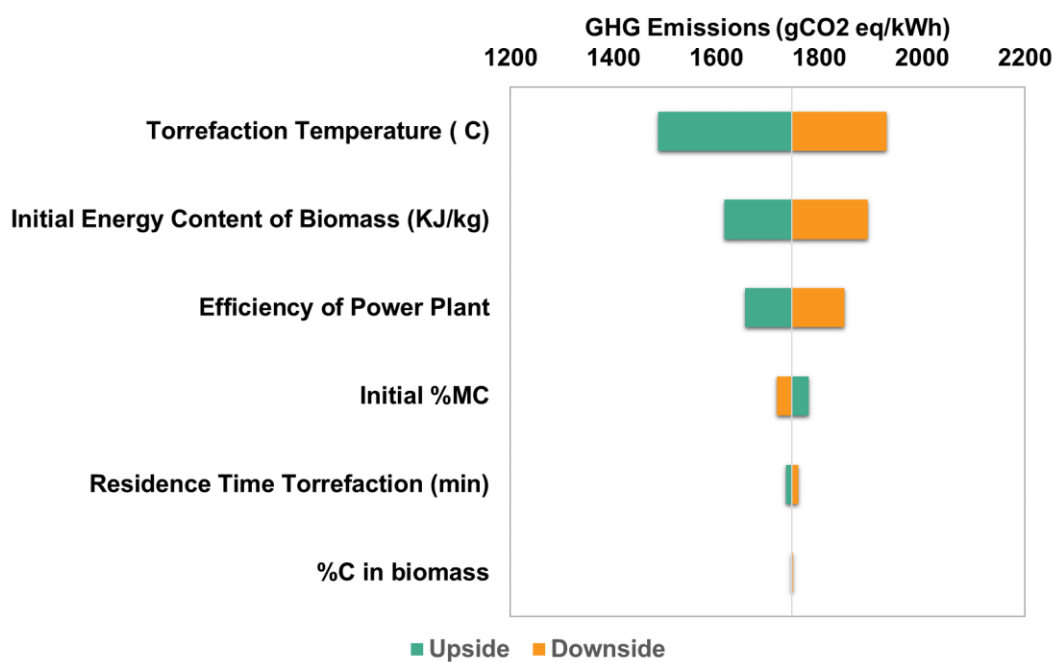


B



**Figure 3.11.** Life cycle inventory of the Green House Gases (GHG) produced by the combustion of three alternative fuels. a) With natural gas b) Without natural gas.

Using a sensitivity analysis with a variations of +/- 10%, the main parameters impacting the total GHG emissions were evaluated, Figure 3.12. According to this analysis, torrefaction temperature, in energy content and efficiency of the final use for electricity generation are part of that. Less obvious variable are the initial moisture content and residence time. As it was mention above reactor temperature will determine several properties that will affect the final outcome. Quality on the final product and the use of an extra utility fuel required are two critical parameters.



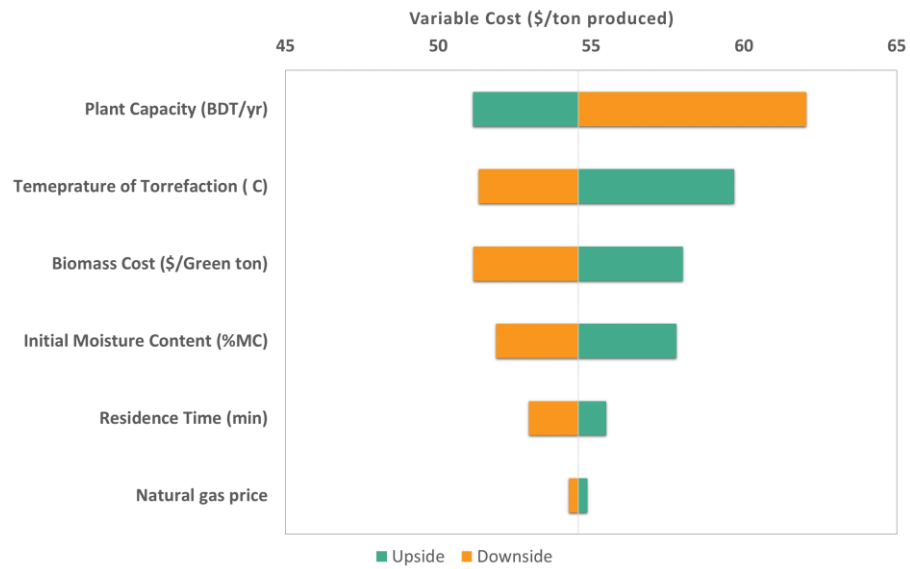
**Figure 3.12.** Tornado Analysis on GHG emissions for torrefaction process

## Financial Assessment

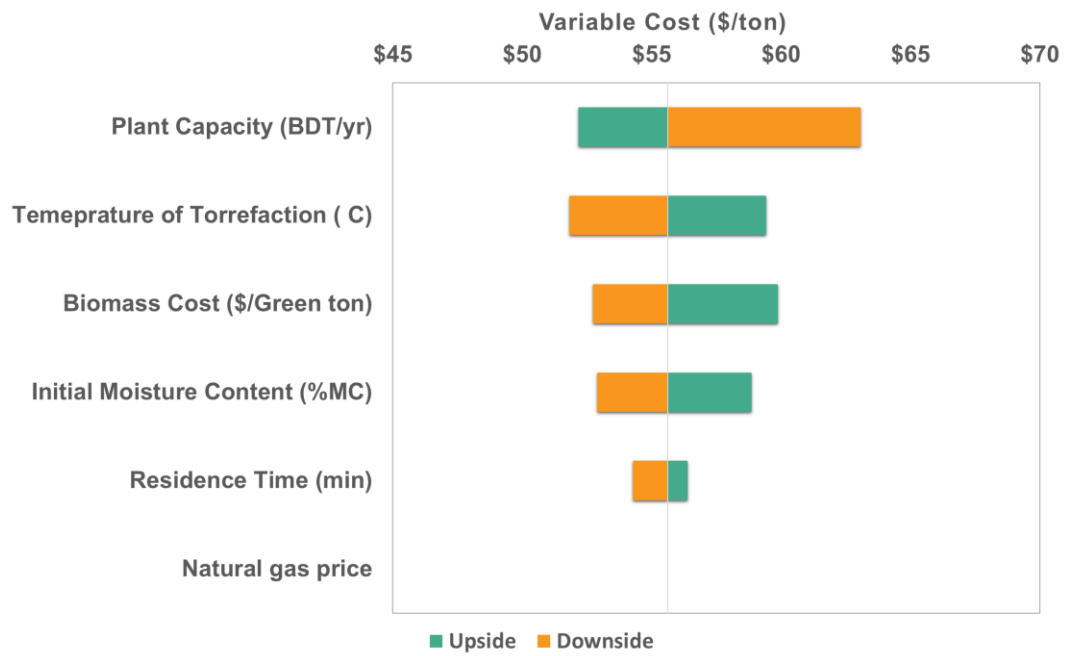
The initial implications for the operational costs are shown in Figure 3.13. The plant capacity, reactor temperature and biomass cost all have the greatest impact on the overall cost of the torrefied product. The influence of varying the plant capacity comes from different cost components. Increasing the manufacture volume does not directly increase fixed costs, higher capacity

operation may result in lower per-unit product costs and greater potential profits. Although, for any new technology such as torrefaction to total cost that an investor is willing to risk is also a key consideration in defining the plant size. Increasing the torrefaction temperature will lower the mass yield, and thus have an indirect impact on the total cost of purchased biomass for a given plant capacity.

A

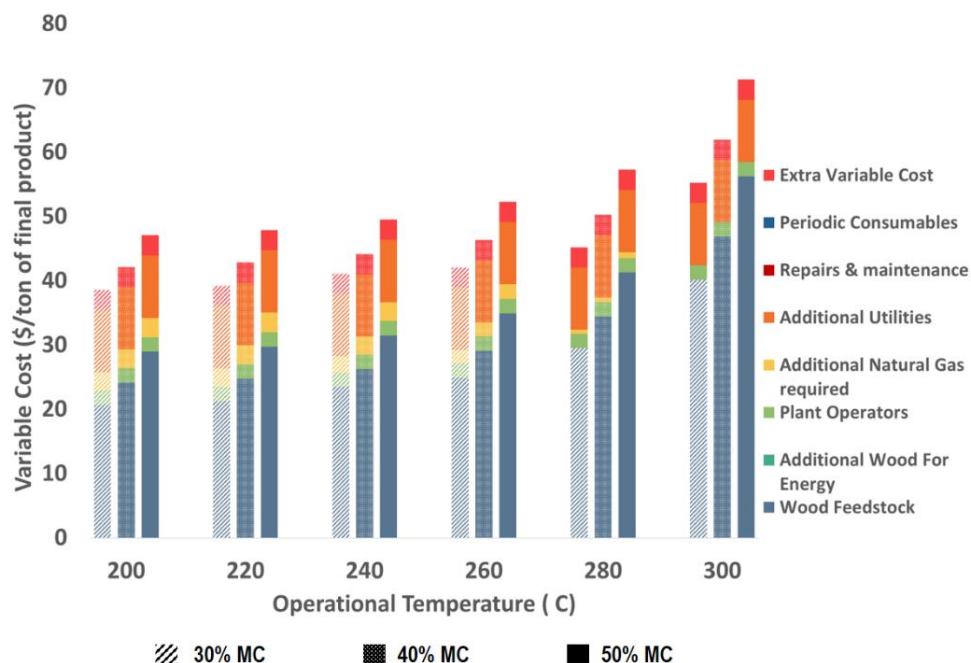


B



**Figure 3.13.** Tornado analysis variable operating cost. a) With natural gas b) without natural gas

Figure 3.14 shows the interaction between the torrefaction reactor temperature and the biomass moisture content. Wood feedstock and the potential use of natural gas are the main parameters that affect the value either for a fixed or variable operational temperature. The cost of heat from biomass or natural gas that is needed for drying and torrefaction has the greatest impact, followed by the need purchase more tons of the raw material (green biomass) to obtain a fixed output of OD torrefied product. Not surprisingly, the actual cost of the green biomass also has a significant impact on the total annual operating costs. As mentioned above in Figure 3.13a where natural gas is included, the cost of natural gas is significant. When no natural gas is purchased (Figure 3.13b) there is still a need for some supplemental biomass for process heat. The transportation of the final product is also contributor to the final costs. Note, since these are costs, the implications of the sales price of final torrefied product does not enter into the calculation.



**Figure 3.14.** Variable Cost as function of Torrefaction Temperature

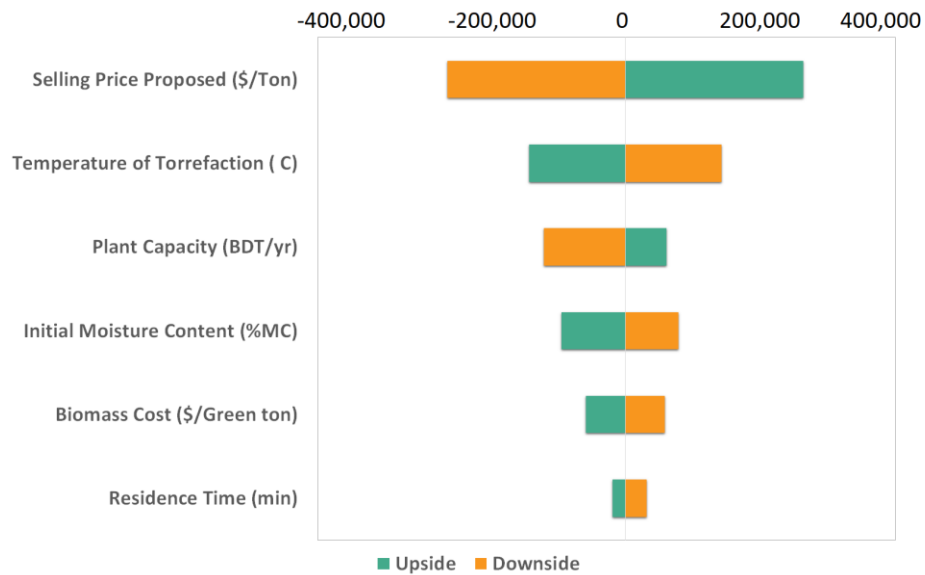
NPV is commonly applied in capital budgeting and investment planning to examine the profitability of a proposed investment or project.

In this study fixed price is assumed for all operational conditions as shown in Table 3.13. Usually, fuel price are determined by quality on the final product (Bloomberg, 2022c; U.S Energy Information Administration. eia, 2022). Also, unexpected situations such as war in Russia-Ukraine might affect the fuel price due to the high demand where the loss of natural gas may also cause coal surge(U.S Energy Information Administration. eia, 2021a). At better quality, higher sales price could be suggested. Hence, as operating cost is increasing with an improved feature product and same revenue is presented, the NPV on the project might not profitable for some operational conditions as Figure 3.15 presents in a sensitivity analysis of the process. All of the rest parameters make impact on the NPV value because the change on the variable cost present.

A



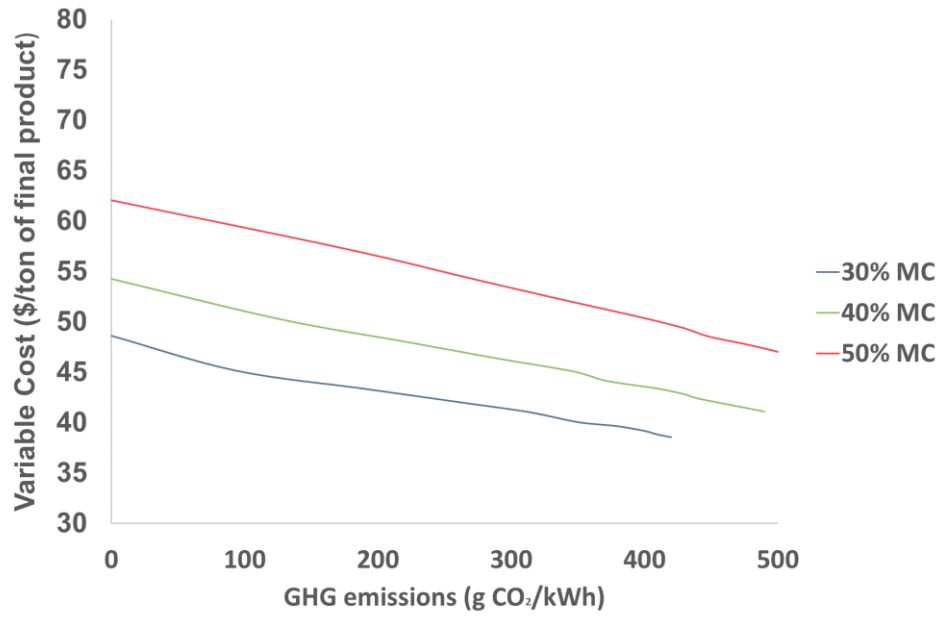
B



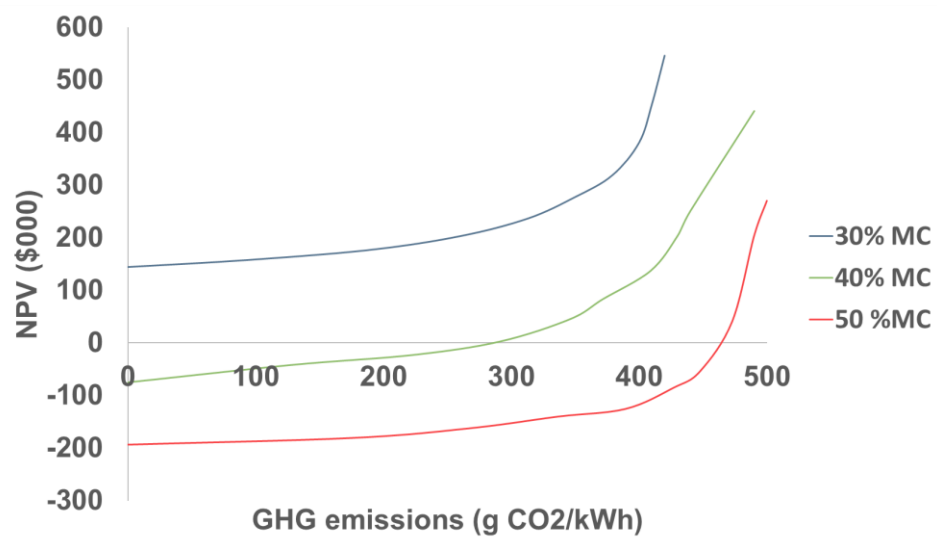
**Figure 3.15.** Tornado analysis on Net Present Value (NPV). a) With natural gas b) without natural gas.

One final test of the combined modeling approach was to select a narrow range of operating conditions and calculate the mass and energy balance for the process. This mass and energy balance was then used to calculate the gate-to-gate global warming potential (GWP) for the torrefaction manufacturing plant. This same range of mass and energy was then used as an input for the financial model. This allowed calculations on the costs and NPV for this particular set of operating conditions.

Variations in the variable operating cost and GHG emissions as a function of the initial biomass moisture content is Figure 3.16a. This initial analysis was conducted for a fixed mass of torrefied product. As Figure 3.14 shows, reaction temperature and initial moisture content also considerably influence the variable cost. Therefore, since the biomass is procured on a 'green' basis for higher moisture content, more feedstock requires purchasing more materials to achieve a constant production target.



A



B

**Figure 3.16.** Tornado analysis on Net Present Value (NPV). a) With natural gas b) without natural gas

In Figure 3.16b, the NPV is plotted against the GHG emission for three different moisture content values. As is less obvious to observe, there are the changes in the GWP that result from changing the torrefaction temperature. The highest GWP emissions occur at lower torrefaction temperatures due to the lower mass loss, the resulting low amount of torrefaction gases available for drying and process heat, the need to purchase more natural gas, and the latter's resulting emissions impact on GWP. This trend is most dramatic for the highest.

On the other hand, the differences in the NPV follow the predictable pattern where the higher the moisture content, the lower the NPV. As discussed above, for a fixed production value, and the use of the current commercial standard of purchasing green wood, the higher MC requires purchase of more wood, and this higher cost drives the lower NPV. There is a secondary factor related to the costs of drying the higher moisture content wood.

### **3.5. Conclusions**

This work was intended to model the carbon flows for an integrated system with three components

- ✓ Production of woody biomass and transportation.
- ✓ Production of a torrefied product that could be used to replace coal.
- ✓ Combustion of the coal or torrefied product to generate electricity.

Production of the torrefied product was studied using an engineering process model that related the mass and energy balance to the processing conditions, the moisture content of the starting biomass and the caloric value of the final torrefied product. This process model showed that if the moisture content of the incoming biomass was high (40-50%), and the final torrefied product's caloric value was low, there may be a need for supplemental fuel. Conversely, if the moisture content of the incoming biomass was low (20-30%), and the caloric value of the final torrefied

product was high, then there was excess process heat. However, the torrefied biomass with high caloric value also has a relatively low mass yield requiring a larger volume of starting woody biomass. In all cases torrefied biomass had lower fossil carbon emissions than coal or natural gas. However, the torrefaction system initially had higher total carbon emissions due to emission generated by the combustion of the torrefied biomass, in combination with the process energy needed for drying and process heat.

The financial model developed under this task is useful for the evaluation of the financial returns generated by the conversion of green biomass into a torrefaction product. As with any financial model this requires user to input for key variables, specifically capital and operating costs, and costs related to the mass and energy content of the final product, which then dictates both the costs and NPV.

The mass and energy yields have a very significant impact on the NPV as the both the value and volume of the torrefied product are intimately related to the mass and energy balance. As user defined parameters these values must be estimated from a kinetics models, as was done here, or verified by operational experience.

As part of the evaluation of this financial model it is clear that the business case for torrefied biomass is challenging. This evaluation work used a sales price of started with \$250 /AD ton, which is around 2 times higher than the actual average price of PRB coal with similar caloric content. Even a premium grade of coal, with low sulfur, and Btu/lb in the 12,000-13,000 only sells for 109-138 \$/ton (U.S Energy Information Administration. eia, 2022). As expected the sales price of the final product dominates the financial performance, as measured by the NPV. Thus, if the final price for the torrefied product is the same and the variation cost increase while quality of

product is improved, torrefaction process does not pay' unless you get a subsidy. Future studies should evaluate this change of the price in accordance to the final energy content.

However, most of the business scenarios do not anticipate that the torrefied biomass will compete directly with coal on a BTU basis. Rather the lower GHG emission will command a price premium for avoided fossil fuel emissions, and a sound business case can be developed based on this price premium. In some parts of the western US forest thinning that are conducted to decrease fire risk can also provide a lower cost biomass, or subsidies that can make the overall process attractive. While both of these policy implications were outside the scope of this work, the current model could be used to include these factors in some future analysis.

**Acknowledgements – CAWES, USFS FPL 16 JV-11111137-01.**

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## **CHAPTER IV**

### **4. ENVIRONMENTAL FULL COST ACCOUNTING OF ALTERNATIVE MATERIALS USED FOR RAILROAD TIES: TREATED-WOOD AND CONCRETE CASE STUDY**

#### **4.1. Abstract**

Environmental full-cost accounting (FCA) is a novel analytical framework that describes ecological and human health impacts of products and processes using financial measures. These impacts are generally considered to be external to the cost of the product, and are not traditionally reflected in the sales price of the product or service. FCA methodology provides a novel framework to analyze product alternatives from an inclusive perspective considering economic, societal, and environmental impacts. In this work, researchers use the FCA methodology to compare a series of chemically treated wooden and concrete railroad crossties. For all products analyzed in the study, production of the treatment chemicals and the crosstie, use, and disposal stages were included along with mass of emissions, and associated health and environment costs. This FCA allows for a comparison of alternatives products and insight into the implications of final disposal. Two alternative end of life (EOL) scenarios were explored, e.g., energy recovery where the chemically treated wood is burned for energy production, and disposal in a landfill. This work shows that the EOL scenario for treated crossties play a dominate role when defining environmental and social costs. This contrasts with concrete crossties, where the production stage is the main contributor. Wood treatment utilizing copper-chrome-arsenic (CCA) represents a worst case EOL scenario due to high costs associated with atmospheric emissions of arsenic and CO<sub>2</sub>. Finally, depending on how biogenic CO<sub>2</sub> is treated, concrete or furfuryl alcohol treated wood had the lowest environmental price.

## 4.2. Introduction

Demand for renewable materials has rapidly increased as consumers request products with lower environmental impacts. Historically, wood has been an attractive alternative to steel and concrete building materials for a wide variety of applications (American Wood Council, 2020; Lippke et al., 2019; Sathre & González-García, 2013). Smith (2019) estimated the North American market share for alternative railroad cross tie materials to be wood (91.5%), concrete (7.9%), and steel (0.9%). These products represents 207,000 miles of railroad track in the United States with an estimated 620 million individual ties (Smith, 2019). Wooden ties are attractive due to their specific toughness and elasticity, relative lightweight, and simplicity of manufacturing and installation. These advantages have allowed chemically treated wood to become the dominant material used for crossties for the past 150 years, covering approximately 82% of the railway track in the US (Bolin & Smith, 2013b).

A variety of commercial chemical treatment systems have been developed to increase decay resistance and durability of wood crossties (IASC, 2010). These chemical treatments provide decay resistance through the chemical (preservative) impregnation of the porous wood structure, limiting decay (IASC, 2010). Treatments cover a wide array of formulations including water-borne, inorganic salts (e.g., copper, chrome, arsenic, boron, others), or oil-borne organic compounds (e.g., creosote and pentachlorophenol). These chemical treatments all work through the same basic mechanism, serving as a toxic agent to wood decay organisms. Reactive organic systems (e.g., furans or phenolics), which can be thermally 'cured' to convert a liquid precursor impregnated into the wood into a solid, offer an alternative approach. The cured resin changes the properties of the wood so it is no longer easily degraded by decay fungi. This treatment may even improve crosstie strength properties (Pries and Mai, 2013b; Sandberg et al., 2017; Shupe et al.,

2006; Skrede et al., 2018). Depending on the treatment system, mechanical strength, tendency for corrosion, and flame retardant properties may also be improved (Ibach, 2010; Nestler, 1974). Water-based preservatives are typically lower cost than oil-borne systems (Archer & Lebow, 2006; Barnes & Carey, 2020).

All wood treatment systems have hazards related to the manufacturing of the treatment chemicals, evaporation in use, and leaching of the chemicals during the use and EOL stages. Some treated wood products have been considered carcinogenic, excluding their use in countries with strict heavy metal emission standards or with strict control over volatile organic compounds (VOCs) (Cimboláková et al., 2018; Donatello et al., 2017; Lodge, 2017).

The performance and long-term environmental impacts of concrete materials have been debated (Gustavsson et al., 2006; Khasreen et al., 2009). Concrete production currently accounts for more than five percent of annual world-wide carbon dioxide (CO<sub>2</sub>) emissions, mainly from fossil fuel use during cement clinker manufacturing (Gursel, 2014). More recently, it has been observed that in some applications, concrete slowly adsorbs CO<sub>2</sub> during service life and demolition stages (Possan et al., 2016). Common deterioration effects of concrete during its service life are caused by corrosion, alkali aggregated, sulphate attack, leaching, abrasion, and acid attack (Budelmann et al., 2012). The corrosion effect is one of the main contributors to a decline in concrete durability, dominated by chloride penetration and carbonation (Pillai et al., 2019). Deterioration by chloride can be pronounced where a structure is located in, or near, a saltwater environment.

Judging the relative merits of alternative materials is complex and requires consideration of environmental, social, and economic aspects (Cardon et al., 2011; Thomassen et al., 2019). Life Cycle Assessment (LCA) is commonly used to evaluate the environmental burdens associated with manufacturing a product, from the extraction of the raw materials to disposal at the end-of-life.

However, LCA commonly focuses on 'mid-point' measures of a product or process (e.g., emissions of CO<sub>2</sub>, ozone, acidic compounds, small particulates, etc.), rather than 'end-point' analyses which attempts to describe the actual 'damage' caused chemical emissions (Bruyn et al., 2010).

Although LCA is a well-developed methodology for evaluating environmental impacts ("ISO14040," 2006), the results are not always comparable or easily understood by non-practitioners. Additionally, financial and social implications of materials are generally not considered in a standard LCA. For example, ecosystems and human health damages associated with products or processes are not reflected in LCA results (Durao et al., 2019). Due to these limitations, there is interest in developing more comprehensive analytical methods that include monetary implications (harm, damage, or cost) coupled with LCA findings (Hagedorn, 2019; Jasinski et al., 2015).

Full-Cost Accounting (FCA) is a novel analytical framework that combines the environmental impacts measured by LCA with the social and financial implications of alternative products or processes. FCA considers both direct and indirect costs, including external costs (damages) or adverse effects of an activity or decision, and assigns these direct and indirect costs to the process or product. Estimating FCA costs requires making multiple assumptions that can be non-linear and complex. For example, damage costs produced by point source atmospheric emissions are influenced by secondary factors such as location, height of release, emission pattern, and pollution concentration (Lodge, 2017). One approach to this complexity is to present a range of possible results that describes product or process emission variability. De Bruyn et al. (2018) addresses this variability by assigning pollutant costs a lower, central, and upper value based on emission characteristics.

FCA techniques have been applied to a number of products or systems, including oil and gas, energy, and waste management sectors (Jasinski et al., 2015). Roth and Ambs (2004) used FCA to compare energy costs across 14 different electricity generation technologies. The study included damage from air pollution, energy security, transmission, and distribution costs, and concluded that clean and efficient generation technologies are the most attractive when the all costs are considered. Epstein et al. (2011) studied the life cycle of US coal and its waste streams, concluding that its external cost ranged from \$300-500 billion annually. More recently, our research group has used FCA to evaluate costs associated with wood or steel highway barrier posts. This work showed that the cradle-to-grave costs of CCA treated wooden posts was lower than that of galvanized steel posts. This outcome was primarily due to the significant sulfur dioxide emissions and fossil CO<sub>2</sub> emissions associated with steel recycling (Scouse et al., 2021).

LCA is a thorough and well-developed analytical framework for assessing process or product ecological impacts. The commonly used TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) methodology utilized for LCA studies produces seven measures of environmental damage, including human health impacts, climate change, ozone depletion, acidification, eutrophication, smog formation, and ecotoxicity, along with several subcategories. Former LCA practitioners have found it challenging to reduce these different impact categories into a single score (Abbati de Assis et al., 2017; Daystar et al., 2015). The process is further complicated by the challenge of comparing kilograms of CO<sub>2</sub> or SO<sub>2</sub> equivalents to grams of carcinogens. Comparing the relative impacts of these emission types is complex, requiring a number of assumptions (Kalbar et al., 2017). FCA offers one approach to comparing these different emissions and impacts by creating a single score solution where each individual emission is assigned a 'cost.' This 'cost' is then combined with the mass of the emission, allowing for creation

of a single score using a financial base unit. Results can incorporate external environmental and societal costs that are not normally reflected in an item's sales price. This FCA single score can be used to compare product alternatives while tracking the magnitude of environmental and human health costs throughout the life cycle stages. Combining the cradle-to-grave systems approach of LCA with the financial methodology of a FCA provides decision-makers with the information necessary to directly compare full life-cycle cost impacts of products or process.

In this study, the FCA methodology was used to estimate the costs of concrete and wood railroad ties. Five types of treated wooden railroad ties were investigated: CCA, Copper-Boron-Arzone (CBA), Creosote, Pentachlorophenol (Penta), and Furfuryl Alcohol. The analysis included cradle-to-grave emissions. Sensitivity analysis was used to identify the largest sources of emission uncertainty influencing total costs estimates, and the natural variation of emissions outputs.

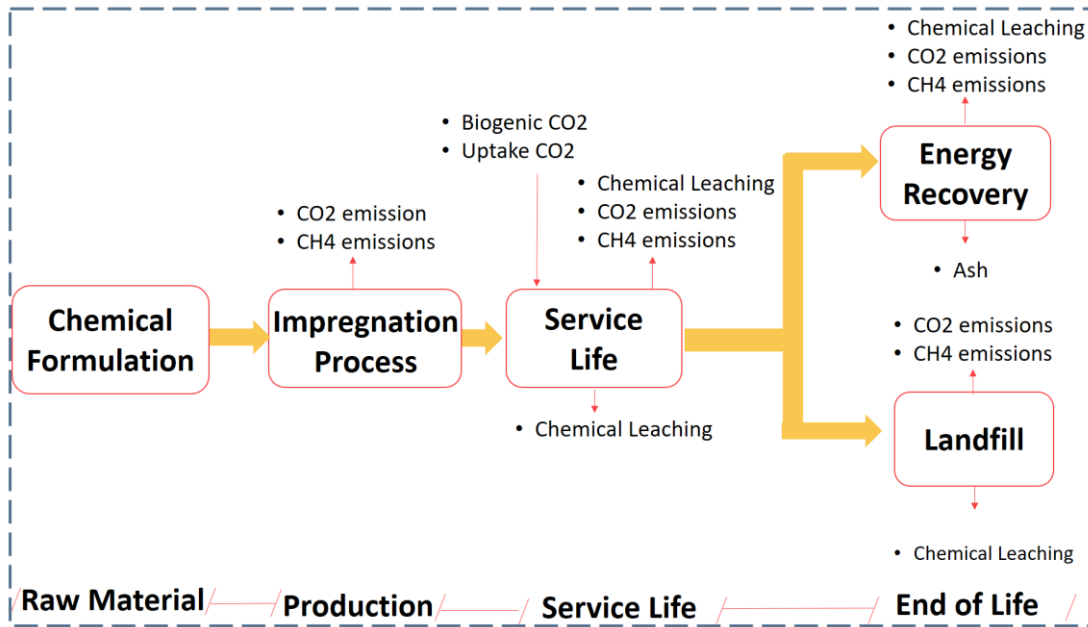
### **4.3. Materials and methods**

#### **4.3.1. System Boundary Conditions**

To evaluate total damage costs, a life-cycle inventory was conducted according to ISO 14040. The system boundary included emissions from the production of the wood preservation chemicals, wood impregnation, high-temperature drying (if needed), crosstie service life, and EOL disposal<sup>1</sup>, as indicated in Figure 4.1. The functional unit was defined as one railroad crosstie with a service life of 20 years. The study includes emissions leaching or chemical volatilization during use, potential leaching from ash following combustion, and CO<sub>2</sub> or methane emissions from the alternative EOL scenarios. The potential reabsorption of CO<sub>2</sub> by concrete was also considered.

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<sup>1</sup> The analysis started with an air dried, wooden crosstie. This eliminated the issues with allocation of the wood residues generated at the sawmill. Prior work has shown that emissions from the harvesting and transportation of the logs is low (Lan & Yao, 2019). Depending on the sawmill, and local markets, these residues could be used for paper or particleboard production, or combusted for industrial heat and power.



**Figure 4.1.** System of Boundaries

#### 4.3.2. Concrete Production

Crosstie concrete formulations may vary by manufacturer. The concrete formulation used for this work is provided in Table 4.1. The effects of alternative formulations were evaluated using sensitivity analysis.

**Table 4.1.** Mixture compositions of concrete (Tae et al., 2011)

Key Characteristics	Unit	Amount
<b>Strength</b>	MPa	24
<b>Water/Cement Ratio</b>	%	0.5
<b>S/A*</b>	%	0.48
<b>Water</b>	kg/m <sup>3</sup>	169
<b>Cement</b>	kg/m <sup>3</sup>	337
<b>Fine Aggregated</b>	kg/m <sup>3</sup>	859
<b>Coarse Aggregated</b>	kg/m <sup>3</sup>	919

\* Sand (Fine aggregate) to Aggregate (Fine aggregate + Coarse aggregate) ratio.

Details describing the calculations of CO<sub>2</sub> reabsorption by concrete are provided in Appendix 1.

#### 4.3.3. Wood Treatment

The wood treatment process began with an air-dried tie, and was followed by two steps: impregnation and, in the case of the furfuryl resin, a thermal curing step. If the high temperature curing step was not needed, crossties were assumed to be air dried following treatment.

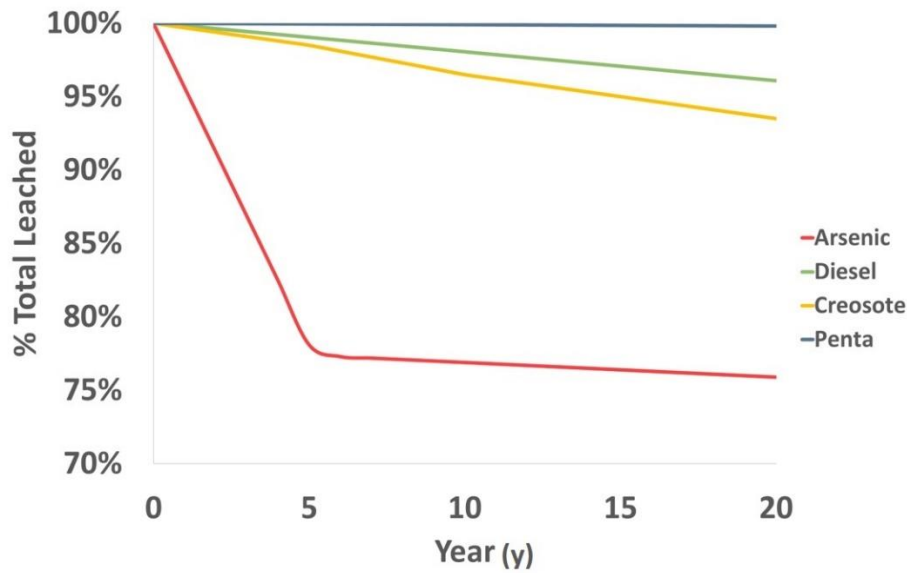
- **Impregnation:** Wood-preservation processes are generally divided into two classifications: pressure and non-pressure process. To increase production rates, most wood treatments use a series of vacuum and pressure steps to force treatment solution into the wood. The specific operating conditions (e.g., pressure and vacuum processes) differ by manufacturer, but the general principle is the same (Ibach, 2010). The wood is placed into a long cylinder, vacuum is applied, removing air and some additional moisture. The cylinder is then filled with preservative and pressure is applied, forcing the preservative into the wood until the desired amount has been absorbed. The pressure is then released, and the treatment liquid is drained from the cylinder and reused. Depending on the treatment system, treated wood might be air dried for varying lengths of time before shipping. The summary of chemical formulations and crosstie composition used for this work are provided in **Table 4.2**.
- **Curing:** A curing step is necessary when the impregnation chemical is reactive. An example of this type of treatment is furfuryl resin. For these types of treatment systems, polymerization is initiated using heat (e.g, 160-180 C), driving off moisture and starting the chemical reactions that cause the furfural resin solution to solidify.

**Table 4.2.** Wood tie characteristics by treatment chemical (Bolin & Smith, 2011a, 2010, 2013b; Keboney®, 2015)

Key Characteristics	Dry Mass Wood (kg/tie)	% MC*	Chemical Retention (kg/m <sup>3</sup> )	Chemical (kg/tie)	Whole Mass of Tie (kg/tie)
Air Dry Tie	67	25%	0.0	0.0	83.7
CCA*	67	18%	8.0	0.9	80.3
CBA*	67	18%	6.4	0.7	79.8
Creosote	67	18%	88.1	9.3	88.5
Pentachlorophenol	67	18%	7.2	0.8	79.8
Furfuryl Alcohol (Keboney®)	67	18%	-	16.3	95.7

\*%MC: Percentage Moisture Content, CCA: Chromated Copper Arsenate, CBA: Copper-Boron-

Arzole



**Figure 4.2.** Chemical Leaching Curve

#### **4.3.4. Service Life**

##### **4.3.4.1. Reinforced Concrete**

This study considers the carbonization effect for reinforced concrete cross ties with a 70 year service life (Pillai et al., 2019; Possan et al., 2016). In most exterior applications, CO<sub>2</sub> induced carbonization takes place during product use and disposal. Concrete CO<sub>2</sub> adsorption estimates used in this study are based on models developed by Tae et al. (2011) and Possan et al. (2016). The details of the carbonization process, and the assumptions which were adopted from those studies, are provided in Appendix 1.

##### **4.3.4.2 Emissions from Treated Wood**

Wooden railroad tie service life is related to wood species, wood qualities and anatomical features (e.g., knots, twist, the ratio of earlywood to latewood), the type of treatment, and environmental conditions. During product use, there is potential for chemical evaporation and leaching into the

air or ground. Figure 4.2 illustrates the leaching rates of different components within wood treatment chemicals used for this study (Bolin & Smith, 2011b, 2013b; T. Townsend et al., 2019). Wooden railroad ties were assigned a 20 year service life (Bolin & Smith, 2011b, 2013b).

Two alternative EOL pathways were considered in our analysis. Ties could be burned for energy recovery or disposed of in a licensed landfill. Wooden railroad ties recovered for energy production should be combusted in a boiler that integrates scrubbers or electrostatic precipitators. These devices remove harmful chemical constituents to permitted levels but may reduce operational efficiency of combustion (Bolin & Smith, 2010; Cheremisinoff & Rosenfeld, 2010).

Carbon released from wood during combustion is biogenic, while the treatment chemicals should be considered as fossil derived. Inorganic preservative (e.g., CCA or CBA) emissions must also be carefully tracked, especially the arsenic from CCA, which is easily volatilized (Lebow, n.d.; Stook et al., 2005; T. Townsend et al., 2019). In the energy recovery process, combustion is assumed to destroy chlorophenols, but approximately 50% of fuel based chlorine is released as hydrochloric acid (HCl) gas, requiring removal via scrubbers (Bolin & Smith, 2011a). These combustion processes generate residual ash with varying levels of hazardous contaminants that must be sent to a licensed landfill.

As an alternative to combustion, this study also considers the direct disposal of used crossties in a landfill. When untreated wood is disposed of in a landfill, 77% of wood-based carbon is sequestered, 17% is released as CO<sub>2</sub>, and 6 % is released as methane (USEPA, 1992). It is assumed that that degradation of treated wood in a landfill will be slower than for untreated; however, no data from published sources were found. The impact variations in CO<sub>2</sub> and methane emission are described using sensitivity analysis.

In the case of reinforced concrete, the study relies upon life cycle inventory data provided by Saca et al. (2017), who describing an end-of-life process that includes demolition and one year of storage before landfilling. Over time, carbonization rates rise as the material breaks down and aggregate surface area increases.

#### 4.3.4.3. Costs for Alternative Emissions

Research by De Bruyn et al. (2018) provides lower, central, and higher environmental cost estimates in US dollars<sup>2</sup> for chemical emissions to the atmosphere and soil. The costs used in this work are presented in **Table 4.3** and in the supplementary materials. By tracking chemical emissions during each life cycle step, the total costs for treated wooden crosstie and concrete crosstie were calculated using equation 1.<sup>2</sup>

**Table 4.3.** Total Emission Cost (USD/kg of emission in 2015) (Bruyn et al., 2018)

Emission Price		Atmosphere			Soil		
Treated wood	Chemicals	Lower Value	Central Value	Upper Value	Lower Value	Central Value	Upper Value
CCA	Arsenic	6.90E+02	1.01E+03	1.12E+03	1.17E+01	4.45E+01	1.11E+02
	Chromium	9.13E-02	5.85E-01	6.67E-01	3.16E-05	4.91E-04	1.17E-03
Creosote	Naphthalene	1.03E-01	1.87E-01	2.69E-01	3.63E-03	5.27E-03	7.96E-03
	Fluorene	2.11E-01	2.93E-01	4.56E-01	1.40E-02	2.34E-02	3.39E-02

<sup>2</sup> The original data from De Bruyn was converted from Euro to dollars using a conversion of 1.17 USD to 1.0 Euro and a 2% inflation rate in the period of 2015 to 2021.

**Table 4.3** (continued).

	<b>Phenanthrene</b>	<b>1.29E-04</b>	<b>9.59E-04</b>	<b>1.09E-03</b>	<b>0.00E+00</b>	<b>0.00E+00</b>	<b>0.00E+00</b>
<b>Penta</b>	<b>Penta</b>	2.11E-01	4.10E-01	5.73E-01	2.34E-02	3.28E-02	5.03E-02
	<b>Fluorene</b>	2.11E-01	2.93E-01	4.56E-01	1.40E-02	2.34E-02	3.39E-02
<b>CBA</b>	<b>Copper</b>	6.90E-01	4.56E+00	5.50E+00	6.90E-03	1.76E-01	4.56E-01
<b>Furfuryl Alcohol</b>	<b>Furan Resin</b>	4.45E-08	3.39E-07	3.74E-07	1.64E-08	1.17E-07	1.29E-07
<b>Others</b>	<b>Carbon Dioxide</b>	2.57E-02	6.67E-02	1.10E-01	0.00E+00	0.00E+00	0.00E+00
	<b>Methane</b>	7.84E-01	1.99E+00	3.39E+00	0.00E+00	0.00E+00	0.00E+00

$$\text{Total External Cost} = \sum (\text{emission damage cost}) \quad \text{Equation 21}$$

#### 4.4. Results and Discussion

Environmental FCA results for CCA, CBA, creosote, pentachlorophenol, furfuryl alcohol-treated wood, and concrete were totaled at each of the three life cycle stages, e.g., production, use, and EOL. Total external costs, described in 2021 USD, are summarized in **Figure 4.3**. Total External Cost at 2021 of five-treated wood and reinforced concrete for the gate-to-grave railroad ties life cycle. Energy recovery scenario. Landfill scenario Figure 4.3 . The figure illustrates the main cost contributors for the five alternative treated wood and reinforced concrete railroad ties. Details for each treatment type and life cycle stage are described below, but Figure 4.3 highlights several key observations. There are five main attributes driving costs:

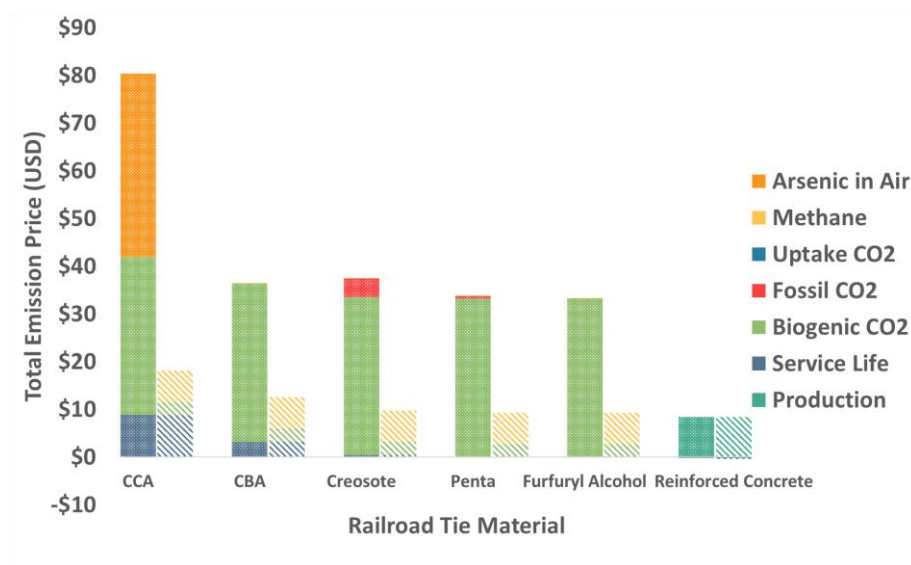
- When burned for energy recovery (EOL scenario), wooden crosstie total costs are driven by CO<sub>2</sub> emissions produced during combustion.

- When burned for energy recovery (EOL scenario), CCA treated crosstie total costs are driven by arsenic emissions to air during combustion.
- Wooden crosstie total costs are heavily dependent upon the methodological decision to include or exclude biogenic CO<sub>2</sub> emissions.
- When wooden crossties were landfilled (EOL scenario), external costs are driven by methane emissions generated by decomposition of wood.
- Concrete crossties have a comparatively low total cost compared to wooden crossties.

### **Costs including Biogenic Carbon Emissions**

As highlighted in **Table 4.3**, total costs are generated by two conditions: a large mass of low cost emissions, or a small mass of high cost emissions.

One unexpected outcome is the impact of biogenic CO<sub>2</sub> during EOL for the energy recovery scenario. Excluding arsenic emissions from CCA, biogenic CO<sub>2</sub> emissions resulting from burning wood dominated overall life cycle cost for all treated wood systems. For our study, this near-term CO<sub>2</sub> emission was viewed as a cost. One can argue that this cost diminishes over time, as emitted CO<sub>2</sub> can be recaptured by naturally re-growing or replanted trees. However, for high-density hardwoods commonly utilized for crossties, tree growth rates are slow. Under this kind of scenario, it may take more than 100 years to recapture atmospheric CO<sub>2</sub> (Sterman et al., 2018). Due to the slow regrowth rates of US hardwood species, study authors suggest that biogenic carbon emissions should be included when calculating total costs.



**Figure 4.3.** Total External Cost at 2021 of five-treated wood and reinforced concrete for the gate-to-grave railroad ties life cycle. ■ Energy recovery scenario. ▨ Landfill scenario

Alongside biogenic emissions, fossil CO<sub>2</sub> emissions are also included in the analyses. Fossil CO<sub>2</sub> emissions are linked to the petroleum derived chemicals used as components of the creosote and penta preservative systems. The impact of producing the inorganic treatment chemicals is negligible.

CCA treated crossties have the highest environmental cost of all product alternatives. Total costs are driven by treated crosstie burning for energy recovery, resulting in arsenic air emissions that escape scrubber and control systems. Combustion in the EOL scenario results in the volatilization of approximately 70% of the original arsenic (McMahon et al., 1986). There are essentially no fossil-based CO<sub>2</sub> emissions associated with the production of arsenic. Instead, arsenic leaching and ground contamination during service life is the third largest contributor to the product's total cost. Costs associated with the leaching of the other treatment chemicals, e.g., Cu and Cr, are less

than 1% of the total result for CCA treated ties. Specific data about each case and scenario are included in the supplementary information.

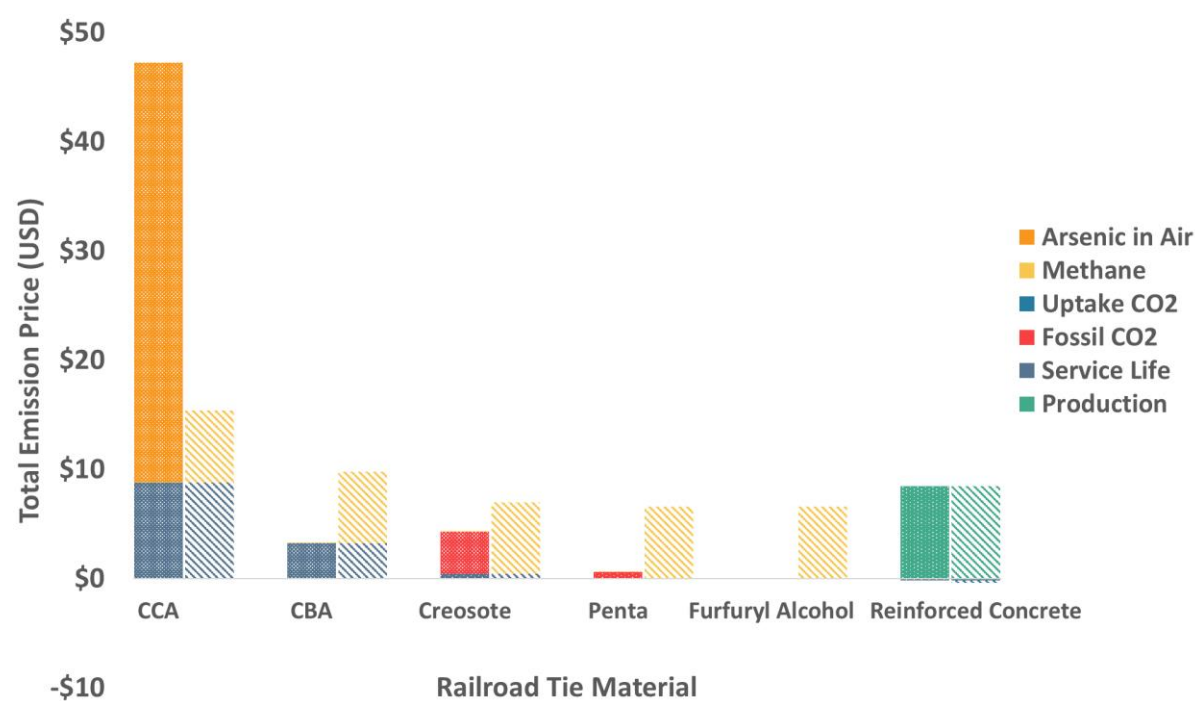
When wooden ties are landfilled, the major contributor to total cost is methane generation during wood (see Figure 4.3). While the mass of methane emissions is relatively low compared to CO<sub>2</sub>, methane has a higher cost per kilogram of emission. The combination of higher costs and moderate mass means that the methane becomes a higher impact emission. Under this scenario, there is also a small amount of chemical leaching, although the total costs from leaching is low. The impacts of methane and CO<sub>2</sub> emission variability from landfilled treated wood ties is addressed within the sensitivity analysis section below.

For the landfill EOL scenario the total cost of concrete and treated railroad ties are compared (Figure 4.3). Concrete is the lowest total cost product alternative. This is due, in large part, to the longer service life of concrete ties, which require less maintenance and replacement (Bolin & Smith, 2011b). The EOL emissions for concrete are essentially zero since there is no chemical leaching or biodegradation associated with concrete.

### **Costs Excluding Biogenic Carbon Emissions**

One of the advantages of using bio-based materials is the natural cycling of biogenic carbon between the atmosphere and terrestrial biomass; in this case a tree. From a long-term perspective, tree growth can be considered as one method for reducing atmospheric CO<sub>2</sub>. When tree growth takes place at an approximately equivalent rate of wood decomposition, biogenic CO<sub>2</sub> release can be considered carbon neutral. While this assumption is accurate from a long term perspective, e.g., hundreds of years, it is questionable in the short term, e.g., 10-50 years (Sterman et al., 2018). Thus, this work has evaluated two alternatives for including the ‘costs’ of biogenic CO<sub>2</sub> emissions.

Figure 4.4 illustrates the total emission costs in 2021 USD for the six alternative products, without the costs associated with biogenic CO<sub>2</sub>. When biogenic emissions are excluded, energy recovery is now the preferred EOL option for CBA, Creosote, Pentachlorophenol and Furfuryl Alcohol treated ties. When biogenic emissions are excluded, the total cost of the treated wooden crossties are smaller than for concrete, with the exception of the CCA treated crosstie.



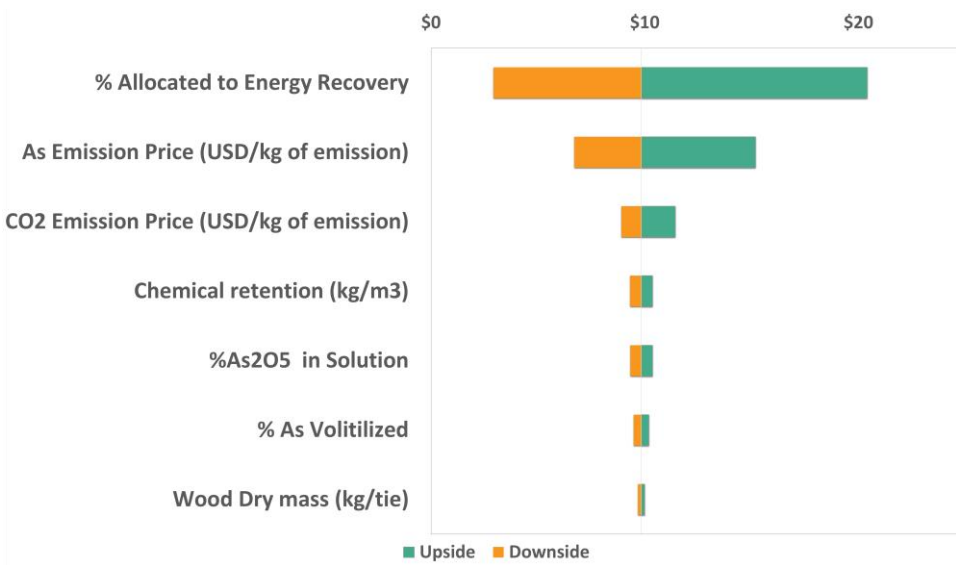
**Figure 4.4.** Total External Cost at 2021 of five-treated wood and reinforced concrete for the gate-to-grave railroad ties life cycle. Energy recovery scenario. Landfill scenario.

### Sensitivity Analysis of FCA

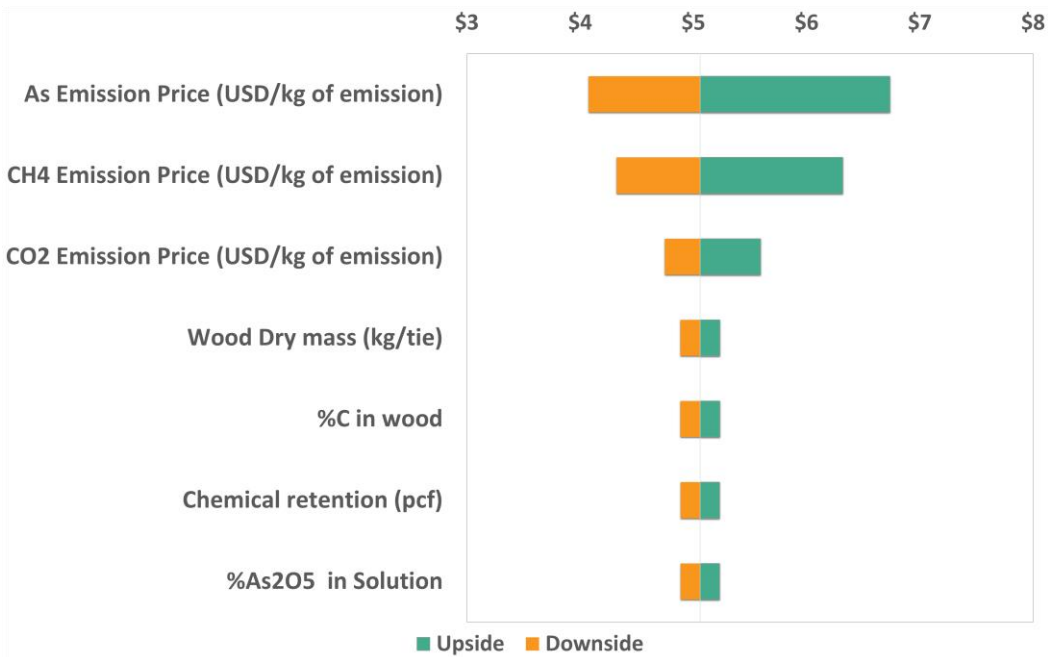
Given the large variability in emission release, environmental costs, and human health damage costs associated with methodological assumptions, this study used sensitivity analysis to identify the critical factors influencing the overall results.

For CCA treated crossties, total cost is greater when the product is burned for energy recovery than when the product is landfilled, around \$9.8 (95% CI: \$1.2, \$22.5) vs. \$5.3 (95% CI: \$4.1, \$6.8) in external costs, respectively (Figure 4.5A and 4.5B). Arsenic impacts both landfilling and energy recovery EOL scenarios. In the case of energy recovery (Figure 4.5A), the dominate contributor to this result is the mass of wood sent the boiler and the corresponding emission of biogenic CO<sub>2</sub> and arsenic. The damage costs used for arsenic and CO<sub>2</sub> emission where also key drivers for these results. When the crossties are landfilled (Fig. 4.5B), the total cost is driven by methane, CO<sub>2</sub>, and other chemical emissions. It is important to note that there are reports describing wood decay and the related emissions from landfills (Bolin & Smith, 2013b, 2013a; T. Townsend et al., 2019), there were no references found describing the decay of treated wood, and the associated air emissions from landfills.

For all other wood treatments systems (besides CCA), similar trends in the sensitivity analysis results were observed, and thus these are detailed in the supplementary information.



**a**

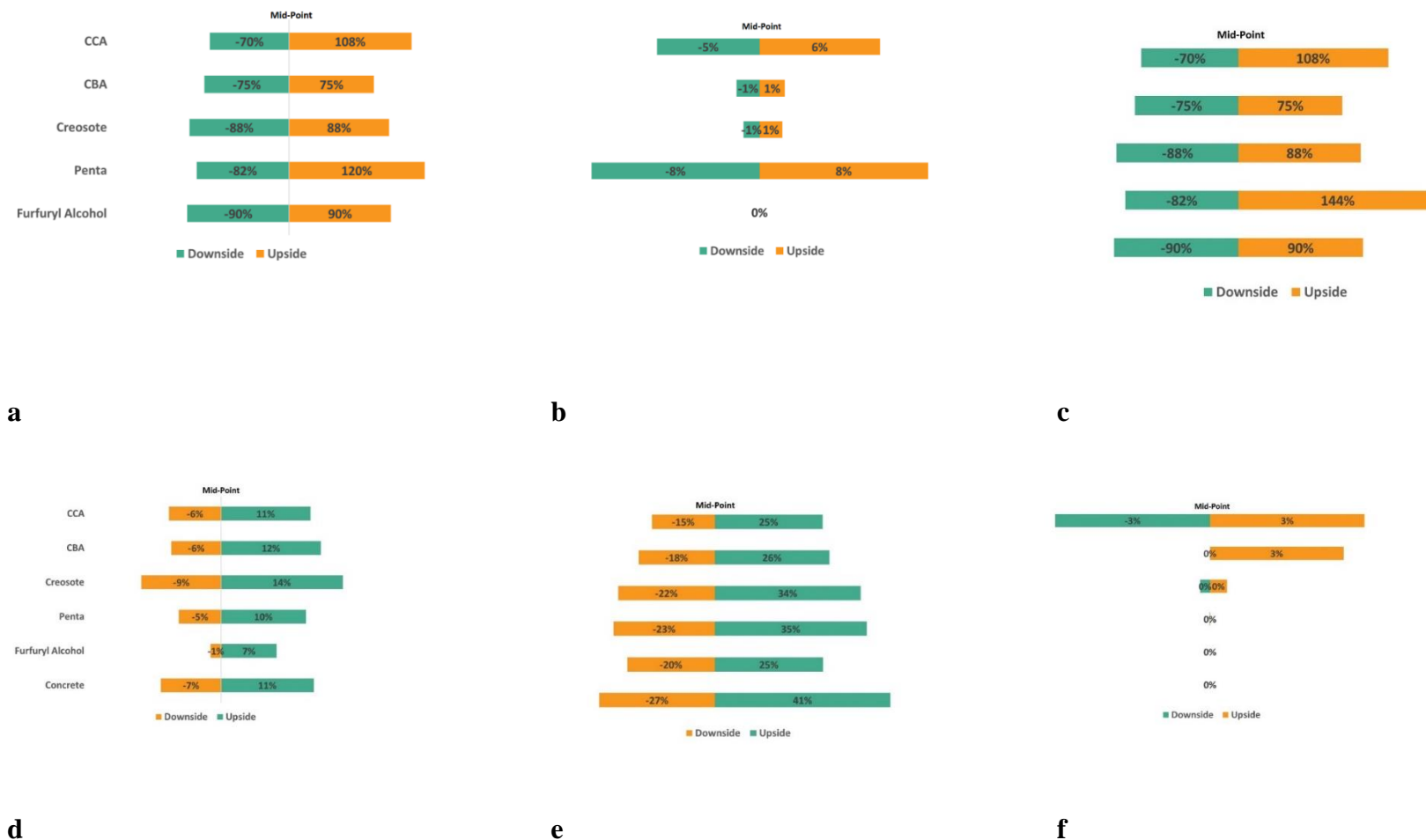


**b**

**Figure 4.5.** Sensitivity Analysis of the Total Emission Cost of specific End of life. a) Energy Recovery. b) Landfill

Figure 4.6 shows the impact of the different chemical treatments on selected emissions. The figure highlights the relative impact across different treatment processes and scenarios such as A) CO<sub>2</sub> Emission Cost (\$/kg of emission) into the energy recovery, B) Chemical retention (kg/m<sup>3</sup>) inside the crosstie sent to the energy recovery, C) % Railroad tie sent to energy recovery, D) CO<sub>2</sub> Emission Cost (\$/kg of emission) into the Landfill, E) Methane Emission Cost into the Landfill (\$/kg of Emission), F) Chemical retention (kg/m<sup>3</sup>) inside the crosstie sent to the landfill.

Variations of plus or minus 10% with respect to the midpoint were used for each attribute, illustrating how these variations impact the overall cost differentials. For most instances the effects of a 10% increase or decrease in the input data produces a symmetrical change in the corresponding costs.



**Figure 4.6.** Variations of Plus or Minus 10% with Respect to the Midpoint for Some Key Factor Considered in the Sensitivity Analysis of Each Treatment. a) CO2 Emission Cost (\$/kg of emission) into the energy recovery, b) Chemical retention (pcf) in the crosstie sent to the energy recovery, c) % Railroad tie sent to energy recovery, d) CO2 Emission Cost (\$/kg of emission) into the Landfill, e) Methane Emission Cost to the Landfill (\$/kg of Emission), f) Chemical retention (pcf) in the crosstie sent to the landfill.

## 4.5. Conclusions

This work utilizes a combination of LCA and FCA to estimate damage costs associated with the processes and materials used to manufacture railroad crossties. The system boundary included gate-to-grave manufacturing processes, and two EOL scenarios. The EOL scenarios considered were combustion with energy recovery, and landfilling. The total FCA costs are a combination of the intrinsic cost of an emission (\$/kg), and the mass of the individual emission stream.

For the energy recover EOL scenario, the inclusion of CO<sub>2</sub> emissions from combustion as ‘biogenic CO<sub>2</sub>’ is a key decision point for this analyses. The combustion of biogenic carbon is commonly treated as carbon neutral, thus it does not carry any cost. Slow growing hardwood trees are commonly used to produce wooden crossties. Many of these trees require 50-70 years, or more, to reach maturity before harvest. Thus, the assumption of biogenic carbon being carbon neutral may not hold when the analysis framework is limited to 100 year (Sterman et al., 2018). If the carbon from combustion of the wood is included as an environmental cost, this dominates the energy recovery alternative for all five wood treatment systems.

Considering the most common, commercially viable wood treatment technologies, the CCA treatment system had the highest external cost due to the cost of arsenic emissions. Leaching of arsenic during the service life has a moderate emission cost. However, in the energy recovery case, arsenic emissions to air during combustion, even after scrubbing the combustion gases, had a high cost. For the landfill EOL scenario arsenic leaching is a minor cost, while methane emission can dominate the EOL scenario if significant decay takes place in the landfill.

CBA is promoted as a less damaging (costly) inorganic wood treatment system. This work supports that claim. The costs from emissions during the service life and EOL are both lower than for the

CCA. Again, the costs of methane emissions from the landfill EOL scenario were also significant, depending on the extent of wood decay.

For a system using organic treatments such as creosote and chlorophenols as the 'active' ingredient to prevent decay, and including organic 'carriers' that assist with processing, the environmental costs were dominated by methane emissions from the landfill EOL scenario. The emissions of the organic actives and carrier during the service life were surprisingly low.

For a reactive treatment system using a crosslinkable resin, such as the Keboney system, which limits leaching during use and at EOL, the overall environmental costs were very low. With the polymerization step, leaching of the furan resin during service life, and at the end of life are very small.

Finally, the environmental cost for using a concrete railroad crosstie, with its projected 70-year lifetime, is very low. Essentially all life cycle emissions are generated during the production of the concrete crosstie, in particular, emissions from the production of cement and steel rebar. However, there are no emissions over the 70 year use, and even a slight 'recovery' due to reabsorption of atmospheric CO<sub>2</sub> by the concrete.

Sensitivity analysis shows that the assumed cost for arsenic, CO<sub>2</sub> and methane have the highest leverage on the overall cost for the alternative treatments. The mass of the chemicals used in the different treatments, or the mass of the emissions, have a much smaller impact.

Based on this initial work, which shows the high cost of emission of arsenic to air in the energy recovery scenario, experimental data for different combustion/scrubber systems would be very valuable. Also, better data on the decay and emissions from treated wood in landfills would be

useful. Finally, the temporal aspects the emission and recapture of biogenic carbon for trees with differing growth rates would be useful.

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## SUPPLEMENTARY INFORMATION

### Concrete Production

The manufacture of concrete is relatively simple. First, the cement, commonly a "Portland cement" product is manufactured by heating a mixture of finely ground limestone, clay, and sand in a rotating kiln at around 1400°C. This outcome is an intermediate product in the manufacture of cement known as clinker. Then, this material is cooled and ground to a fine powder where gypsum is added during this process. The concrete is then mixed with the other ingredients such as sand, other aggregates materials, and water to obtain the final product.

### Degree of Carbonation

The degree of carbonation depends on different parameters such as type of concrete, such as the type of cement, water to cement ratio, CO<sub>2</sub> concentration in the surrounding area, temperature, and relative humidity.

$$CO_2(kg/m^3) = k * \sqrt{t} * c * CaO * r * A * M \quad \text{Equation 22}$$

*k:carbonation rate coefficient, t:time, c:amount of cement used to produce 1 m<sup>3</sup> of concrete, CaO:amount of CaO in Portland Cement, r:amount of CaO that is totally carbonated, A:surface area of concrete exposed to CO<sub>2</sub>, M:Molar Fraction of CO<sub>2</sub>/CaO.*

$$t(year) = \left(\frac{d}{k}\right)^2 + \frac{80 * d}{\phi * \vartheta_0} \quad \text{Equation 23}$$

*t:time, k:carbonation rate coefficient,  $\phi$ :bar diameter and  $\vartheta_0$ : carbonation speed.*

The degree of carbonation is highly dependent on different parameters such as type of concrete, type of cement, water to cement ratio, CO<sub>2</sub> concentration in the surrounding area, temperature, and relative humidity.

$$d(mm) = A_c \sqrt{t} \quad \text{Equation 24}$$

*d: carbonation depth (mm), A<sub>c</sub>: carbonation velocity coefficient.*

$$A_c = \alpha_1 * \alpha_2 * \alpha_3 * \beta_1 * \beta_2 * \beta_3 \quad \text{Equation 25}$$

*α<sub>1</sub>: coefficient type of concrete, α<sub>2</sub>: coefficient type of cement, α<sub>3</sub>: W/ tio, β<sub>1</sub>: Temperature, β<sub>2</sub>: Relative Humidity, β<sub>3</sub>: CO<sub>2</sub> Concentration.*

$$\beta_1 = \frac{T + 23.7}{47.3}$$

*T: Temperature (C)* Equation 26

$$\beta_2 = \frac{H_u * (100 - H_u) * (140 - H_u)}{19200}$$

*H<sub>u</sub>: Relative humidity (%)* Equation 27

*CO<sub>2</sub>: Carbon Dioxide Concentration* Equation 28

$$\beta_3 = (CO_2)^{0.5}$$

**Table 4.4.** Total Emission Cost (USD/kg of emission at 2015)<sup>3</sup> (Bruyn et al., 2018)

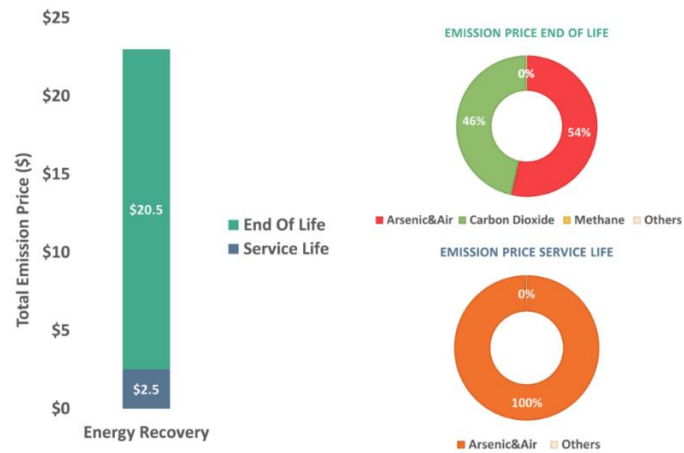
Emission Price		Air			Soil		
Treated wood	Chemicals	Lower	Central	Upper	Lower	Central	Upper
		Value	Value	Value	Value	Value	Value
CCA	Arsenic	6.90E+02	1.01E+03	1.12E+03	1.17E+01	4.45E+01	1.11E+02
	Chromium	9.13E-02	5.85E-01	6.67E-01	3.16E-05	4.91E-04	1.17E-03
	Copper	6.90E-01	4.56E+00	5.50E+00	6.90E-03	1.76E-01	4.56E-01
Creosote	Naphthalene	1.03E-01	1.87E-01	2.69E-01	3.63E-03	5.27E-03	7.96E-03
	Acenaphthene	7.61E-02	1.04E-01	1.64E-01	2.34E-03	3.39E-03	5.27E-03
	Fluorene	2.11E-01	2.93E-01	4.56E-01	1.40E-02	2.34E-02	3.39E-02
	Anthracene	3.04E-02	4.21E-02	6.55E-02	9.48E-05	7.14E-04	8.07E-04

**Table 4.4** (continued).

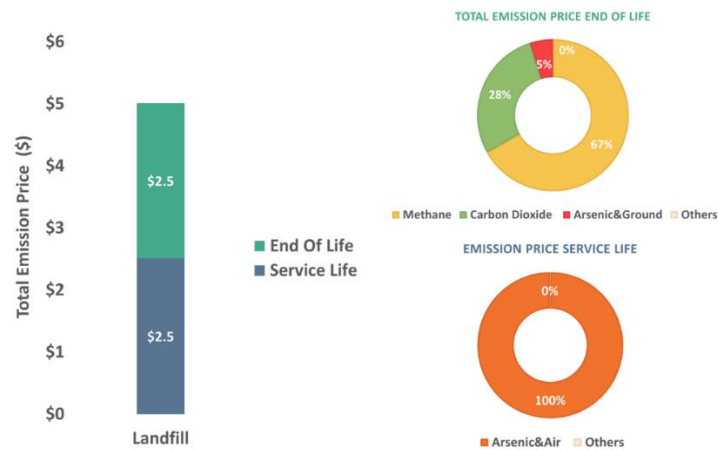
<b>Penta</b>	<b>Phenanthrene</b>	<b>1.29E-04</b>	<b>9.59E-04</b>	<b>1.09E-03</b>	<b>0.00E+00</b>	<b>0.00E+00</b>	<b>0.00E+00</b>
	<b>Fluoranthene</b>	1.64E-01	2.34E-01	3.51E-01	5.62E-05	3.74E-04	4.21E-04
	<b>Pyrene</b>	1.11E-01	1.52E-01	2.34E-01	7.37E-05	5.50E-04	6.20E-04
	<b>Pentachlorophenol</b>	2.11E-01	4.10E-01	5.73E-01	2.34E-02	3.28E-02	5.03E-02
	<b>Acenaphthene</b>	7.61E-02	1.04E-01	1.64E-01	2.34E-03	3.39E-03	5.27E-03
	<b>Fluorene</b>	2.11E-01	2.93E-01	4.56E-01	1.40E-02	2.34E-02	3.39E-02
	<b>Phenanthrene</b>	1.29E-04	9.59E-04	1.09E-03	4.45E-03	6.67E-03	1.01E-02
	<b>Ethylbenzene</b>	3.16E-03	1.17E-02	1.40E-02	9.48E-05	7.14E-04	8.07E-04
	<b>Tetrachlorophenol</b>	2.34E-03	1.76E-02	1.99E-02	1.29E-02	3.04E-02	4.10E-02
	<b>Trichlorophenol</b>	1.40E-04	1.08E-03	1.17E-03	1.11E-01	1.52E-01	2.34E-01
<b>CBA</b>	<b>Copper</b>	6.90E-01	4.56E+00	5.50E+00	6.90E-03	1.76E-01	4.56E-01

**Table 4.4** (continued).

<b>Furfuryl</b>	<b>Furan Resin</b>	<b>4.45E-08</b>	<b>3.39E-07</b>	<b>3.74E-07</b>	<b>1.64E-08</b>	<b>1.17E-07</b>	<b>1.29E-07</b>
<b>Alcohol</b>							
<b>Others</b>	<b>Carbon Dioxide</b>	2.57E-02	6.67E-02	1.10E-01	0.00E+00	0.00E+00	0.00E+00
	<b>Methane</b>	7.84E-01	1.99E+00	3.39E+00	0.00E+00	0.00E+00	0.00E+00

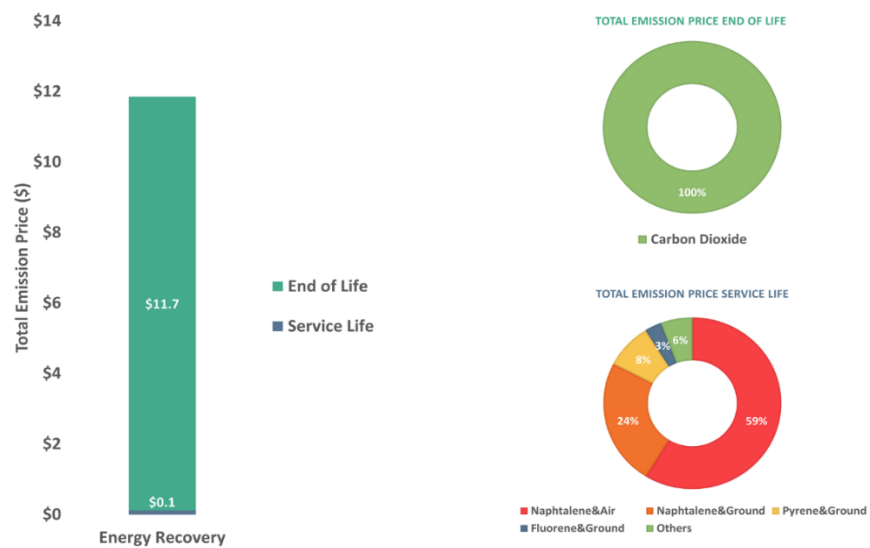


**a**

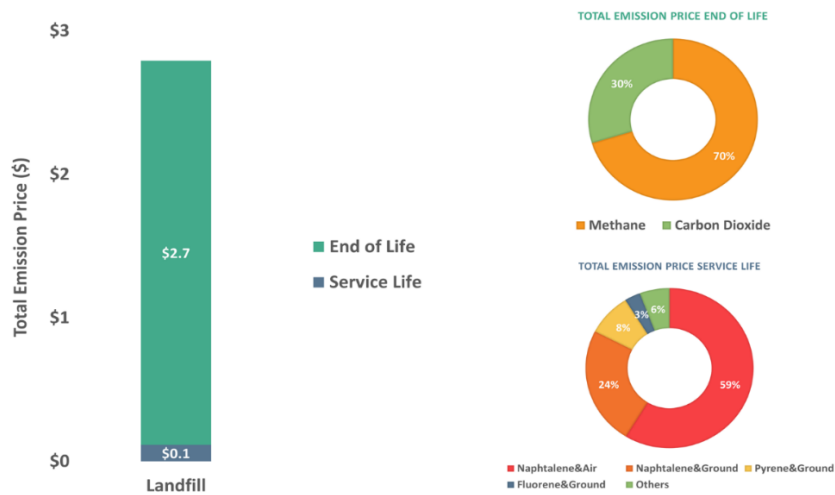


**b**

**Figure 4.7.** Breakdown of the Total Emission Price of CCA at specific end of life. a) Energy Recovery. b) Landfill



a

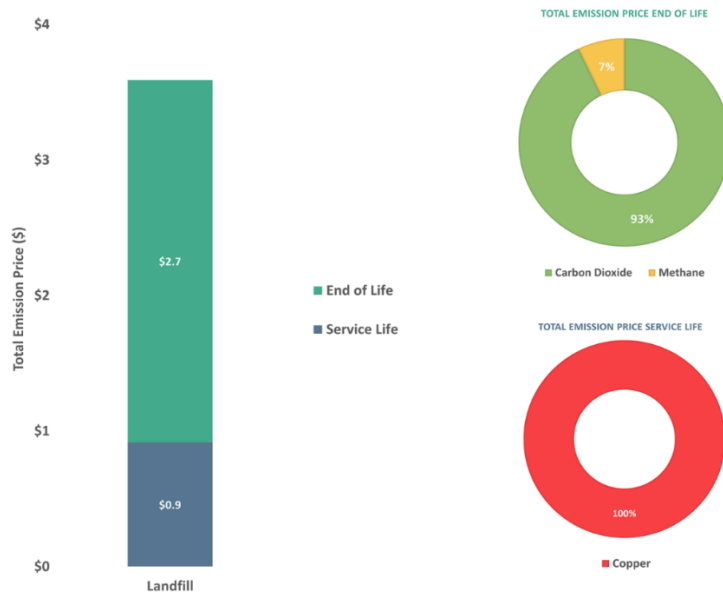


b

**Figure 4.8.** Breakdown of the Total Emission Price of Creosote at specific end of life. a) Energy Recovery. b) Landfill

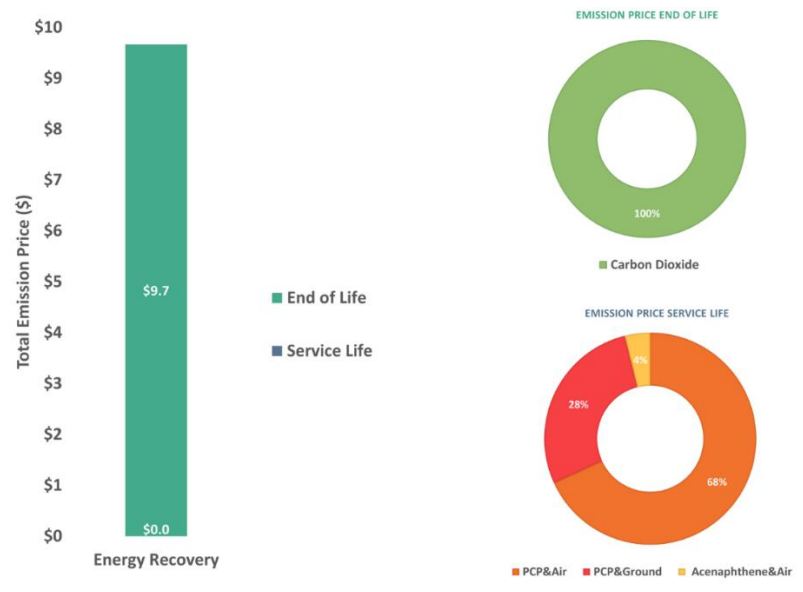


**a**

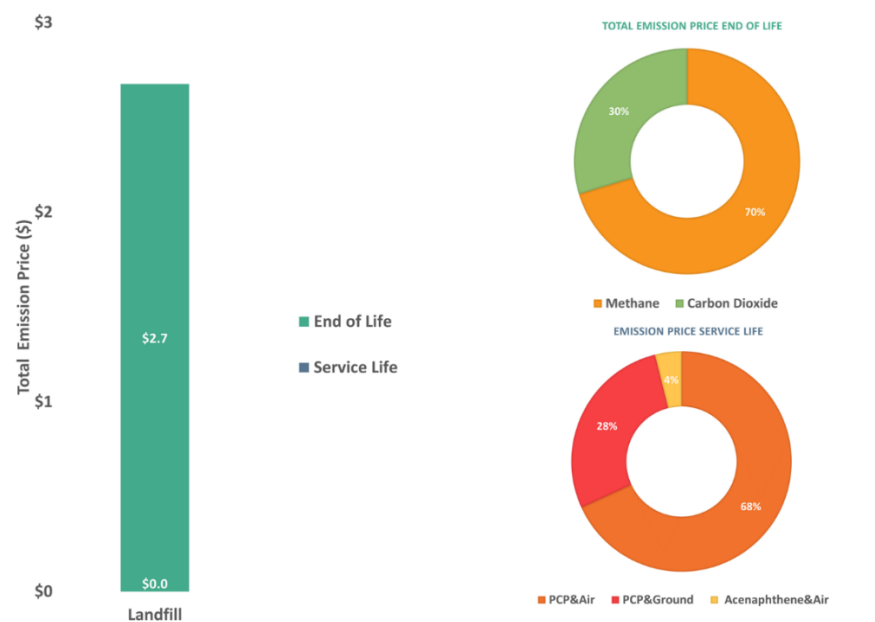


**b**

**Figure 4.9.** Breakdown of the Total Emission Price of CBA at specific end of life. a) Energy Recovery. b) Landfill

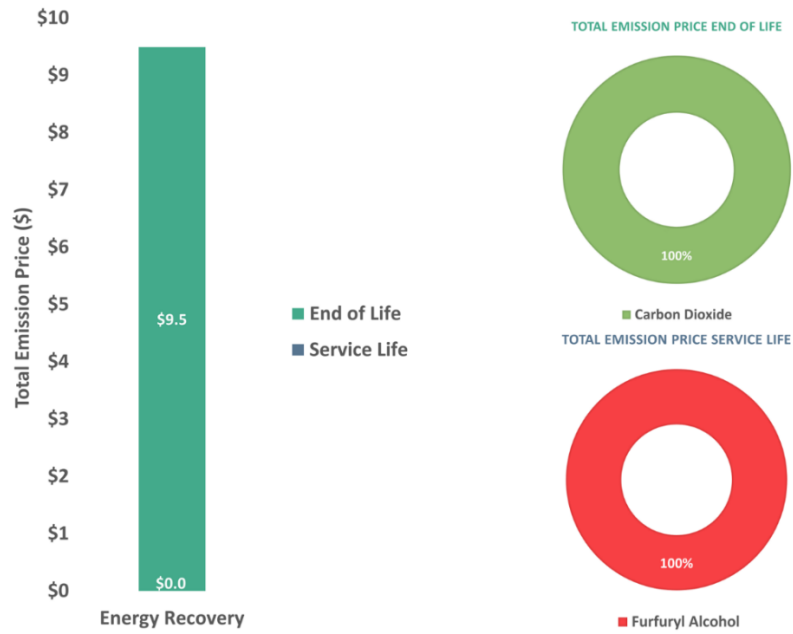


**a**

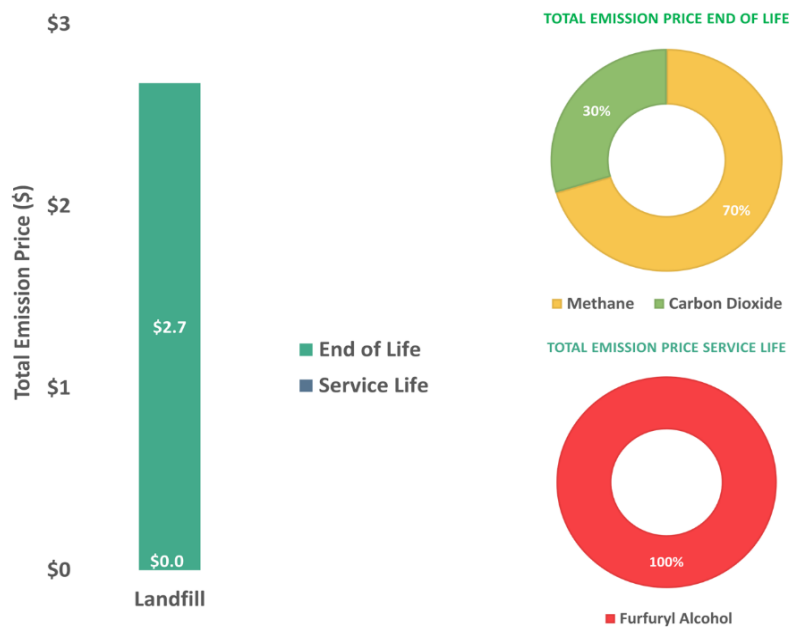


**b**

**Figure 4.10.** Breakdown of the Total Emission Price of Pentachlorophenol at specific end of life. a) Energy Recovery. b) Landfill

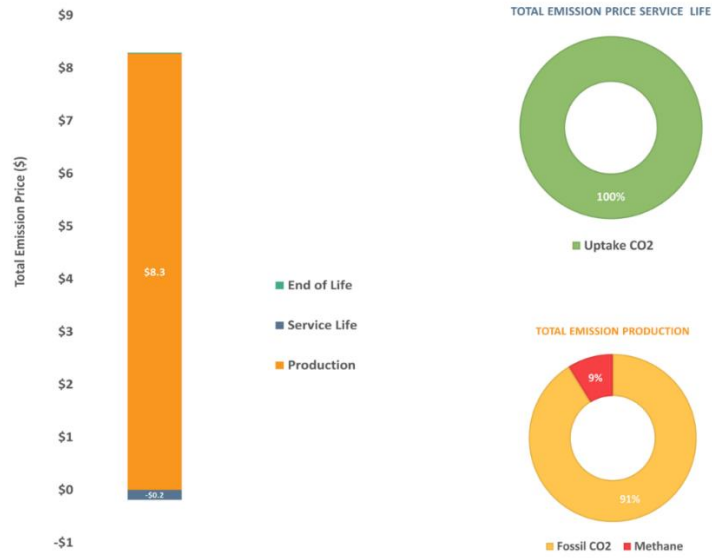


**a**

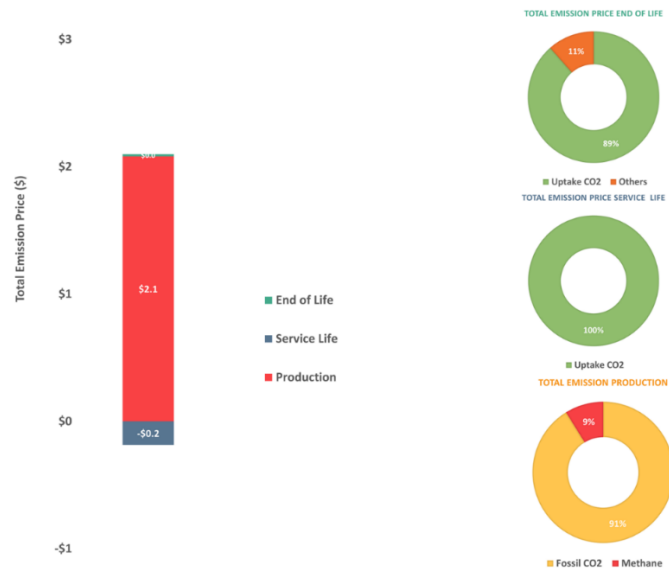


**b**

**Figure 4.11.** Breakdown of the Total Emission Price of Furfuryl Alcohol at specific end of life. a) Energy Recovery. b) Landfill

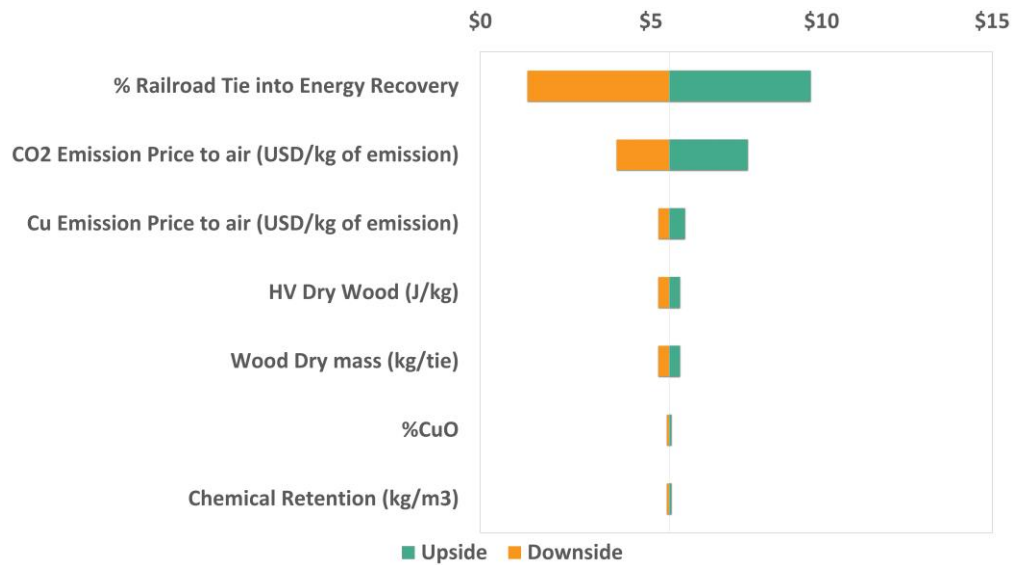


a

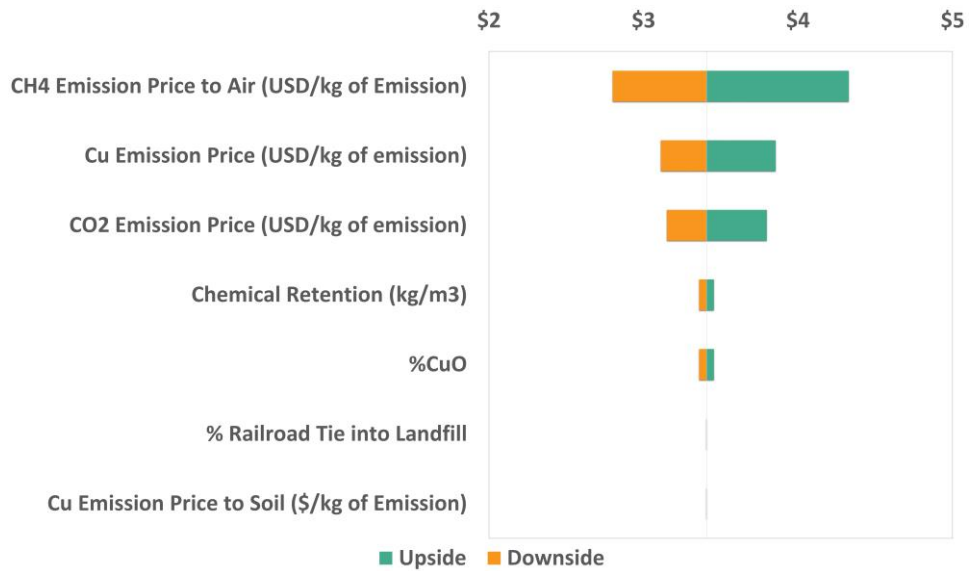


b

**Figure 4.12.** Breakdown of the Total Emission Price of Concrete at specific end of life. a) Energy Recovery. b) Landfill

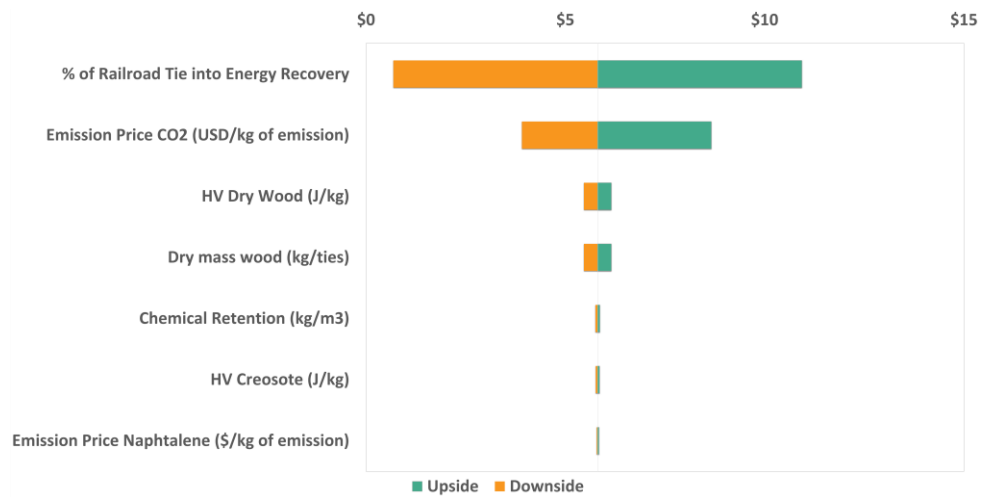


**a**

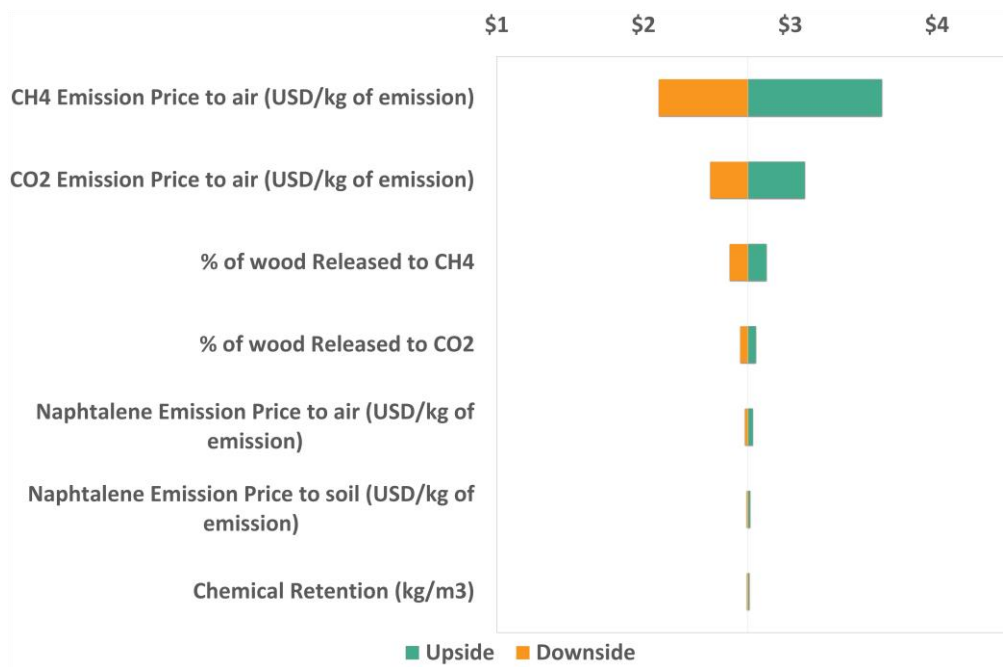


**b**

**Figure 4.13.** Sensitivity Analysis of the Total Emission Price of CBA at specific end of life. a) Energy Recovery. b) Landfill

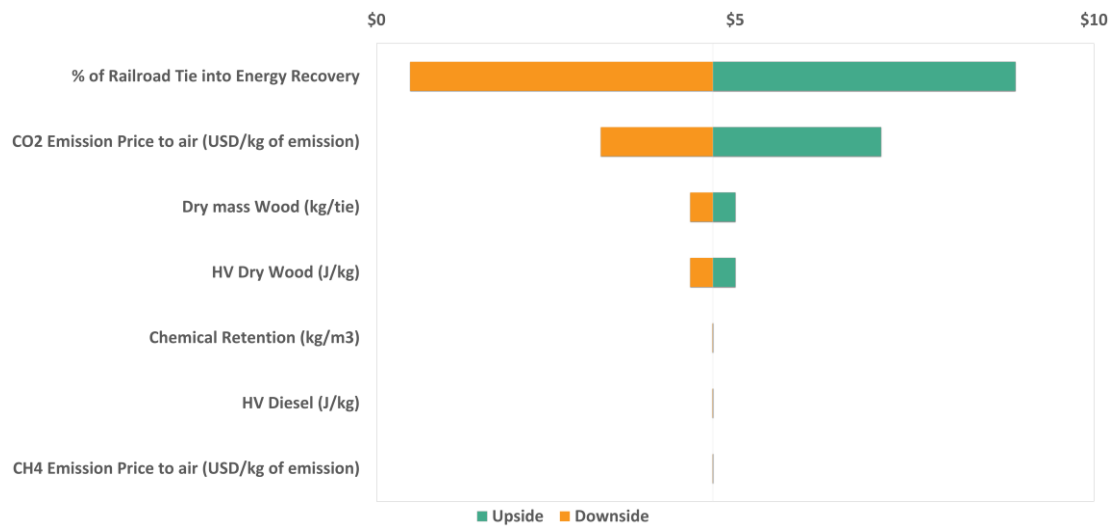


a

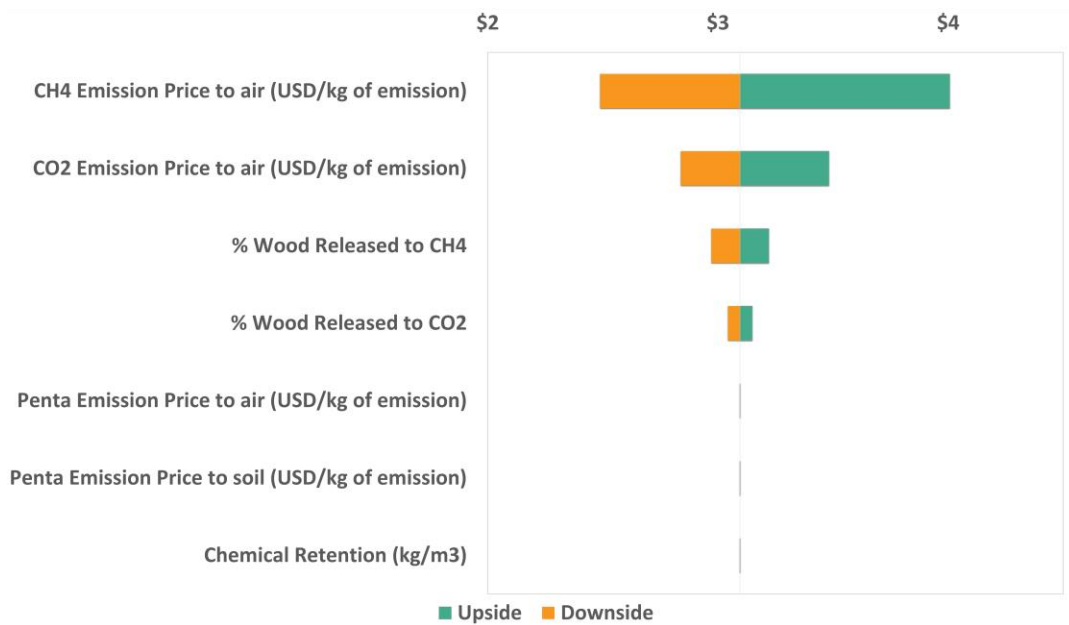


b

**Figure 4.14.** Sensitivity Analysis of the Total Emission Price of Creosote at specific end of life. a) Energy Recovery. b) Landfill

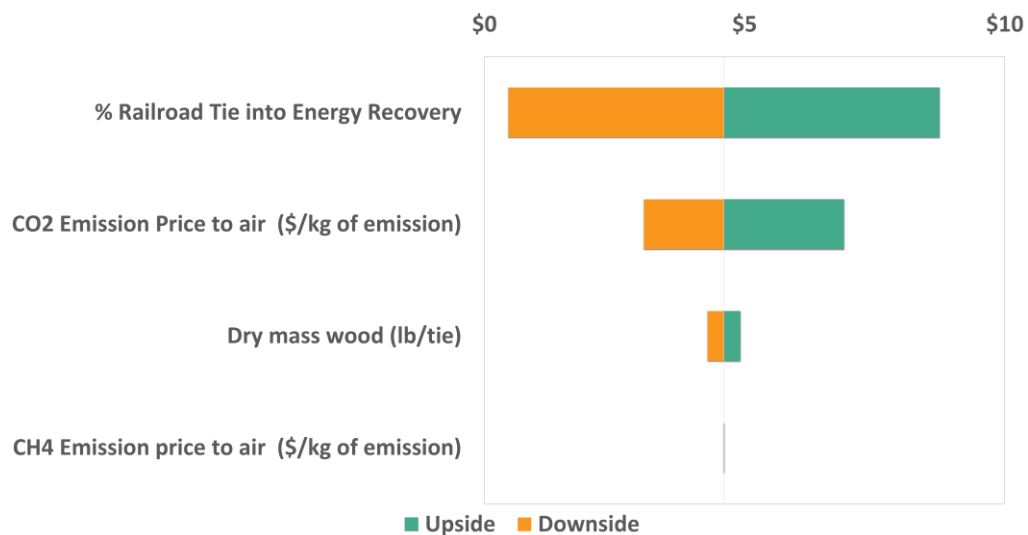


a

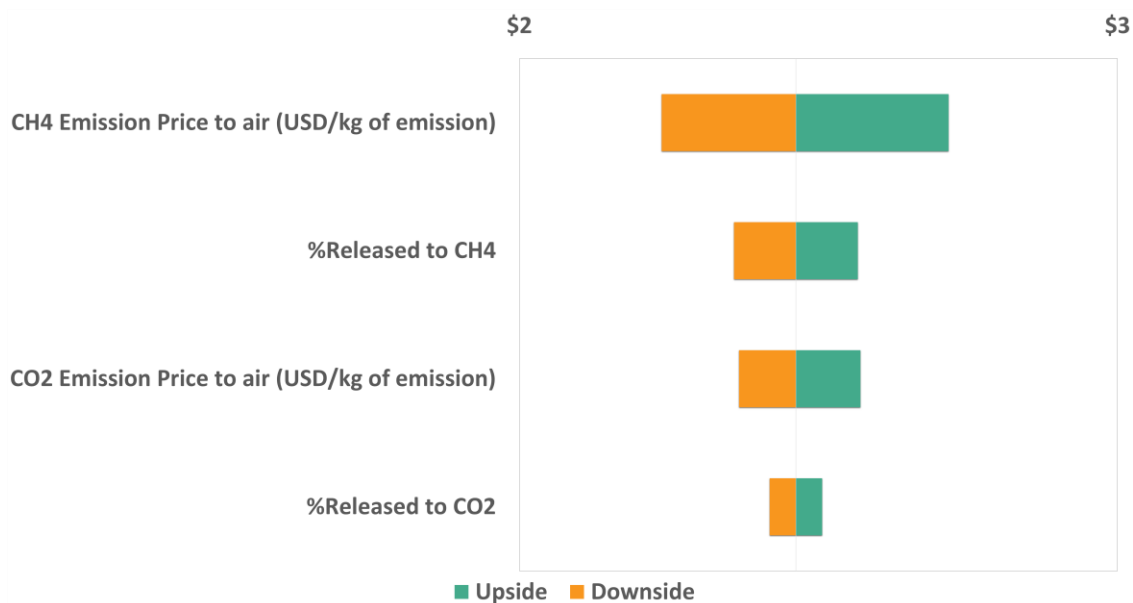


b

**Figure 4.15.** Sensitivity Analysis of the Total Emission Price of Pentachlorophenol at specific end of life. a) Energy Recovery. b) Landfill

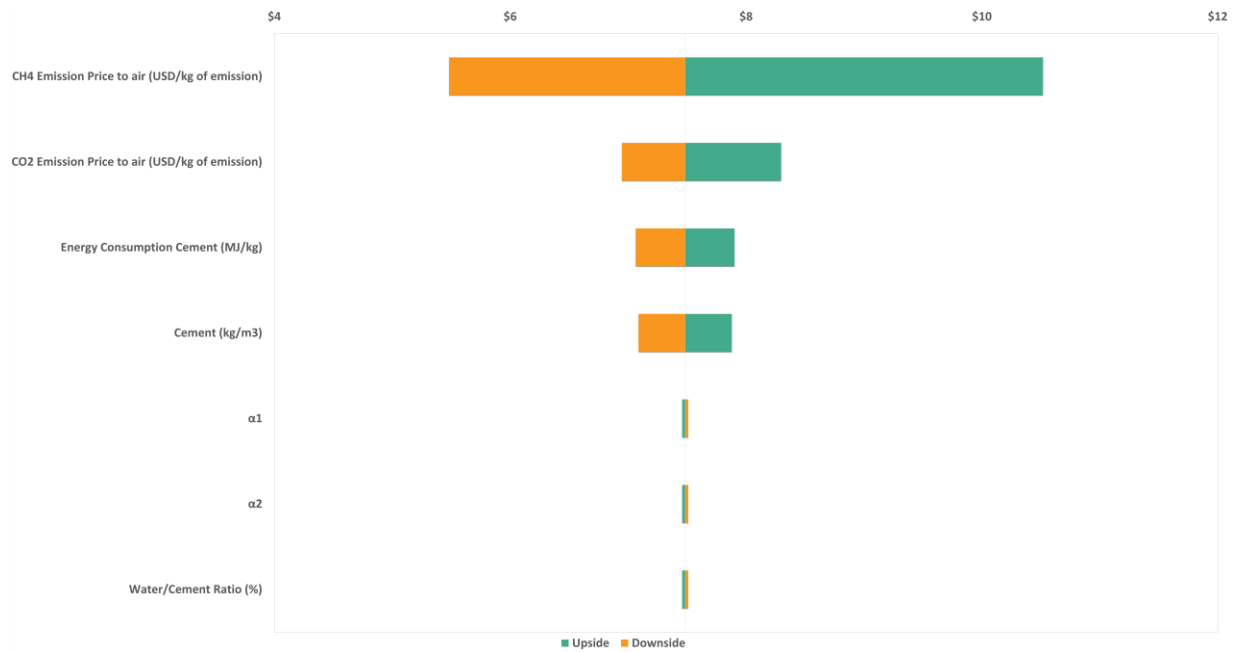


a



b

**Figure 4.16.** Sensitivity Analysis of the Total Emission Price of Furfuryl Alcohol at specific end of life. a) Energy Recovery. b) Landfill



**Figure 4.17.** Sensitivity Analysis of the Total Emission Price of Concrete at specific end of life in Landfill

## **CHAPTER V**

### **5. RELATIONSHIP BETWEEN ENVIRONMENTAL, SOCIAL AND GOVERNANCE (ESG) RATINGS AND THE FINANCIAL PERFORMANCE OF PULP AND PAPER, AND WOOD PRODUCT COMPANIES**

#### **5.1. Abstract**

Sustainability assessment has become an important measure for many companies, although assessing sustainability remains a very complex evaluation process. This is particularly true for pulp and paper, and wood products companies, and companies that own industrial forest lands. Sustainability metrics are typically traditionally categorized into environmental, economic and social attributes. More recently, investors have focused on Environmental, Social, and Governance (ESG) attributes, which can be added to financial performance and influence investor decisions. However, the interaction between corporate ESG measures and financial performance is poorly understood. The forest-based industry is particularly sensitive to real and perceived environmental damage, and associated social pressures, and reputational risks. This study evaluates the causal relationship between several measures of a company's financial performance, and their total ESG scores, and the score for each of the individual ESG attributes. A simple correlation coefficient, and a more demanding Granger causality test were used to evaluate the cause and effect linkage between these performance measures. Ten years of Bloomberg data for the ESG attributes of a series of forest products companies was used to provide a consistent data set. This analysis reveals positive causality relationship between the total ESG score and market capitalization, net sales, and return on equity. The environmental score alone showed the same trends.

## 5.2. Introduction

The neoclassical market economy, which exploits nature, cultures, and individuals, is known to chiefly maximize short-term economic growth, with little regard for nonmonetary costs. As society and governments have begun to recognize some of the ‘hidden’ environmental and social costs of this economic approach there are growing demands that companies more clearly document their environmental, social and governance costs, and the risks associated with these hidden costs, and begin to minimize these costs. In particular as the world has become more globalized, new generations of investors and fund managers are more aware of environment and social liabilities can create real and reputational risks for companies (Bloomberg, 2022d; Ketola, 2009). Thus, consideration of materials and energy consumption, toxic and nontoxic industrial emissions, biodiversity, employee satisfaction, community relations, gender diversity, etc., is attracting interest from companies and investors. (Forte, 2013).

The expectation that companies report their ESG attributes, and the growing rigor of these reports are growing around the world (Campbell, 2021). There are two common frameworks to tracking these new responsibilities: corporate social responsibility (CSR) and the triple bottom line (TBL).

A precise definition of CSR has been debated for many years (Barauskaite & Streimikiene, 2021). Nevertheless, most observers agree that this concept requires measures of how companies define and document their sustainability activities to benefit society and communities, by improving the environment and the quality of life and satisfaction of employees and communities that they operate in (Barauskaite & Streimikiene, 2021; Hinze & Sump, 2019; Linnea & Bråtenius, 2015; Mughal et al., 2021). As a specific theory of how corporations interact with the surrounding community and the larger world, there are four implied obligations: economic, legal, ethical,

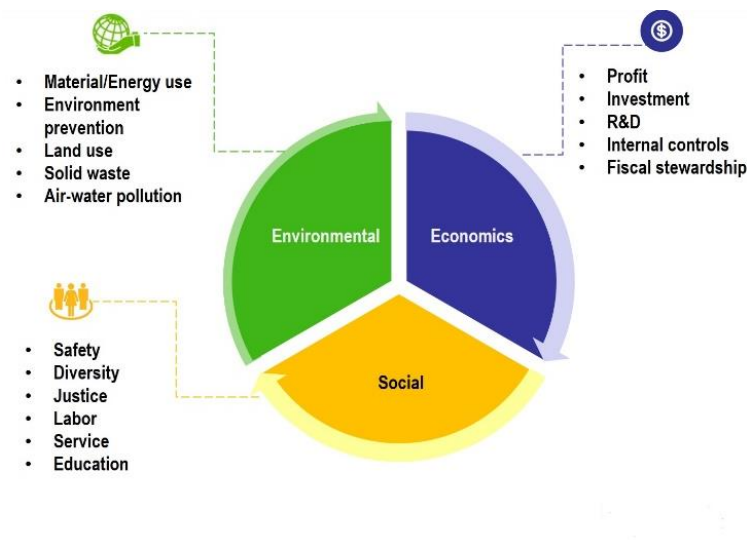
philanthropic responsibility (Brusseau, 2018; Grewatsch & Kleindienst, 2017; Mohammed, 2020; Palmer, 2012).

The economic responsibilities is essential and generally recognized as the basis upon “which all others rest” (Mohammed, 2020). Corporations need to have competitive economic performance to achieve the others responsibilities. In this circumstance, businesses can demonstrate economic social responsibility by being transparent with entirely stakeholders concerning the financial position of the company. Legal responsibility oblige an organization to carry out the laws of the specific locations where they operate, and more generally exhibit universally acceptable behavior (Brusseau, 2018). This view of organized ethics includes elementary notions of rational operations as recognized by the governments. Ethical responsibility is a wider expectation to do what is correct and fair, minimizing risk to stakeholders (Safar zad et al., 2019). Philanthropic responsibility suggest that firms are projected to be corporate citizen by contributing economically and human resources by enhancing the quality of life for the communities in which they operate (Brusseau, 2018; Safar zad et al., 2019).

These actions are voluntary, dictated by a company’s desire create a positive image, and to be to involve in social activities that are not required by law and do not have an immediate tangible reward. By combining all of these goals, companies attempt to balance profitability, follow the rules and regulations, e.g., do what is right, and contribute to the growth of a healthy society (Brusseau, 2018; Mohammed, 2020; Safar zad et al., 2019).

The balancing of economic, ecological and social goals are the fundamentals of a triple bottom line as illustrated in Figure 5.18 (Bautista et al., 2016; Pan et al., 2021). This business operation means the long-term maintenance of the balance of these different attributes. Environmental considerations might include the use of resources, both regulated and non-regulated emissions,

and the treatment of wastes. Social aspects include the treatment of employees, local communities and more recently customers and suppliers. Economic attributes include the long-term financial return over more volatile, short-term profits (Brusseau, 2018). Singh et al. combined all these three notions of sustainability by declaring: “businesses are guided toward actions fitted to the corporation's inclusion in considering not only economic performance, if not they include environmental and social aspects” (Singh et al., 2012).



**Figure 5.18.** Illustration of the Triple Bottom Line (Bautista et al., 2016; Pan et al., 2021)

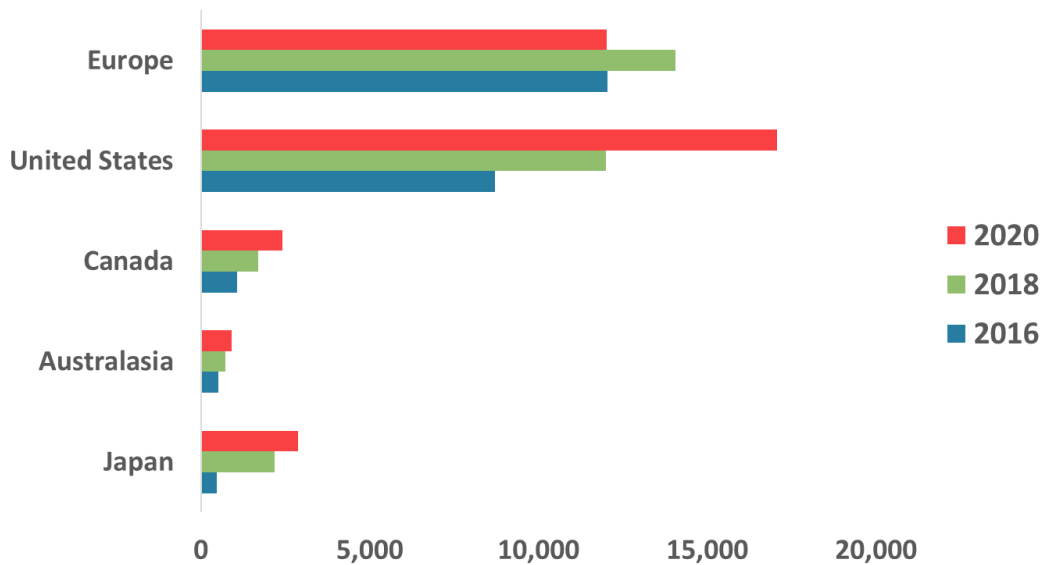
An evolution of both the general goals and the specific attributes of both CSR and TBL concepts have been the consequence of diverse events. The foundation of socially responsible investing (SRI) started to attract significant attention and investments in the 1970s. This interest was generally influenced by the antiwar movement, racial equality, women's rights, consumer protection, and the environment (B. Townsend, 2020). Part of this interest was inspired by consumer boycotts of the South Africa apartheid of racial segregation. By the 1990s, global sustainability legislation was passed by the United Nations in an attempt to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent climate change (United Nations,

1992). Also, in 1994, SRI was used as a tool to bring important transformation in society during South Africa Apartheid (Naqvi, 2019). With more than 75% of all business enforced to negotiate the dismantling of the movement (Scorgie, 2017).

In 2000, the United Nations Global Compact was launched as an international framework for companies to measure and improve responsible business practices, including compliance with environmental standards, employee and community standards, and good governance and anti-corruption (Benoît et al., 2013; Deloitte, 2014). In 2006, the United Nations' Principle for Responsible Investment (UNPRI) reporting framework was approved to provide further details on ESG metrics that could be used by companies, and investors (Benoît et al., 2013). Since then the number of international ESG standards and policy frameworks have increased significantly. The policies and standards vary depending on national governments, but in combination the effect is to move ESG measures for corporate performance to a top priority for many individual investors and fund managers. (Armstrong, 2019). The United Nations General Assembly established the 17 Sustainable Development Goals (SDGs) in 2015. This created an additional set of metrics that companies can use as a baseline for their CSR discloses (ONU, 2020). In 2021 the Sustainable Finance Disclosure Regulation (SFDR) covering market members in the European Union was launched. This legislation is intended to promote strong ESG values and mandate fund managers to disclose their ESG performance (Deloitte, 2021). Most recently, the US Securities and Exchange Commission (SEC) has proposed rules for companies to disclose the impacts of climate change on their business practices (Raghunandan, 2022; Rajgopal, 2022).

The continuous growth of CSR investments over time has been reported in various studies. Companies and investors in different regions with varying ESG claims and metrics attracted tens of trillions of dollars in investments. (Amir & Serafeim, 2018; Barman, 2018b; Deloitte, 2016;

Espahbodi et al., 2019; Kocmanová & Šimberová, 2014; Makepeace et al., 2018). According to Global Sustainability Investment Alliance (2020), global investment using some element of an ESG screen has reached \$35.3 trillion in 2020 (Global Sustainable Investment Alliance, 2021), and it is projected to be \$50 trillion by 2025 (Bloomberg, 2022d). This represents an increase of 15% from the past two years (2018-2020) and 55% in the past four years (2016-2020). These trends are illustrated in Figure 5.19. The largest absolute investments were in the United States, followed by Europe, with \$17 and \$12 billion, respectively. The greatest percentage increase over the past two years (2018-2020) was in Canada, with an increase of 48% sustainably managed assets, followed by the United States with growth of 42% and Japan at 34%. Following these rapid increases the growth rate has moderated or the totals even declined. This is due in large part due to more rigorous definitions and national reporting policies. For example the EU passed the European Sustainable Finance Action Plan, which required to re-adjust investments concerning more and new sustainable technologies and businesses, finance progress in a sustainable style over the long-term and contribute to the establishment of a low-carbon, climate tough and circular economy (European Commission, 2021).



**Figure 5.19.** Global sustainability investing assets (Global Sustainable Investment Alliance, 2021).

### ESG Tools and Agencies

Environmental, Social, and Governance (ESG) is a general concept, but these concepts can be used to construct quantitative, auditable measures of a company's activities. As noted above the specific metrics used to measure these ESG attributes have been changing rapidly over the past 10 years. In some ways these changing metrics and standards have made tracking and comparisons difficult, but they have also created a general positive pressure for companies around the world to increase their awareness and compliance with these general expectations.

All the ESG frameworks have some common environmental metrics that include attributes such as energy consumption, carbon emissions, water usage, waste production, and general environmental compliance. Common social metrics includes treatment of employees and communities, and aspect of diversity, equity and inclusion. Common governance attributes are more general measures such as diversity of the board and general business ethics. In combination

ESG ratings assess a company nonfinancial performance, and it's risks and impacts the broader society. As they have become more structured ESG ratings can also be used to compare companies to their peers.

As investors increasingly rely on ESG principles to inform their investment decisions, the number of organizations have developed rating systems, which in turn require both quantitative and qualitative measures. This growing suite of tools can be categorized into five segments: general rating agencies, data aggregators, leading frameworks<sup>3</sup>, stock exchange initiatives, and credit rating agencies, as shown in **Table 5.1**. Some ESG rating frameworks can be included in multiple categories where there is overlap in terms of the ESG data, scoring metrics, and adoption of new methodologies (Armstrong, 2019).

**Table 5.1.** ESG Organizations (Armstrong, 2019).

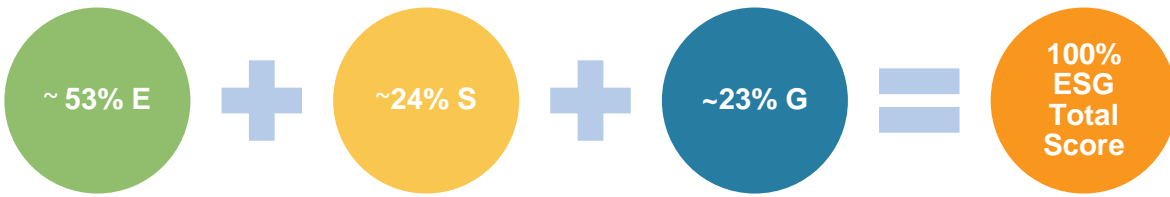
Organizations	ESG Rating Agencies	Data Aggregators	Leading Frameworks	Stock Exchange Initiative	Credit Rating Agencies
MSCI					
Bloomberg					
Climate Disclosures Standard Boards					
Dow Jones Sustainability Indices					
NASDAQ					
S&P Global					

<sup>3</sup> **Leading framework:** nonprofit groups that create guidance to support businesses in ESG material (Armstrong, 2019).

**Table 5.1** (continued).

Global Initiative	Reporting			
GRESB				
U.N Responsible Investment	Principal			
Institutional Shareholders Services				
Sustainable Exchange Initiative	Stock			
Sustainalytics				

The Bloomberg database is a global collection of financial data, with more than 325,000 terminals that serve more than a third of the economic data market (Bloomberg, 2022e). In 2009, Bloomberg acquired New Energy Finance, which offers renewable energy and carbon market data (Mazzucato & Semieniuk, 2018). Based on this foundation they launched Bloomberg ESG Data Service (Reuters, 2009). In 2018, the Bloomberg started to provide ESG data by establishing a licensed data feed of financial information that is delivered annually. Bloomberg gathers, confirms, and shares data for more than 11,500 companies in more than 100 countries (Bloomberg, 2021). Bloomberg ESG Disclosure Scores rate companies based on their self-disclosure of quantitative and managerial ESG data. Scores for each specific metric are verified and then used to estimate a total ESG score using a normalized 100-point scale. These ESG ‘scores’ are compiled based on a company’s ESG information reveal through CSR reports, or direct company contact on annual reports, and then audited and reported by Bloomberg (Park & Ravanel, 2013).



**Figure 5.20.** Contributions of each ESG Bloomberg category (Bloomberg, 2016)

Using the Bloomberg format the total ESG score has three attributes with environmental metrics given 54% of the total weight, social metrics earning 24% of the weight, and governance receiving 23% of the total ESG score (Bloomberg, 2016).

The environmental score has been adjusted to increase the importance attributed to greenhouse gas emissions since this is of interest to many investors (Lueg & Pesheva, 2021; Pyles, 2020). Moreover, information such as water consumption, and toxic and nontoxic wastes emissions are also included. The social score includes information on human rights, employee turnover, fair remuneration policies, and health and safety at the workplace. Finally, the shareholder-oriented governance score is based primarily on board activities and structure, sustainability practices, audit practices, meetings, and shareholders' rights (Lueg & Pesheva, 2021). Specific considerations for Bloomberg is presented in the supplementary material.

### **ESG and Financial Performance**

Metrics for establishing the company's financial performance are common to both investors and academics. Depending on the goals of the evaluation, this metrics could include: income or profits, return on the company assets. Few of these metrics are viewed in isolation, and are most commonly viewed relative to the performance of similar companies. Thus, the value of a company is

determined by its absolute financial performance, tangible assets, and also nonfinancial factors, such as reputation and image.

There are ongoing discussions about how to include ESG concepts into standard financial analysis. Opinions on ESG scores and their importance vary widely. For example, Warren Buffet, known as one of the most prominent investors on Wall Street, noted in 2021 at the Berkshire Hathaway in the annual shareholder meeting that he was still skeptical about the incorporation of ESG metrics into his investment decisions (Buffet, 2021). At the opposite end of the spectrum, Larry Fink, chairman, and CEO of Blackrock corporations, 2021, highlighted significant investment opportunities, and avoidance of risks, created including the impacts of climate change and extreme weather events (BlackRock, 2021). He indicated that sustainability has become a critical influence in determining companies long-term value (BlackRock, 2021). Also, Cathie Wood, CEO of Ark Invest, launched ESG exchange-traded fund (ETF) in 2021, and during the first nine months of that year, more than \$577 billion have flowed into ESG fund (Evie Liu, 2022).

Academics still argue about the relationship between ESG and financial performance. Some of the these studies and meta analyses, and their conclusions are summarized in **Table 5.2** (Barauskaite & Streimikiene, 2021; Bennani et al., 2019; B. Townsend, 2020). The differing conclusions obtained by different authors can be rationalized with one of five main theories for the correlations between financial and ESG performance.

- ✓ **Stakeholder theory** infers that conceived the needs of several corporate stakeholders will lead to satisfactory financial performance. Therefore, positive correlation is assumed to enhance the company's reputation within the community, which attracts the interest of investors and other stakeholder and, in turn, can increase the organization's profits (Freeman & McVea, 2005).

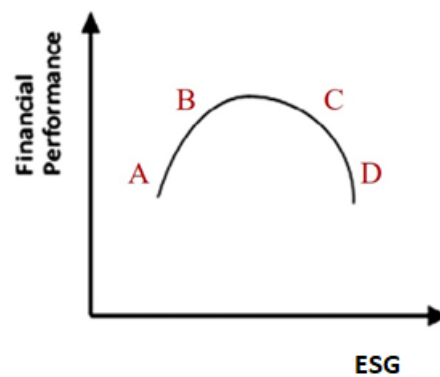
- ✓ **The trade-off hypothesis** assumes a negative impact of ESG on economic performance. This theory is based on the neoclassical economists' point, which suggests that socially responsible behavior will net few economic benefits (Preston & O'Bannon, 1997). Thus, there will be a negative interaction with the costs incurred by companies due to their ESG practices that can negatively affect their prices, wages, corporate profits, and dividends.
- ✓ **Lack of resources theory** suggests that better financial performance might increase the availability of resources, which gives corporations the opportunity to invest in additional socially responsible activities (Makni et al., 2009).
- ✓ **The managerial hypothesis** suggests that corporate managers might track their own incentives that are commonly tied to financial measures, to the detriment of the long-term well-being of shareholders and other stakeholders. Managers may decrease voluntary environmental or social expenses to create short-term financial performance that benefits them (Lin et al., 2019a).
- ✓ Finally, the **neutrality hypothesis** suggest that due to the large number of specific ESG metrics that there is an arbitrary link between CSR and financial performance (Gerard Hirigoyen & Poulain-Rehm, 2015). Prevailing correlations are affected by intermediate variables acting unpredictably, making it impossible to develop strong correlations the two frameworks.

**Table 5.2.** Summary of Review on the correlations between social responsibility and financial performance authors.

Authors	Year	Relationship	CSR measure	Financial measure	Performance
<b>Olaf Weber</b>	2008	Positive	GRI indicators	EBITDA margin, ROE, TR	ROA,
<b>Guidry Patten</b>	<b>and</b> 2010	Neutral	Published sustainability reports	Shares price	
<b>Barnett Salomon</b>	<b>and</b> 2012	Alternative	“KLD” index	Return on assets, net income	
<b>Lucie Chen</b>	2015	Positive	GRI Report	Sales growth, Return on equity (ROE), and Cash flow/Sales ratio.	
<b>Mentor</b>	2016	Negative	“ESG” index	Company market value, change in stock return	
<b>Han, Kim, and Yu</b>	2016	Alternative	“ESG” index	Return on equity, Tobin Q, return on equity	
<b>Zakari</b>	2017	Positive	Social expenditures	Earnings, earnings after tax, earnings per share	
<b>Yasir Hayat Mughal, et al</b>	2021	Positive	Global CSR	ROA, ROE, EPS	
<b>Miralles-Quirós, M et al</b>	2021	Positive	Sustainability Report	Stock Market	

An additional interaction has been suggested by Brammer and Millington (2008), known as the alternative link. In this case the individual companies CSR performance and financial performance are not linear, and are represented by a U-shape relationships shown in **Figure 5.21** (Brammer & Millington, 2008). This relationships suggests that a company's profitability can turn positive and negative by implementing CSR criteria. Specifically, some studies suggest that by initially

implementing CSR practices (moving from point ‘A’ to point ‘B’), organizations may positively affect operations by identifying wastes and inefficiencies, improve image and reputation; increase employees’ morale, retention, and recruitment; increased income from higher sales and market share (Galant & Cadez, 2017). However, other authors suggest that over investing in CSR practices (moving from point ‘C’ to point ‘D’), the focus is directed on less significant activities, increasing costs and decreasing overall financial performance (Cheng et al., 2014).



**Figure 5.21.** Proposed relationship between corporate social responsibility and financial performance (Barauskaite & Streimikiene, 2021)

A related approach is motivated by the causal relationship between ESG and financial performance. A summary of this work is presented in **Table 5.3**. Different conclusions were identified in the different studies. A positive synergy assumes that a strong ESG ‘score’ improves the financial performance of the corporation (Makni et al., 2009). Conversely, a high ESG score may also be associated with higher costs leading to a decrease financial performance. The majority of past studies have focused on whether a company’s ESG score can improve financial performance. A related but less well studied question is whether financial performance can drive

an improvement in the ESG score. If a company is struggling financially will it choose to invest in arguably voluntary ESG activities as a pathway to increasing profitability?

**Table 5.3.** Summary of Review on the correlations and causation between social responsibility and financial performance authors.

Authors	Year	Measurements	Statistic Method Applied	Relationship	Causality
(Makni et al., 2009)	2009	KLD and the CSID databases, Stock, ROA, ROE	OLS and Granger Causality Test	Negative	E-> stock market return
(Pätäri et al., 2014)	2014	MSCI ESG Research, ROA, MC, Net sales	Panel Data Granger causality	Positive	CSR+> MC CSR--> ROA
(Gérard Hirigoyen & Poulain-Rehm, 2014)	2014	Human resources, human rights in the workplace, societal commitment, respect for the environment, market behavior, and governance. Return on equity, Return on assets Net, Market to book ratio Market.	Linear regression analysis and the Granger causality test	Negative	No Causality
(Testa & D'Amato, 2017)	2017	EMT, Market Value, Stock Price	Fixed effect panel data regression	Positive	CPF-> CER
(Lundgren & Zhou, 2017)	2017	Malmquist indexes	data envelopment analysis Panel VAR	Positive	CSR-> CFP CFP-> CSR
(Nana et al., 2018)	2018	NCSR, PCSR, CA (competitive action)	Tobin's Q	Positive	PCSR->CPF

**Table 5.3** (continued).

(Chollet & Sandwidi, 2018)	2018	ESG ASSET4, Systematic, Specific, and Total Risk	Panel VAR and GMM	Positive	CSR-> CFP
(Lin et al., 2019a)	2019	CSR, ROA, ROE, ROIC	Panel Vector Autoregression, Panel Granger Causality Test	Negative	CSR-> CPF CPF->CSR
(Jha & Rangarajan, 2020)	2020	Bloomberg, Prowess	Granger causality test and multiple regression for panel data	Positive Negative	Tobin's Q -> S, ROE->ESG, ROA-> G, G-> ROA, E-> ROA
(Karim et al., 2020)	2020	ROA, TQ, MKT, ENV, CMM, WRK, BSIZE, BIND, BDIV, SIZE, LEV	GMM, panel regression	Negative	No causality
(Lueg & Pesheva, 2021)	2021	TSR, FDI, SALES M-CAP MTB R&D, ESG ESG_E ESG_S ESG_G	fixed effects regression models	Positive	ESG-> TSR G->TSR

### ESG in the Pulp and Paper, and Wood Product Industry

The wood products and the pulp and paper industries have created economic, social, and environmental benefits, and costs, worldwide. Fortune Business Insight projected that worldwide sales by this industry will be \$370 Billion by 2028, and it will continue to attract more investment and expand overseas (Fortune Business Insights, 2021). Global Forest Resources Assessment in 2020 concludes that forest covers nearly 31% of the world's land area (United Nations, 2020). Much of the forest in developing countries is impacted by individual or communities based activities such as gathering firewood or charcoal production. At the same time large industrial

operations have significant financial, environmental and social impacts on the forests and communities in which they operate. The well-known industrial environmental impacts of pulp and paper, and wood products manufacturing include emissions to water and air, bleaching by-products, and also the forest management practices used in the harvesting of industrial forests (Panwar & Hansen, 2006). To address these issues, the sector has increased its emphasis on sustainable use of natural resources and avoidance of climate change emissions through increased energy efficiency, which reduce total emissions, and implementation of certification frameworks for the management of the forests (Bloomberg, 2022a; Korhonen et al., 2015; Pätäri et al., 2016). The adoption of ESG metrics has had a significant impact on actions of pulp and paper and wood product companies. Various ESG rating agencies have recently assessed forest and paper products, and offered their perceptions of these industries. In 2019, the Standard & Poor's Global Ratings Agency analyzed thirteen companies in the sector around the world (Menjivar et al., 2019). The agency reached three main conclusions.

- ✓ Sustainable forest management is crucial for these businesses.
- ✓ Decreasing water pollution and energy management in paper production require additional attention.
- ✓ Several companies were effective at limiting health and safety risks by automating many activities (Menjivar et al., 2019).

Bloomberg, in 2022, released an updated methodology and data for measuring ESG performance. Table 5.4 and Table 5.5 highlights some of the fundamental challenges and opportunities faced by the Paper and Packaging sector. (Bloomberg, 2021, 2022a). Two related sectors are also presented in Table 5.4 and Table 5.5 for comparison. The scale was presented from 1 to 8, where a rating

of one symbolizes the high priorities. By comparing different sectors common opportunities and challenges can be identified. Also, the overall ESG performance between companies and sectors can be examined.

**Table 5.4.** Environmental Issues and Priorities on Container and Packaging sector  
(Bloomberg, 2022a).

	<b>Paper Container &amp; Packaging</b>	<b>Plastic Containers &amp; Packaging</b>	<b>Metal Containers &amp; Packaging</b>
<b>Air Quality</b>	4	4	4
<b>Ecological Impact</b>	8	7	7
<b>Energy Management</b>	1	1	1
<b>Environmental Supply Chain Management</b>	1	1	1
<b>GHG Emissions Management</b>	4	4	4
<b>Sustainable Product</b>	1	1	1
<b>Waste Management</b>	6	4	6
<b>Water Management</b>	6	7	6

**Table 5.5** Social Issues and Priorities on Container and Packaging sector (Bloomberg, 2022a).

	Paper Container & Packaging	Plastic Containers & Packaging	Metal Containers & Packaging
<b>Occupational Health and Safety Management</b>	1	1	1
<b>Product Quality Management</b>	2	2	2

This present study addresses the causal relationship between ESG scores and the financial performance for companies in the pulp and paper, and wood product sector. The innovative aspects of the work include 1) the use of a single data source (Bloomberg), and 2) evaluation of the strength of relationships using the granger causality analysis. Using this approach two central hypotheses are presented:

**H1:** *For this industrial segment (pulp and paper, and wood products) a high ESG score has a causal relationship with measures of improved corporate financial performance.*

**H2:** *For this industrial segment (pulp and paper, and wood products) a high individual ESG category score also has a causal relationship with measures of improved corporate financial performance.*

### 5.3. Materials and methods

#### 5.3.1. Data collection

This study uses data from 2010 to 2019 provided by Bloomberg for 41 pulp and paper, and wood product companies worldwide. Both ESG data and the financial data were used as reported. The Bloomberg ESG data provides a total of 61 specific metrics for companies. Due to missing data we used a total of 48 individual metrics. Of this total 22 metrics were used to measure the environmental attributes, and these account for 53% of the ESG score (see Figure 5.3). In addition, 11 total metrics were used to evaluate the social attributes, and these account for 24% of the total ESG score. Finally, 15 attributes were used to measure the governance contributions to the total ESG score, account for 23% of the total score. All of the 48 specific attributes used in this analysis are shown in the supplementary materials.

The measures of financial performance included percent change in market capitalization (MC), percent change in net sales (NS), return on equity (ROE), and return on capital (ROC). Again this data was collected from Bloomberg. General equations for MC, ROE and ROC is presented in Equation 29, Equation 30, and Equation 31.

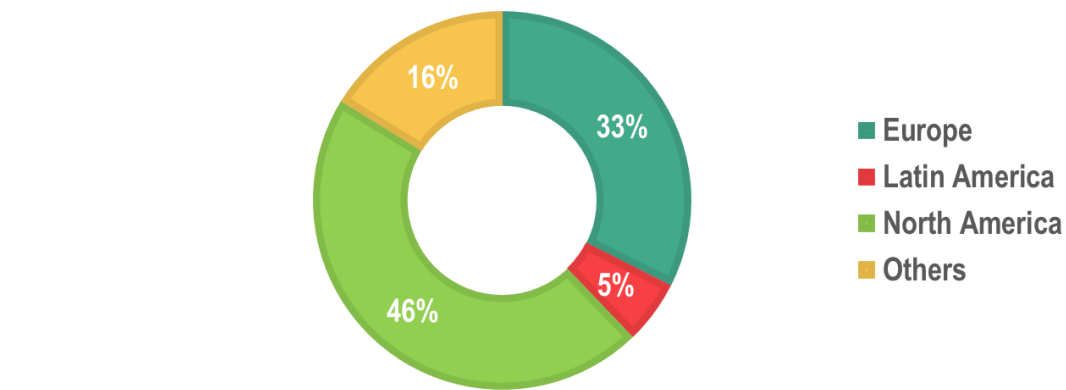
$$MC = \text{share price} \times \# \text{ shares outstanding} \quad \text{Equation 29}$$

$$ROE = \frac{\text{Net Income}}{\text{Average Shareholders' Equity}} \quad \text{Equation 30}$$

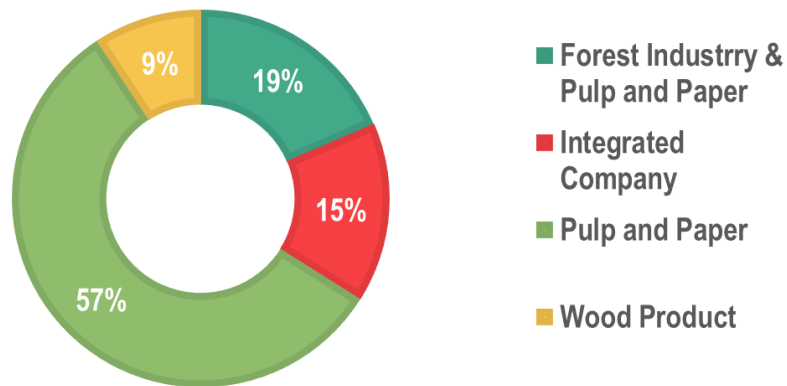
$$ROC = \frac{Net\ Income}{Debt + Equity}$$

Equation 31

The regional distribution and main business of the 41 companies are shown in **Figure 5.22a** and **Figure 5.22b**, and listed individually in the supplemental materials.



A



B

**Figure 5.22.** Distribution of the data. a) Region b) Type of company

### 5.3.2. Statistical Analysis

This study evaluate both the correlation between the ESG and financial performance, and more importantly the causational links between ESG and financial performance. STATA 14 or Excel were used for the data processing. Both the ESG scores and financial data is reported annually.

### 5.3.3. Correlation coefficient

In all these cases a correlation between ESG and financial performance is different than causation, which is evaluated with the Granger causality approach detailed below. Equation 32 shows the calculation for the correlation analysis. Testing for correlations was done with Excel.

$$\rho_{x,y} = \frac{cov(X,Y)}{\sigma_x \sigma_y} \quad \text{Equation 32}$$

Where: *Cov*: covariance  $\sigma_x$ : standard deviation of  $X$   $\sigma_y$ : standard deviation of  $Y$

### 5.3.4. Panel Data

#### 5.3.4.1. Granger Causality Test

The Granger causality test was developed to assessed the causation between two variables (Lin et al., 2019b; Pätäri et al., 2014). Specifically can one variable, or set of variables, be used to predict the future outcome of a second variable, or set of variables. In this work the total ESG score with 48 individual criteria for each of the 41 company. In addition three individual ESG pillars were used to produce subsets with 22 criteria used to measure the environmental score, 11 criteria used to measure social attributes, and 15 criteria for the governance as one data set, and the company's financial performance was used as the second data set.

The intent of the Granger modeling is that a variable X, or set of X variables, can be used to predict a response in a second variable Y, or set of Y variables, if the past values of X were useful for explaining past values of Y. Additionally, if the past X values causes changes in Y, these changes in X should precede changes in Y.

In practice, the test for bilateral causality can be performed following the equations:

$$Y_t = \alpha_o + \sum_{j=1}^N \alpha_j Y_{t-j} + \sum_{k=1}^N \beta_k X_{t-k} + \mu_i + e_{1t} \quad \text{Equation 33}$$

$$X_t = \alpha_o + \sum_{j=1}^N \alpha_j X_{t-j} + \sum_{k=1}^N \beta_k Y_{t-k} + \mu_i + e_{2t} \quad \text{Equation 34}$$

Where  $e_{1t}$  and  $e_{2t}$  are assumed to be uncorrelated.

X is said to Granger-cause Y if the estimated coefficients of the lagged values of X in equation 1 are statistically significantly different from zero as a group and, respectively, Y is said to Granger-cause X if the estimated coefficients of the lagged values of Y in equation 2 are statistically significantly different from zero as a group. Three other causalities could be resulted: unidirectional, bilateral, or the independent variables.

In the study, the model follows:

$$CFP_{it} = \gamma_o + \sum_{j=1}^N \gamma_j ESG_{i,t-j} + \sum_{k=1}^N \delta_k ESG_{i,t-k} + \gamma_i + e_{1t} \quad \text{Equation 35}$$

$$ESG_{it} = \gamma_o + \sum_{j=1}^N \gamma_j ESG_{i,t-j} + \sum_{k=1}^N \delta_k CFP_{i,t-k} + \gamma_i + e_{1t} \quad \text{Equation 36}$$

Where CFP: corporate financial performance.

#### 5.4. Results and discussion

Biomass Using data from Bloomberg the relationship between the total and individual ESG score's, and financial performance of pulp and paper, and wood product companies were examined for studied using the correlation coefficient and Granger causality test.

##### Correlations Results

Table 5.6 summarizes the results of the correlation. There are three main conclusions that can be drawn from this data these.

- ✓ Most of the significant correlations were positive. There is a strong connection between the individual E, S scores and the total ESG score. This contrasts with the governance attribute that does not provide robust link to the total ESG.
- ✓ There were no strong correlations between the total ESG or the individual ESG pillars, and financial performance.

**Table 5.6.** Correlation Coefficients Results

	<b>ESG</b>	<b>E</b>	<b>S</b>	<b>G</b>	<b>MC</b>	<b>NS</b>	<b>ROE</b>	<b>ROC</b>
<b>ESG</b>	1							
<b>E</b>	0.93	1						
<b>S</b>	0.91	0.72	1					
<b>G</b>	0.62	0.51	0.52	1				
<b>MC</b>	0.52	0.44	0.36	0.37	1			
<b>NS</b>	0.20	0.34	0.05	0.26	0.36	1		
<b>ROE</b>	0.02	0.02	0.01	0.14	0.24	0.05	1	
<b>ROC</b>	0.02	-0.04	0.07	0.03	0.21	-0.03	0.71	1

This analysis shows a strong relationship between environmental and social scores. The correlation of either of these measures with the governance score is weaker. Different individual criteria included in the ESG analysis (shown in supplementary materials) suggest some of the motives for these results. One of them could be associated with the connections between ecological impact and health and safety issues. Companies that effectively measure their environmental emission such as CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, PM, etc., may also have rigorous safety program and relationships with their communities, both of which are included under social pillar. On the other hand, as much trained worker is in the companies could generate new ideas related to environmental improvement. The governance pillar is dominated by criteria that reflect the activities and composition of the executive team, and board. While the actions of the executive team and board can have a significant impact on criteria such as employee pay and working conditions and these governance criteria are less impactful on day to day operations. More details are shown in the supplementary materials.

Positive correlations between some ESG measure and financial performance does not show the underlying cause and effect. Does a strong ESG score increase a company's financial performance by reducing wastes or increasing brand loyalty, or does a strong financial performance provide the company with the resources to invest in ESG activities which enhance the company's image but that are more likely to have a cost, and unlikely to direct financial benefits (Fonseka et al., 2019; Luo et al., 2019; Raimo et al., 2021).

Even though there is a positive correlation between the total ESG score and the individual ESG pillars, and the percent change in market capitalization, the correlation is modest, with correlation coefficients between 0.52 and 0.36. While modest this correlation could imply that investors are aware the importance of these nonfinancial aspects and potential reputational risks associated with all ESG attributes, and the environment pillar in particular. In addition, the overall rigor and awareness ESG measures, was increasing during the period of this study, 2010-2019, and the US SDG where implemented during this period which may have created to a change in report metrics. (ONU, 2020).

To better understand the relationships between ESG metrics and financial performance Granger Causation analysis we used to examine this same data set. As highlighted in Equation 33 and Equation 34, the Granger Causation analysis is intended to measure if a series X variable, annual ESG data in our case, can be used to predict a future outcome in some financial response.

### **Granger Causation Results**

The following tables summarize the outcomes from the Granger Causation analysis on ESG data with the financial performance. Four main conclusions are presented below:

- ✓ Growth or decline in a company's percent market capitalization is caused by the total ESG scores and also environmental pillar alone.
- ✓ A companies percent net sales growth is caused by the total ESG score, and also the environmental and social pillars alone.
- ✓ The total ESG and each individual ESG pillar cause a change in the return on equity. Also, an increase in the return on equity may cause an increase in the individual social and governance scores.
- ✓ The individual social and governance scores have a significant impact on the return on capital.

### Percent growth in market capitalization

**Table 5.7.** Causality results in the percent growth of the market capitalization

Causality	Causation	p-value
<b>ESG -&gt; %Growth Market Capitalization</b>	Yes	0.07
<b>E -&gt; %Growth Market Capitalization</b>	Yes	0.01
<b>S -&gt; %Growth Market Capitalization</b>	No	0.7
<b>G -&gt; %Growth Market Capitalization</b>	No	0.9

**Table 5.8.** Causality results in the percent growth of the market capitalization.

Causality	Causation	p-value
<b>%Growth Market Capitalization -&gt; ESG</b>	No	0.5
<b>%Growth Market Capitalization -&gt; E</b>	No	0.7
<b>%Growth Market Capitalization -&gt; S</b>	No	0.2
<b>%Growth Market Capitalization -&gt; G</b>	No	0.4

The value of a business can be viewed from many different perspectives. Changes in market capitalization is one common financial attribute that indicates an investor's view of the long-term value of the company. Since the companies studied in the work were significantly different in their market capitalization, a percent change in the market capitalization was used as the response variable (Grainger Y variable).

For this financial measure, Table 5.7 shows that a higher total ESG score causes a higher percent growth in market capital. These results also show that the environmental pillar alone causes a higher percent growth in market capitalization. Conversely, neither the social nor governance scores caused a change in the percent growth in market capitalization.

One possible reason for this result maybe the inclusion of sustainable forest, energy, water and waste metrics in the environmental as the S&P500 disclose (Menjivar et al., 2019). Reducing these emissions improve the environmental score, and also can save the company money, increasing profits and attracting investors. Also, the pulp and paper, and wood products company's included in this analysis all have a significant manufacturing base, and lowering emissions may also reduce reputational risk from an accidental emission or from being seem as a consistent underperformer in the environmental arena. Conversely the social and governance alone pillars contain fewer metrics that are directly related to costs or profitability.

Similar results for the impact of ESG scores have been presented by other authors who mention that high ESG scores have a significantly positive impact on economic value (Henisz et al., 2019; Janicka, 2022; Șerban et al., 2022; Valente & Atkinson, 2019). Recently fund managers and individual shareholders have been considering ESG principles in their investment decisions, which should also increase the market price of shares.

Using this same data set the reverse causality question can be asked. Does a change in percent growth in market capitalization cause an increase in the overall ESG score for a company, or a change in the individual ESG components? Said another way, does an increase in percentage market capitalization cause companies to invest more time and resources to their overall ESG activities. As shown in Table 5.8 there is no causal relationship to suggesting that a change in percent growth in market capitalization leads to an increased ESG performance for these companies.

### Percent growth of the net sales

**Table 5.9.** Causality results in percent growth of the net sales

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>ESG-&gt; %Growth Net Sales</b>	Yes	0.01
<b>E-&gt; %Growth Net Sales</b>	Yes	0.01
<b>S-&gt; %Growth Net Sales</b>	Yes	0.05
<b>G-&gt; %Growth Net Sales</b>	No	0.5

**Table 5.10.** Causality results in percent growth of the net sales

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>%Growth Net Sales -&gt; ESG</b>	No	0.8
<b>%Growth Net Sales -&gt; E</b>	No	0.4
<b>%Growth Net Sales -&gt; S</b>	No	0.3
<b>%Growth Net Sales -&gt; G</b>	No	0.7

Improved ESG scores should help a company improve its overall image, and avoid missteps that can damage a company's image or generate real costs in terms of fines or required investments in

waste treatment infrastructure (Martínez-Campillo\*, Almudena, Cabeza-García & Marbella-Sánchez, 2012; Martinez-Conesa et al., 2017; Mughal et al., 2021; Saudi et al., 2018).

Some elements of corporate sustainability plans are aimed at attracting and retaining customers based on a positive corporate image, which could translate into increased sales. Table 5.9 shows that a higher value on the total ESG, and also for the scores for the individual environmental and social pillars will cause an increase percent growth in the net sales. This relationship is more understandable for companies that sell directly to consumers, but the avoidance of negative publicity is important for all companies whether they sell direct to consumers, or are business-to-business and land-owning companies. Today's customers have access to more information than ever before to inform their purchasing decisions, and a poor track record on either environmental or social pillars can impact companies anywhere in the supply chain, as well as companies that sell directly to consumers.

Table 5.10 shows that there is no causation between the percent net growth of net sales and the total ESG score or for any of the individual ESG pillars. This suggests that simply increasing sales does not fundamentally alter a company's commitment to ESG goals.

### **Growth in return on equity**

**Table 5.11.** Causality results in the growth in return on equity

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>ESG -&gt; %Growth Return on Equity</b>	Yes	0.002
<b>E -&gt; %Growth Return on Equity</b>	Yes	0.03
<b>S -&gt; %Growth Return on Equity</b>	Yes	0.02
<b>G -&gt; %Growth Return on Equity</b>	Yes	0.01

**Table 5.12.** Causality results in the growth in return on equity

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>%Growth Return on Equity -&gt; ESG</b>	No	0.9
<b>%Growth Return on Equity -&gt; E</b>	No	0.8
<b>%Growth Return on Equity -&gt; S</b>	Yes	0.02
<b>%Growth Return on Equity -&gt; G</b>	Yes	0.04

Return on equity and return on capital are well recognized metrics used by investors to select between competing investments options for companies in the same industrial section. Return on equity measures a corporation's profitability relative to stockholders' equity, while return on capital includes debt financing and equity. Integrating ESG practices into a company's strategic vision and everyday operations should help manage risk and enhance operational efficiency, leading to revenue growth (Schramade, 2016). Table 5.11 shows strong causality between the total ESG and each individual ESG pillar, and the growth in the return on equity. One of the reason for the total ESG and environmental value presenting this robust causation might be associated the rise of revenue that the growth on the net sales present Table 5.9, and also the share price related with the market capitalization as Table 5.7 reveal. In this case both the social and governance pillars also have a causal relationship with the growth in the return on equity. Social factors tends to deal with social trends, labor, and politics. Prior work has concluded that employees satisfaction is precursor of stronger equity performance on the corporations (Edmans, 2011). Strong corporate governance and culture should reduce litigation costs associated with abuse of authority, unfair labor practices, and objections from shareholders. The board and executive team would set the tone for the company in this arena. Other work has concluded that board independence, gender diversity, CEO duality and CEO tenancy all affect the return on equity (Rostami et al., 2016).

Therefore, the high the strong causality is expected for well management and all these ESG pillars. These results show that for this specific industrial segment the individual practices embodied in ESG can increase corporate cash flow and shareholder value (Schramade, 2016; Serafeim et al., 2015). This increase in shareholder value can be attributed to several features including consistent potentially lower borrowing costs (Schramade, 2016; Serafeim et al., 2015).

Conversely, the results in Table 5.12 show that growing the return on equity will increase social and governance scores. With additional capital the business may choose to increase investments in social and governance activities that are unlikely to provide an immediate return, but that put a company on the pathway to long-term success (Kumalasari & Pratikto, 2018). With the rise in debt can be refereed that the company has worthy projections for the future. As the S&P 500 disclose in their work presented above, this sector is aware on automation to help the safety and risk of the employments (Menjivar et al., 2019). Hence, it appears that the investment on this aspect will increase the value on the social factor.

### **Growth of return on capital**

**Table 5.13.** Causality results in the growth of return on capital

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>ESG -&gt; %Growth Return on Capital</b>	No	0.6
<b>E -&gt; %Growth Return on Capital</b>	No	0.6
<b>S -&gt; %Growth Return on Capital</b>	Yes	0.05
<b>G -&gt; %Growth Return on Capital</b>	No	0.5

**Table 5.14.** Causality results in the growth of return on capital

<b>Causality</b>	<b>Causation</b>	<b>p-value</b>
<b>%Growth Return on Capital -&gt; ESG</b>	No	0.6
<b>%Growth Return on Capital -&gt; E</b>	No	0.5
<b>%Growth Return on Capital -&gt; S</b>	Yes	0.05
<b>%Growth Return on Capital -&gt; G</b>	Yes	0.06

The granger causality assessment results for return on capital are very different that the results for the prior three financial measures. , Table 5.13. In the three prior cases the total ESG score had a significant impact on the financial measurements. In the case of growth in return on capital only the individual social pillar has a significant result. The social pillar is only 24% of the total ESG score so it is reasonable that the social pillar alone cannot drive a causal relationship for the total ESG score. But it is less obvious why the social pillar alone predicts the growth in the return on capital. This rationale may be similar to the causal relationship between the social pillar and the return on equity. Again, social trends, such as an engaged labor force, and safe and secure workplace that lead to employee satisfaction and increase productivity and the company's return in capital (Edmans, 2011).

On the other hand, disclosing a high social and governance score will significantly impact the measure analyzed as Table 5.14 shows. The explanations of this appears to be similar to that for the return on equity. Basically, well run companies with strong reputations are able to borrow money, take on debt, at a competitive rate.

One additional explanation for some of these different causalities' outcomes might be related to the selected data used in this study. Around 79% of the data comes from Europe and North America, which are leaders in ESG investment (Global Sustainable Investment Alliance, 2021).

Firms from those regions are commonly in the top ranks in all sustainability ratings. From most of the causalities studied here, the total ESG and environmental category are significant and have the same positive relationship. In the case of return of capital, this tendency is the opposite concerning the correlation effects, in which total ESG still has a positive relationship, but the environmental pillar has an inverse relationship with the financial metric. Even though the environmental pillar represents a significant portion of the overall ESG score, the combination of social and governance pillars still influence the total value, and show different aspects of the companies (Figure 5.20). This explains the similar trends for the total ESG and the individual environmental pillar.

This industrial sector is currently highly motivated to mitigate the global warming potential by increasing renewable energy use as different studies show (Cepi, 2021; Kramer et al., 2007; Lipiäinen et al., 2022). Also, the awareness of employee risk is essential for the sector (Menjivar et al., 2019) . Thus, this type of incentive makes customers and investors influence the improvement of the financial performance.

## 5.5. Conclusions

This work measures both the correlation and the causation between the ESG attributes and financial performance of 41 pulp and paper, and wood product companies worldwide. Using a single consistent data set, Bloomberg, the total ESG score, and the score for each individual pillar is compared to four measures of financial performance: percent growth in market capitalization (MC), percent growth in net sales (NS), percent on return on equity (ROE), and percent return on capital (ROC). The correlation coefficient and Granger causality test were both used to perform these analyses.

The correlation between the ESG scores and financial measures were modest to poor.

However, when using the Granger Causal Analysis for this set of 41 pulp and paper, and wood products companies the overall ESG score, and the score of the environmental pillar alone could very effectively predict percent growth in market capitalization, percent growth in net sales, and percent return on equity. The response of return on capital to ESG practices was different than all the other financial responses.

The total ESG score and the environmental pillar alone had the same overall trends, while social and governance trends were more complex in standings of causality evaluation. Contrary to social and governance factors that significantly impact the growth of net sales for the social aspect and return on equity and return on capital for both of them. In addition, it is suggested that bidirectional causality from social attributes, return on equity, and capital is presented. Also, the same result is manifested in the governance feature and growth in the return on equity. But just the increase in the return on capital may cause the governance score.

Some of the limitations of this study are related to the period included and the data region considered. According to different studies, around 2015, when the UN SDGs were established many of the specific ESG measures and concepts changed as this investing approach began to attract new investors and investment funds. At the same time multiple alternative rating schemes were proposed and developed. It is important to note that for the time period covered by this work (2010-2019) the field was relatively immature, and both the ESG ratings and actual quality of the data is variable. Finally, 33 of the 41 companies included in this study were from the US or western Europe, so domestic policy and cultural difference need to be further studied.

However, these results do suggest that building an ESG culture within a company, and having well-documented practices that allow for high scores can benefit the financial performance for companies in this sector.

## 5.6. REFERENCES

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## SUPPLEMENTARY INFORMATION

### Environmental Attributes

**Table 5.15.** Environmental Attributes included in this analysis (Bloomberg, 2022a)

<b>Air Quality</b>	<b>GHG Emission Management</b>
Air Emissions	GHG Emissions
Air Emissions Policy	GHG Emissions Policies
<b>Climate Exposure</b>	GHG Regulations
Transition Risk	GHG Target
<b>Ecological Impact</b>	<b>Sustainable Product</b>
Ecosystem Protection	Green Product
Environmental Fines	<b>Waste Management</b>
Environmental Incidents	Hazardous Waste Generation
<b>Energy Management</b>	Hazardous Waste Recycling
Energy Consumption	Waste Generation
Renewable Energy Use	Waste Recycling
<b>Environmental Supply Chain Management</b>	<b>Water Management</b>
Sustainable Source	Wastewater
	Water Use
	Water Use Policies

### Social Attribute

**Table 5.16.** Social attributes included in this analysis (Bloomberg, 2022a)

<b>Community Right and Relations</b>	<b>Occupational Health and Safety Management</b>
Community and Human Right	Fatalities
Community Relations	Health and Safety Fines
<b>Ethics &amp; Compliance</b>	Health and Safety Policies
Business Ethics	Safety Incident
Competitive Behaviors	<b>Operation Risk Management</b>
Legal & Regulatory Management	Operational Incident
<b>Labor &amp; Employment Practices</b>	Operational Preparedness
Labor Actions	<b>Product Quality Management</b>
Organized Labor	Product Quality & Safety
Training	<b>Social Supply Chain Management</b>
	Supply Social Compliance

## Governance

**Table 5.17.** Board composition attributes included in this analysis (Bloomberg, 2022b)

<b>Director Roles</b>	<b>Independence</b>
CEO Roles	Board Leadership Independence
Chair Roles	Board Independence
Board Roles	<b>Refreshment</b>
<b>Diversity</b>	Board Refreshment
Age Diversity	Chair Refreshment
Gender Diversity	

**Table 5.18.** Executive compensation attributes included in this analysis (Bloomberg, 2022b)

<b>Incentive Structure</b>	<b>Pay Governance</b>
CEO Incentive Plan Design	Compensation Board Oversight
Executive Incentive Plan Design	Gender Diversity
Executive Pay Equity	Say on Pay
Executive Pay Linkage	Pay Policies
<b>Pay for Performance</b>	
Fixed Pay Alignment	
Variable Pay Performance	

**Table 5.19.** Shareholder right attributes included in this analysis (Bloomberg, 2022b)

<b>Shareholder Policies</b>	<b>Director Voting</b>
Takeover Defense	Director Terms
Voting Rights	Board Support
Director Election Policies	

## Companies included in the study

**Table 5.20.** List of companies used in the study

<b>Region</b>	<b>Sector</b>	<b>Company</b>
<b>Europe</b>	Pulp and Paper	Smurfit Kappa
<b>Europe</b>	Pulp and Paper	Stora Enso
<b>Europe</b>	Pulp and Paper	UPM
<b>Europe</b>	Pulp and Paper	Svenska Cellulosa AB SCA
<b>Europe</b>	Pulp and Paper	Mondi Group
<b>Europe</b>	Pulp and Paper	Metsä Group
<b>Europe</b>	Pulp and Paper	DS Smith plc
<b>Europe</b>	Integrated Company	Lenzing
<b>Europe</b>	Pulp and Paper	ENCE
<b>Europe</b>	Pulp and Paper	BillerudKorsnäs
<b>Europe</b>	Pulp and Paper	Holmen AB
<b>Europe</b>	Pulp and Paper	The Navigator Co
<b>Europe</b>	Pulp and Paper	Essity
<b>Latin America</b>	Pulp and Paper	Suzano do Brasil
<b>Latin America</b>	Pulp and Paper	CMPC Celulose Riograndense
<b>North America</b>	Pulp and Paper	IP
<b>North America</b>	Integrated Company	Kimberly & Clark
<b>North America</b>	Pulp and Paper	Westrock
<b>North America</b>	Integrated Company	Eastman
<b>North America</b>	Pulp and Paper	Domtar
<b>North America</b>	Integrated Company	P&G
<b>North America</b>	Wood Product	Weyerhaeuser
<b>North America</b>	Pulp and Paper	Sonoco Products Company
<b>North America</b>	Pulp and Paper	Graphic Packaging Holding Company
<b>North America</b>	Pulp and Paper	Packaging Corporation of America (PCA)
<b>North America</b>	Pulp and Paper	Cascades Inc
<b>North America</b>	Pulp and Paper	Resolute Forest Products Inc
<b>North America</b>	Pulp and Paper	Canfor Pulp Products Inc
<b>North America</b>	Wood Product	Western Forest Products Inc
<b>North America</b>	Pulp and Paper	Rayonier A.M.
<b>North America</b>	Pulp and Paper	Verso Paper
<b>North America</b>	Pulp and Paper	Glatfelter

Table 5.20 (continued).

<b>North America</b>	<b>Wood Product</b>	<b>West Fraser Timber</b>
<b>North America</b>	Wood Product	Stella-Jones
<b>Others</b>	Pulp and Paper	YFY
<b>Others</b>	Pulp and Paper	Nine Dragons Paper (Holdings) Limited
<b>Others</b>	Pulp and Paper	CHENMING Group
<b>Others</b>	Pulp and Paper	Marubeni
<b>Others</b>	Pulp and Paper	Nippon Paper
<b>Others</b>	Pulp and Paper	Rengo
<b>Others</b>	Pulp and Paper	Mitsubishi Paper Mills
<b>Others</b>	Integrated Company	ITC
<b>Others</b>	Pulp and Paper	Lintec