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PLASTICLESS: A COMPARATIVE LIFE-CYCLE, SOCIO-ECONOMIC, AND POLICY ANALYSIS OF ALTERNATIVES TO PLASTIC STRAWS

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PLASTICLESS: A COMPARATIVE LIFE-CYCLE, SOCIO-ECONOMIC, AND POLICY ANALYSIS OF ALTERNATIVES TO PLASTIC STRAWS

By

Karuna Rana

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental and Energy Policy

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Environmental and Energy Policy.

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Abstract

Around 500 million plastic straws per day are being consumed in the U.S. (U.S. National Park Service, 2019), and nearly 7.5 million straws are reported to lie around U.S. shorelines (Borenstein, 2018). The estimated cost of plastic pollution is reported to be $13 billion in economic damage to marine ecosystems each year (Avio et al., 2017). The ongoing action against the use of single-use plastic straws has created a surging demand for sustainable alternatives to plastic straws, with nearly ten types of single-use and reusable drinking straws now on the market. Given that no one study quantifies and compares the environmental impact of these various straw types, this study uses the Cumulative Energy Demand and the IPCC 2013 GWP 100a V1.03 impact assessment methods in the SimaPro8.5 database to conduct a limited life-cycle assessment (LCA) of the standard plastic straw and its most commonly used alternatives: the paper straw, the bioplastic/compostable (PLA) straw, and the (reusable) metal straw. The study also assesses the blue carbon and carbon dioxide sequestration potential of the seaweed-based straw. The use of a (reusable) metal straw was found to have a significantly lower overall environmental impact than that of other straws over one year, provided that the use of hot water is avoided when washing the metal straw and that the standard washing time is cut to half. Over 85 percent of the environmental impacts reported came from the washing of the metal straw, indicating that human behavior is a key driver of environmental impact. For the single-use straw types, the standard plastic straw was found to have less than half of the energy demand and nearly one-third of the global warming potential of that of a paper straw and a bioplastic straw. Thus, these alternative material straws are not empirically reducing the environmental impacts of straw use. Conversely, the CO_2 sequestration potential of the seaweed-based straw was estimated to be 0.00165 kg per straw, indicating the straw's potential to be carbon neutral or even carbon negative, depending on how the straw's life-cycle is designed when production is scaled-up. Public policy instruments play a key role in reducing the consumption of plastic straws. While a variety of command-and-control, market-based, investment-based, education-based, and voluntary policy instruments exist to reduce the use of plastic straws, the default choice modification policy instrument has been the most successful in reducing the consumption of plastic straws while minimizing impacts to businesses. Data from this study recommends a default choice modification (straw upon request) framework combined with certification and environmental labeling, and investments in waste management infrastructure and R&D as the most effective set of policies to reduce single-use plastic straw consumption in the U.S. The study concludes with proposals for five areas for further research: (1) ecotoxicology of marine plastics integrated into LCA; (2) LCA of other drinking straw types; (3) a comprehensive economic assessment of plastic pollution; (4) the development of a new Sustainability Index inclusive of socio-economic indices, blue carbon and ecotoxicology of marine plastics; and (5) a conjoint choice analysis (including a cost comparison study) to assess consumer willingness-to-pay.

1 Introduction

The invention of modern plastics can be called a huge commercial success. For decades, plastics have been used in a variety of applications – from cars and planes, to our clothing, to even teabags (Hernandez et al., 2019). The exponential growth of global plastic production from the 1950s is depicted in Figure 1.1 below. The graph shows that some 359 million metric tons of plastics were produced globally in 2018 (PlasticsEurope, 2019). However, no material on Earth has been so highly revered for its usefulness, yet so maligned by society, as plastic (Stevens, 2002). The very convenient, ubiquitous, cheap, and durable nature of plastics causes several forms of environmental risks and degradation, including plastic pollution. The magnitude of the issue, combined with aggressive grassroots efforts, have made plastic pollution, especially plastic marine debris, rapidly rise on the global environmental policy agenda.

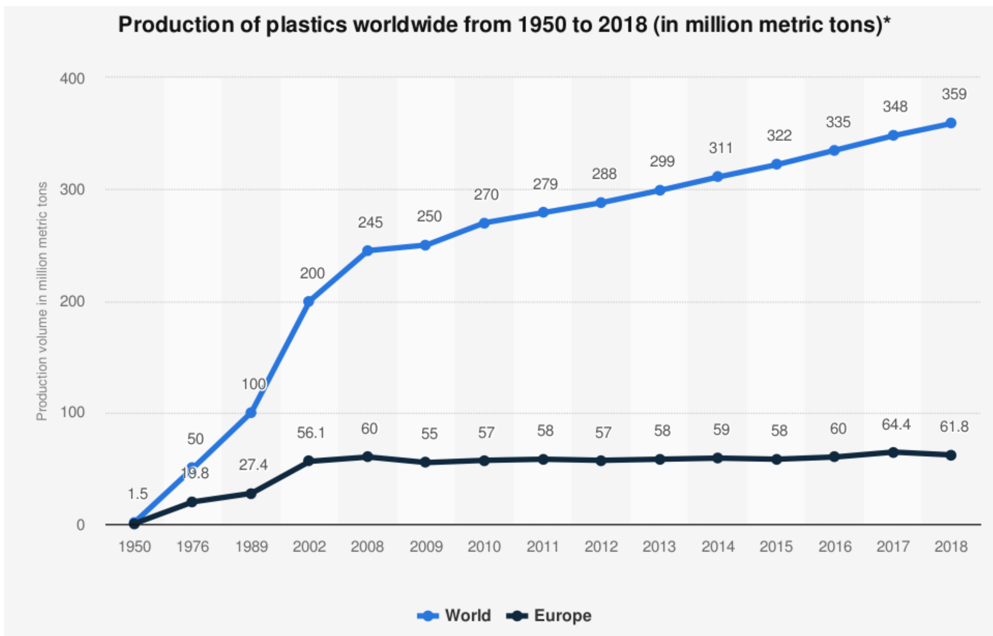

Figure 1.1. Production of plastics worldwide from 1950 to 2018 (Source: PlasticsEurope, 2019)

One such example is single-use plastic drinking straw. A survey by Eunomia (2020) found that drinking straws constituted 36.4 percent of the average annual on-the-go single-use plastic items consumption in the European Union as of 2017, as shown in Figure 1.2. The consumption of plastic straws in the U.S. is as alarming; around 500 million plastic straws per day (U.S. National Park Service, 2019). While other plastic items such as beverage bottles, cigarette butts and food packaging may be higher in volume in terms of production, consumption and waste, plastic straws have remained at the center of the global action against plastic pollution due to both public salience and empirical evidence.

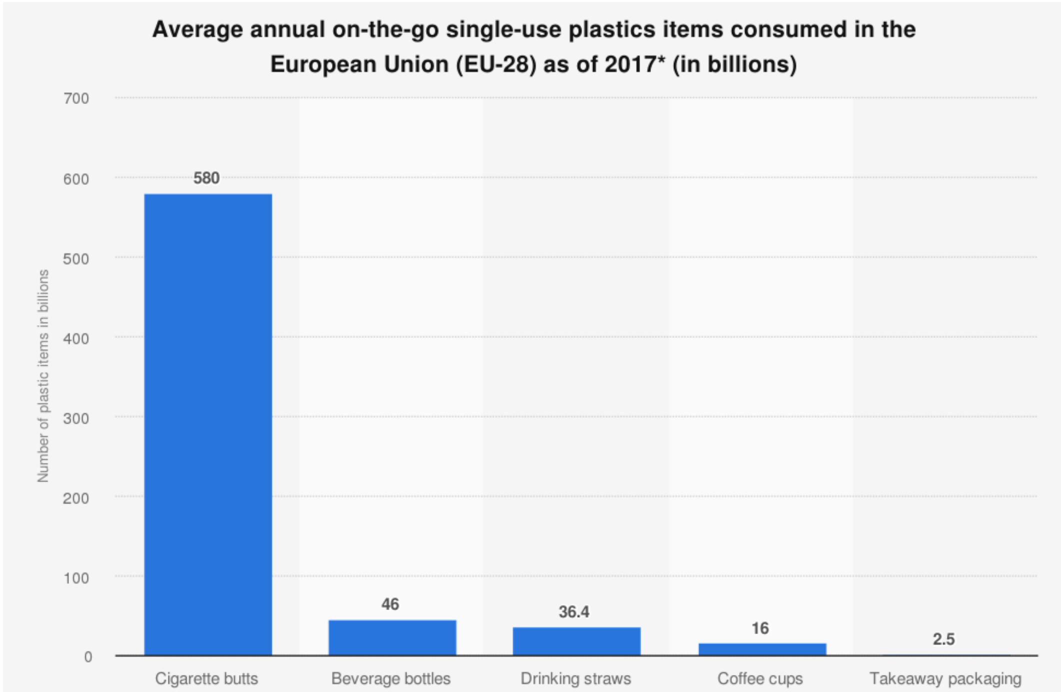

Figure 1.2. Average annual on-the-go single-use plastic items consumed in the European Union as of 2017 (Source: Eunomia, 2020)

Once found in nearly every restaurant and business place, single-use plastic straws are now being slowly eliminated by businesses and even by some governments (Xanthos & Walker, 2017). Instead, new varieties of more "sustainable" alternatives to plastic straws are rapidly entering the market. What are these alternatives and how do they compare to the standard plastic straw? How do we know which straw to choose? Are consumers ready to make the transition from the plastic straw to more sustainable alternatives? What are the roles of economics and policy in accelerating this transition? These are some questions that lie at the core of this project.

This study is structured as follows. First, it introduces the topic and rationale behind conducting this study and then explains the study's goals and hypotheses (Chapter 1). Then it provides a review of literature on the topic, including the environmental impacts of single-use plastic straws, an overview of the non-plastic drinking straws that exist on the U.S. market, the use of sustainability assessment tools for products, the current legislative landscape surrounding plastic straws in the U.S., and studies that highlight consumer preferences and willingness-to-pay for product sustainability (Chapter 2). The third chapter is devoted to the sustainability assessment of drinking straw types, including the methods used, results obtained, and deductions made. Given that the seaweed-based straw is still in its pilot phase of production, its environmental sustainability is assessed and discussed separately in the fourth chapter. The fifth chapter focuses on policy instruments, consumer preferences, and willingness-to-pay to reduce the consumption of plastic straws by conducting a comprehensive review of the literature on existing public policy instruments used to reduce single-use plastics and a limited meta-analysis of relevant studies. The fifth chapter also puts forward a recommendation for the most effective set of policy options for reducing the consumption of single-use plastic straws. The paper concludes by combining the results of all chapters along with specific recommendations for further work.

1.1 Goals and Objectives

The overall aim of this study is to quantify and compare the environmental impact of the standard single-use plastic straw to other drinking straw types available on the U.S. market whilst also analysing the socio-economic and policy aspects of reducing the consumption of single-use plastic straws.

The study also has the following objectives:

a) To conduct a limited life-cycle assessment of the standard single-use plastic straw and its most common alternatives available on the U.S. market;
b) To calculate the blue carbon and carbon dioxide sequestration potential of a seaweed-based drinking straw;
c) To identify potentially effective policies needed to accelerate the shift from standard single-use plastic straws to more sustainable alternatives; and
d) To understand consumer preferences and willingness-to-pay for switching to non-plastic drinking straws.

2 Literature Review

2.1 Environmental Impact of Plastic Straws

The environmental impacts of plastic straws have been widely reported in the literature. To start with, the majority of plastics are made from fossil feedstocks. A study reported that the global lifecycle GHG emissions of conventional plastics were 1.7 Gt CO_2-equivalent (CO_{2eq}) in 2015 and expected to grow to 6.5 Gt CO2eq by 2050, representing 15% of the 2050 global carbon budget (Zheng & Suh, 2019). For North America, the conventional plastics production represented more than 1% of total U.S. GHG emissions and nearly 3% of total U.S. energy consumption in 2013 (Posen et al., 2017).

The majority of plastics are also non-biodegradable. That is, over time, plastics break down into smaller parts, for e.g., microplastics, but they never disappear completely. In fact, the Environmental Protection Agency (EPA) reported that "every bit of plastic made still exists" (Mosquera, 2019). Geyer et al. (2017) highlight the three different fates of plastics waste: recycling, combustion with energy recovery (with potential associated environmental and health impacts), and disposal (either under a managed system such as sanitary landfills or dumped in the natural environment). Out of the 35.4 million tons of plastics waste generated in the U.S. in 2017, EPA reported an 8.4 percent recycling rate, the combustion of 5.6 million tons of plastics waste (15.8 percent of total plastics waste generated), and the landfilling of 26.8 million tons plastics waste (75.7 percent of total plastics waste generated and 19.2 percent of municipal solid waste landfilled) (EPA, 2019). Globally, it was reported that in 2015, 58 percent of plastics waste was discarded or landfilled, and only 18 percent of the waste was recycled (Zheng & Suh, 2019). As a result, significant amounts of waste plastic end up in our oceans, in our water bodies, on our bare lands, and even on our plate through the fish we eat. Recently, the presence of microplastics has also been reported in the salt we consume (Iñiguez et al., 2017) and in human feces (Galloway, 2015).

Marine pollution, more specifically marine debris, has been the most recognizable environmental problem linked with the use of plastic. Every year, 8 million tons of plastic waste enter our ocean and it has been projected that the ocean will have more plastic than fish by 2050 (MacArthur, 2017). Plastic drinking straws comprise a significant portion of this plastic pollution. Due to their small size and light weight, plastic straws cannot be recycled and end up as a common component of litter and input to landfills. Using data collected during clean-ups of U.S. shorelines over five years, some Australian scientists estimate that nearly 7.5 million straws lie around U.S. shorelines and between 437 million to 8.3 billion lie on the entire world's shorelines. Given that straws weigh very little on average, straws make up only 4 percent of this plastic trash by piece and even less by weight (Borenstein, 2018). Nevertheless, their small size means that they could easily enter the ocean and be ingested by seabirds. A study by Wilcox et al. (2015) estimated that 29 percent of studied species of seabirds had plastic in their gut in 2012 and the plastic ingestion rate will reach 99 percent of all species by 2050 if current trends continue. Therefore, it is no surprise that with over 32.6 million views, a viral video of a sea turtle with a straw lodged in its nostrils spurred a mass backlash against single-use plastics and made plastic straws the face of it (Ramey & Tita, 2018).

The presence of plastic, including plastic straws, in the environment, does not merely impact our natural ecosystems. Studies also show that land-based waste and marine debris have negative impacts on tourism, public health, and the economy (Kershaw et al., 2011). Overall, plastic would cost a staggering $13 billion in economic damage to marine ecosystems each year, as per conservative estimates from UNEP (Avio et al., 2017). In one area of Los Angeles, California alone, marine debris costs an estimated $67 M per year from lost tourism revenue (Leggett et al., 2014).

2.2 Alternatives to Plastic Straws

The “war” on single-use plastic straws, reinforced with endorsements from celebrities and social media influencers (Pinnock, 2018), has created a surging demand for sustainable alternatives to plastic straws and presented a business opportunity for the non-plastic straw market. As of now, the following alternatives are known to exist on the market and can be categorized into the following types: (1) single-use straws (paper straws, bioplastic/compostable plastic straws, hay straws, seaweed-based straw, and pasta straw) and (2) reusable straws (metal straws, glass straws, bamboo straws, and silicone straws).

Each straw type comes with its respective pros and cons. When it comes to the most commonly used alternatives, the compostable plastic straw looks and feels like standard plastic, yet it does not break down any faster than regular plastic unless it is disposed of in a proper commercial composter (Mosquera, 2019). Similarly, while paper straws are technically biodegradable, they are known to become soggy, leave an aftertaste, and decompose in landfills to emit methane, a potent greenhouse gas (Ximenes, 2010). Metal straws are thought to be amongst the eco-friendliest option due to their reusable function; however, they could pose safety concerns to the community of disabled individuals who rely on plastic straws (Jenks & Obringer, 2020). In terms of cost, all aforementioned single-use alternatives come at a higher cost than plastic straws. For e.g., the cost of one paper straw is 2.5 cents compared to 0.5 cents for a plastic straw (Ell, 2018), and a metal straw costs between $10 to $20 per straw, making it an infeasible solution for restaurants (Mosquera, 2019). That said, reusable straws (such as metal straws), given their high number of uses, may be the most cost-effective option for the consumer, yet rely on the consumer’s willpower and responsibility to carry them to a food establishment and to clean them afterward. The pasta straws, hay straws, and edible seaweed straws are amongst the newest forms of drinking straws with little to no literature on their efficacy and environmental impact.

2.3 Sustainability Assessment

Life-cycle analysis (LCA) has become an increasingly popular tool for environmental sustainability assessment. LCA takes a step-by-step approach to measure the consequences of production or activity cycles from "cradle to grave" (Mulligan, 2015). This implies the assessment of the product's sustainability along its entire physical lifecycle, that is, from the raw materials extraction stage to its final disposal stage. This makes LCA a strong tool for manufacturers to alter their product design and make processes more efficient and less environmentally harmful. It also makes LCA a strong educational tool for consumers who might either be oblivious to the hidden environmental impacts of a product and/or take these impacts for granted.

A review of the literature indicates the use of LCA for comparative studies between plastic products and its non-plastic alternatives, the most common study being plastic carry bags versus paper carry bags (Muthu et al., 2009; Sevitz et al., 2003). With respect to drinking straws, a study by Boonniteewanich et al. (2014) found the carbon footprint of bioplastic straws to be higher than that of a plastic straw because of the higher amount of wastes generated during the bioplastic straw manufacturing. Another study comparing the polypropylene plastic straw to the bioplastic (PLA) straw report similar results: the PLA straw emitted significantly more CO_{2eq} emissions than the plastic straw (Moran, 2018). There also exists a life-cycle inventory put together by the European Union for plastic products and their alternatives which includes life-cycle inventories for the polypropylene plastic straw, the paper straw, the steel straw and the silicone straw, although no life-cycle impact assessment has been conducted in the study (Paspaldzhiev & Stenning, 2018). Nevertheless, there is currently no combined comparative study done between plastic straws and its nine alternatives to determine the most sustainable alternative to plastic straws.

Given that this study also attempts to assess the environmental impact of the seaweed-based drinking straw, a review of the literature was done on sustainability assessments of coastal ecosystems such as the seaweed (also referred to as macroalgae). It indicated the need to calculate the blue carbon of the seaweed-based drinking straw to determine its environmental footprint as accurately as possible. The methodology used for the calculation of the straw's blue carbon, including the literature sources used, will be explored and discussed in Chapter 4 of this study.

By way of background, blue carbon is the term for carbon captured by the world's ocean and coastal ecosystems. Coastal ecosystems such as mangroves and seagrasses can sequester up to 20 times more carbon dioxide per acre than land-based forests (Krader, 2019). While the seaweed has long been ignored as a key "blue carbon" ecosystem, many studies now provide evidence of seaweed being globally-relevant contributors to oceanic carbon sinks and thus make a strong case for their inclusion in blue carbon assessments (Duarte et al., 2017). In fact, Krause-Jensen & Duarte (2016) compile data from previous studies to roughly estimate that seaweed could sequester about 173 Tg of carbon (C) per year globally (mostly in deep sea). This is about as much as annual emissions of the state of New York. While this figure is considerably smaller for seaweed aquaculture as most of the seaweed grown is harvested, an upper limit to the CO_2 capture potential of seaweed aquaculture has been calculated at 2.48 million tons of CO_2 (0.68 Tg C) per year globally. In terms of the seaweed's CO_2 sequestration potential per km^2, this represents about 1,500 tons CO_2 km^{-2} per year, corresponding to the annual CO_2 emissions of about 300 Chinese citizens (Duarte et al., 2017).

Finally, an increasing number of consumers are now concerned with the socio-economic impacts of a product, rather than just its environmental impact. For a drinking straw, this could translate into indices related to the welfare of employees working in the straw manufacturing company and working to provide raw material inputs, as well as the product's price, amongst other socio-economic indicators. The current LCA assessment methods do not provide a means of consideration for these socio-economic aspects. Therefore, a new Sustainability Index considering all the three core aspects of sustainability – environmental (including both LCA of emissions generated and emissions sequestered such as blue carbon), economic and social dimensions - needs to be developed.

2.4 Policy Instruments and Legislative Landscape to Reduce Plastic Straws in the U.S.

When it comes to reducing waste in the environment, Schuyler et al. (2018) highlight two varieties of legislation used: (1) command and control measures (for e.g. plastic straw bans); and (2) market-based economic instruments (for e.g. plastic bag levies). When it comes to plastic pollution, the magnitude and severity of the problem combined with aggressive grassroots efforts have resulted in various initiatives and legislative actions across the globe. Bans on single-use plastic straws have been announced by governments such as Costa Rica and the European parliament, businesses such as Starbucks and American Airlines, and even Queen Elizabeth II for the Royal estates (Mosquera, 2019). A more comprehensive review of the literature is needed to identify the various public policy instruments available to reduce the consumption of plastic straws and the efficacy of each; see Chapter 5 for this review.

With respect to the legislative landscape in the U.S., it is firstly important to acknowledge that the U.S. adopts the federalism system of political governance. Under federalism, power is divided between the national (federal) government and various state governments. These powers can be exclusive and concurrent for both. Most governmental responsibilities, including environmental protection, are shared by both federal and state governments (USlegal, 2020). The merits and drawbacks of federalism, as applied to U.S. environmental policy, has been long debated in the literature and reflects the "tug-of-war" between the various authorities (Konisky & Woods, 2018). Federalism can foster inter-state competition, policy experimentation and innovation, and contextually appropriate environmental policies. However, it can also result in mixed, even contradictory, messages to policy targets if the differing policies simultaneously occur in overlapping policy jurisdictions, thus potentially jeopardizing the achievement of common policy goals (Siddiki et al., 2018).

The legislative landscape of plastic ordinances is no less complicated in the U.S. Up until the newly adopted federal bill entitled "Break Free From Plastic Pollution Act of 2020"

(H. R. 5845, 2020), U.S. cities and states were increasingly disagreeing on whether it is legal to ban plastic. While states such as California and New York, and hundreds of municipalities banned or fined the use of plastic in some way, around seventeen other states such as Iowa and Tennessee placed a ban on banning plastic items – an effort aided by the plastics industry (Gibbens, 2019).

In terms of plastic straws, Wagner & Toews (2018) report that as of September 2018, there were 31 plastic straw ordinances that had been adopted by local governments (13 in California, 7 in Florida, 3 in New Jersey, 2 each in Massachusetts and Washington, and 1 each in Minnesota, New York, Ohio, and South Carolina). Of these 31 municipal ordinances, 16 are full bans, 6 are partial bans, and 9 default choice modifications ("straw upon request"). California was the first state to enact a plastic straw law - the default choice modification ordinance. In January 2019, a ban on plastic straws in restaurants and other service businesses began in Washington, D.C. (Gibbens, 2019). There have also been numerous resolutions passed by local governments encouraging businesses to reduce the use of plastic straws. Nationally, the newly adopted federal bill entitled "Break Free From Plastic Pollution Act of 2020" uses default choice modification which allows the provision of plastic straws and/or non-plastic straw alternatives only if the customer requests for one (and depending on what the customer specifically requests for) (H. R. 5845, 2020).

2.5 Consumer Preferences for Product Sustainability

When it comes to selecting an alternative to the plastic straw, businesses and consumers are definitely spoilt for choice with the wide range of alternatives entering the market. It makes sense for environmental sustainability to be a key criterion when making that decision, given that negative environmental impact is the fundamental reason plastic straws are being targeted for elimination. A review of the literature proves just that: consumers are indeed becoming more sustainability-conscious about their lifestyles and consumption habits.

A report by The Nielsen Company (US) in 2018 indicates that 73% of global consumers say they would definitely or probably change their consumption habits to reduce their environmental impact. In fact, between 30 to 41 percent of global respondents are willing to pay higher-than-average prices for products that are organic, made with sustainable materials, and deliver on social responsibility claims. For the U.S., nearly half (48%) of consumers claim they would definitely or probably change their consumption habits to reduce their environmental impact. This number is higher for millennials (75%), with 90% of them willing to pay more for products that contain environmentally friendly or sustainable ingredients and 80% of them for products that have social responsibility claims. When it comes to actual sales numbers, the sales of products with sustainable attributes constituted 22% of total store sales in 2018 and is expected to grow to 25% by 2021. To put this in monetary terms, the sustainable fast-moving consumer goods (FMCG) products industry was at $128.5 billion in 2018 and is forecasted to increase to $150 billion in 2021 (The Nielsen Company (US), 2018).

Nevertheless, the sustainable product sales numbers still do not reflect the claim made by surveyed U.S. consumers in The Nielsen Company (US) (2018) report. One reason for this divergence could be a lack of information on sustainable products reaching consumers. Research has shown that consumers often lack the information, cognitive ability, or time required to evaluate every option to arrive at the best choice (Simon, 1955). Meanwhile, an “information overload” wherein consumers are overwhelmed with the number and complexity of options can also hinder optional decision-making (Reutskaja & Hogarth, 2009).

The quality of information required by consumers is also changing. Consumers are no longer happy with mainstream terms like “natural” or “organic” used in potential “greenwashing” marketing tactics. They want to know if a rainforest was destroyed to source the palm oil or if basic wage requirements were met when producing it or just about how much of it is actually organic or recyclable (The Nielsen Company (US), 2018). Further, consumers care about both the environmental and social impacts of a product.

In promoting consumer behavioral change, enabling access to information and pro-environmental (and pro-social) lifestyle choices might not suffice. Incentive structures that reward consumers for sustainable behaviors combined with institutional policy frameworks that favor and sustain these behaviors will be needed (Mulligan, 2015). Demands for a more sustainable lifestyle or product can be built among consumers, but this will not translate into a significant change in consumption patterns if public and private institutions are not responsive to these demands. The private sector in particular plays an imperative role due to the economic nature of their sector, which pushes for more consumption (Portney, 2015). Finally, it is suggested that the chances of boosting behavioral change in consumers are significantly higher when consumers see it as a social activity rather than an individual effort (Mulligan, 2015). The choice of policy instrument in reducing the consumption of plastic straws and its linkage to consumer choice are further explored in Chapter 5 of this study.

2.6 The Role of Economics in Determining Consumers’ Willingness-to-Pay

There is no doubt that we’re entering a new era of sustainability-driven by governments, consumers, and corporations all across the world. The claims made by surveyed U.S. consumers in The Nielsen Company (US) (2018) report prove just that. How do these numbers translate to actual consumer preferences and willingness to pay for non-plastic straws is yet to be quantitively determined. A review of the literature, including market research data cited in this paper, suggests that there are several important areas where economic research can help determine consumer preferences and willingness to pay for non-plastic straws.

The revealed preference valuation method used in economic analysis is a good start. There exists limited literature highlighting how plastic straw ordinances impact businesses and is perceived by consumers. Based on the study conducted by Wagner & Toews (2018), a majority of the 133 surveyed businesses affected by the default choice modification ordinance reported no impact on their business, some indicated a small decrease in costs, and others reported some negative feedback from customers. There were also major criticisms from disability advocates on the complete ban of plastic straws, as plastic straws are often a necessity for many people with disabilities and non-plastic alternatives do not work for them (Wong, 2019).

The market is also starting to see a fashion opportunity for luxury plastic alternatives, including alternatives to plastic straws. With celebrities and social media influencers flaunting their non-plastic straws and plastic alternatives firms committing part of their revenues to ocean conservation efforts, more consumers are willing to pay more for stylish designs of reusable plastic alternatives as a new status symbol, which has made environmental consciousness into a fashionable and desirable trait (Pinnock, 2018).

There also exists some literature on the use of contingent valuation and conjoint analysis to quantify consumer preferences and willingness to pay for various forms of alternatives to plastic. This method has potential value for studying consumer preferences regarding non-plastic straws. This will be further explored in Chapter 5, section 3.

2.7 Conclusion

The destructive impacts that plastic pollution, including from single-use plastic straws, have had on the environment, especially on our ocean, cannot be contested. In fact, its negative impacts on tourism, public health, and the economy has also been reported in literature and continues to be studied. While several alternatives to plastic straws are now entering the market, the high cost and environmental sustainability of these alternatives remain disputed. More specifically, it is proving difficult for sustainability-conscious consumers and businesses to pick the most sustainable non-plastic straw option. While a small number of studies have individually compared the carbon footprint of the paper straw and/or the bioplastic (PLA) straw to the single-use plastic straw, there is not a single study which compares all the ten drinking straw types identified in this study. LCA has been identified as a good tool to assesses the straws' carbon footprints and make such comparisons. Additionally, the estimation of blue carbon has been deemed relevant when assessing the environmental sustainability of the seaweed-based straw.

This literature review also highlights another concern: are the policies which are being considered and/or implemented to reduce the use of plastic straws truly effective? While some studies have proved bans and default choice modifications to be effective policy instruments in terms of reducing the use of plastic straws, there are gaps in terms of considering a larger range of available policy instrument options. Most importantly, there are gaps in assessing these policy instruments against consumer preferences, their willingness-to-pay for the non-plastic alternatives, and the use of scientific data (such as LCAs) when designing such policies.

3 Life-Cycle Assessment of Drinking Straws

3.1 Methods

3.1.1 Goal of the LCA

The overall goal of this LCA is to quantify and compare the environmental profile of the standard single-use plastic straw versus its most commonly used alternatives (as listed in Table 3.1 below), in order to determine the eco-friendliest drinking straw amongst them.

Straw Use Type	Straw Material Type
Single-use	1. Standard (single-use) plastic straw
	2. Paper straw
	3. Biodegradable / compostable plastic straw
Reusable	4. Metal straw

Table 3.1. List of drinking straws being considered in this LCA study

Additionally, the LCA has the following **sub-goals**:

a) Single-use straw comparison: To compare the aforementioned three single-use straw types and determine which one has the least environmental impact.
b) Single-use v/s reusable straw comparison: To determine the environmental impact of choosing a reusable straw (in this case, the metal straw) over a single-use straw.
c) Life cycle stage comparison: To determine which stage of the life cycle of each straw has the most environmental impact and whether consumer/human behavior is a determinant.

3.1.2 Scope of the LCA

3.1.2.1 Functional Unit

Given that the functional unit is a measure of the "service" provided by the products, the aim is to determine equivalence between the various product choices. Therefore, in this case, the functional unit is based on the number of (single-use) straws that an average person in the U.S. uses over a period of one year.

It is estimated that Americans use 500 million drinking straws every day (U.S. National Park Service , 2019). This most commonly cited figure equates to about 1.6 per person each day (Wagner & Toews, 2018), or 584 (1.6 uses x 365 days) straws per person per year.

Therefore, given the assumptions listed below, the functional unit is defined as 584 single-use straws being equivalent to one reusable straw per person per year.

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3.1.2.2 System Boundaries

For the single-use straw types, the following life cycle stages have been included:

- Production of straw materials
- Production of packaging materials
- Manufacture of straws (including packaging)
- Transport related to the distribution of straws
- Disposal of used straws and associated packaging

For the reusable straw types, the following life cycle stages have been included:

- Production of straw materials
- Production of packaging materials
- Manufacture of straws (including packaging)
- Transport related to the distribution of straws
- Use and maintenance of straws

3.1.2.3 Study Assumptions and Limitations

The following assumptions are being made for this project and make this a limited LCA study:

- The study measures the environmental impact of the drinking straws with respect to their energy demand and global warming potential only; impacts such as ecosystem damage, terrestrial and marine ecotoxicity, and human health are not included.
- The use of 500 million drinking straws a day in the U.S. applies to single-use straws only.
- Only primary materials and processes used to manufacture the drinking straws are taken into consideration in this study. Secondary materials such as additives and colorants, and secondary processes such as cutting and packaging (except for materials used) are considered negligible.
- The electricity used for the straw manufacturing process (for all straws) as well as for the washing of the reusable metal straw (using hot water) is assumed to be the average electricity production mix for the U.S.
- For the purposes of this comparison, it is assumed that the drinking straws (and their materials) are sourced, produced and distributed in the U.S. Only transport related to the distribution of the final product is included in this study. It is assumed that each straw type is transported from its respective largest distributor to Plato, Missouri which is the center of the population for the U.S. (U.S. Census Bureau, 2010). All other transport (for e.g. sourcing of raw materials) is considered negligible.
- Foodservice places are the primary customers of drinking straws, all of which are single-use straws and ordered in bulk (for e.g. a case of 10,000 straws).
- The associated packaging for single-use straws is primarily corrugated cardboard. Given that the specifications of the selected single-use straw types (7 ¾” length and

5mm diameter) are the same, their volumes are equal. It is therefore assumed that an equal number of straws can fit one packaging case made of corrugated cardboard.

- Given the above, a standard weight of 1.2 kg corrugated cardboard per 10,000 straws is applied for all the single-use straws to enable a fair life-cycle assessment comparison between the different straw types. This weight was received by a paper straw manufacturer contacted in this study (OKSTRAW Paper Straws) and thus deemed near accurate. For the functional unit equivalence, this amounts to [(1,200 g / 10,000 straws) x 584 straws) = 70.08 g.
- A landfill disposal scenario after use is applied for all the three single-use straw types. While the recycling of the cardboard packaging is a more feasible option, especially in foodservice places with a recycling program in place, the study assumes a landfill scenario as the focus of this study is on the comparison of the environmental impact of the straw types instead of their packaging.
- A reusable metal straw can last at least one year in use (with regular cleaning) and replaces every use of the standard plastic straw a person would otherwise make. Therefore, each metal straw can be used 584 times a year and replaces 584 single-use straws per year.
- A metal straw is washed using a metal straw cleaning brush after every use (except for the dishwasher scenario whereby it is assumed that the dishwasher machine is used only once a day for the sake of efficiency, i.e. a total number of 365 washes is made per year).

3.1.3 Life Cycle Inventory

3.1.3.1 Data Requirements

For the purposes of this study, the best way to collect inventory data on materials used in the manufacturing and packaging of the straws was to directly contact relevant straw manufacturers in the U.S. For each straw type, two different manufacturers were contacted to avoid bias and have as a back-up option. These manufacturers were identified using a simple Google search and selected using the following criteria: (a) they are U.S. based, preferably with all raw materials sourcing and straw production done in the U.S.; (b) they specialize in the manufacturing of that straw type; and (c) their website provides ample information about their company and products (indirectly implying their openness to share data for this study). Where no replies were received from either manufacturer of a straw type, inventory data was sourced from readily available data: online marketplaces providing relevant information on the straw type and peer-reviewed journal articles.

The datasheet shared with the straw manufacturers to gather the straw's data is attached in Appendix A.1 of this report. The responses received from the straw manufacturers is documented in Appendix A.2.

3.1.3.2 Input Data for the Standard (Single-Use) Plastic Straw

The plastic straw manufacturers that were contacted are: (a) Absolute Custom Extrusions, Inc. (ACE, 2019), and (b) Paragon Supply Company, Inc (Paragon Supply, 2019). As replies were not received from either of the manufacturers, the life cycle inventory of the standard plastic straw had to be constructed using the following information and assumptions:

a) Straw specification:

A standard 7 ¾”, clear, unwrapped, plastic straw is selected for this study.

b) Straw manufacturing materials:

- Most plastic straws are made out of type 5 plastic known as polypropylene (Mosquera, 2019).
- Therefore, the quantity of polypropylene added per straw is assumed to be the weight of the straw, i.e. 0.42 g (Borenstein S. , 2018).
- Calculating quantity of polypropylene for the functional unit:
= (0.42 g polypropylene / straw) * (584 single-use straw/person/year)
= 245.28 g

c) Straw manufacturing process:

Polypropylene (plastic) straws are extruded by an industrial straw extruder (Boonniteewanicha et al., 2014).

d) Straw packaging:

Given the assumptions above, the amount of corrugated cardboard used is 70.08 g.

e) Straw distribution (transport):

The leading U.S. manufacturer of plastic straws is the Hoffmaster Group, based in Oshkosh, Wisconsin (Bowman, 2018).
Distance between Oshkosh, WI and Plato, MO = 957.56 km
Therefore, transport associated with straw distribution for the functional unit
= (weight of straw + packaging) * distance covered
= (0.24528 kg + 0.07008 kg) * 957.56 km
= 301.98 kgkm

f) Straw disposal:

The study assumes a landfill scenario for the disposal of used plastic straws and its associated packaging. Literature has constantly reported that even if plastic straws are made of a material (polypropylene) which is recyclable, recycling facilities do not accept plastic straws because they are too small, lightweight, flexible and can damage the recycling machinery. As a result, most plastic straws end up as regular waste (Mosquera, 2019).

The life cycle inventory of the standard (single-use) plastic straw is summarized in Table 3.2 below.

Life Cycle Stage	Inputs (Functional Unit Equivalence)		
	Materials	**Unit**	**Process**
Straw manufacturing	Polypropylene, granulate, at plant/US- US-EI U	245.28 g	Extrusion, plastic pipes/US- US-EI U
Straw packaging	Corrugated board, recycling fibre, double wall, at plant/US- US-EI U	70.08 g	N/A
Straw distribution (transport)	N/A	301.98 kgkm	Transport, combination truck, average fuel mix NREL/US U
Disposal after use	Disposal, polypropylene, 15.9% water, to sanitary landfill/US* US-EI U	77.8%	N/A
	Disposal, packaging cardboard, 19.6% water, to inert material landfill/US* US-EI U	22.2%	N/A

Table 3.2. Life cycle inventory of the standard (single-use) plastic straw (functional unit equivalence)

3.1.3.3 Input Data for Paper Straw

The paper straw manufacturers that were contacted are: (a) OKSTRAW Paper Straws (OKSTRAW Paper Straws, 2019); and (b) Aardvark Straws (Aardvark Straws, 2019). Data was received from OKSTRAW Paper Straws and is used in this study. The following information and assumptions were used to construct the life cycle inventory of the paper straw:

a) Straw specification:

A standard 7 ¾", 4-ply, clear, unwrapped, paper straw from OKSTRAW Paper Straws is selected for this study.

b) Straw manufacturing materials:

The manufacturer reported the use of 1.2 g food grade white kraft paper per straw as the primary material.

Calculating quantity of paper for the functional unit:
= (1.2 g kraft paper / straw) * (584 single-use straw/person/year)
= 700.8 g

c) Straw manufacturing process:

The manufacturer reported the following processes in the manufacturer of their paper straws: printing, slitting, straws making, drying and packaging. However, given the unavailability of most of these eco-profiles for paper production in the SimaPro8.5 database and for the sake of this simplified study, "Production of carton board boxes, gravure printing, at plant/US* US-EI U" is assumed to the closest eco-profile for the manufacture of paper straw (given, also, that the paper straw selected here is a 4-ply straw, i.e. it has a consistency close enough to a carbon board box).

d) Straw packaging:

Given the assumptions above, the amount of corrugated cardboard used is 70.08 g.

e) Straw distribution (transport):

The leading U.S. manufacturer of paper straws is Aardvark Straws, based in Fort Wayne, Indiana (Bowman, 2018).
Distance between Fort Wayne, IN and Plato, MO = 861 km
Therefore, transport associated with straw distribution for the functional unit
= (weight of straw + packaging) * distance covered
= (0.7008 kg + 0.07008 kg) * 861 km
= 663.73 kgkm

f) Straw disposal:

The study assumes a landfill scenario for the disposal of used paper straws and its associated packaging. A study reports that most paper straws are chemically treated to make them stronger, and therefore, cannot be recycled (Mosquera, 2019). As a result, most paper straws end up as regular waste.

The life cycle inventory of the paper straw is summarized in Table 3.3 below.

Life Cycle Stage	Inputs (Functional Unit Equivalence)		
	Materials	Unit	Process
Straw manufacturing	Kraft paper, unbleached, at plant/US- US-EI U	700.8 g	Production of carton board boxes, gravure printing, at plant/US* US-EI U
Straw packaging	Corrugated board, recycling fibre, double wall, at plant/US- US-EI U	70.08 g	N/A
Straw distribution (transport)	N/A	663.73 kgkm	Transport, combination truck, average fuel mix NREL/US U
Disposal after use	Disposal, paper, 11.2% water, to sanitary landfill/US* US-EI U	90.9%	N/A
	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/US* US-EI U	9.1%	N/A

Table 3.3. Life cycle inventory of the paper straw (functional unit equivalence)

3.1.3.4 Input Data for Bioplastic / Compostable Plastic Straw

The bioplastic / compostable plastic straw manufacturers that were contacted are: (a) Eco-Products, Inc. (Eco-Products, 2019); and (b) World Centric (World Centric, 2019). Data was received from Eco-Products and is used in this study. The following information and assumptions were used to construct the life cycle inventory of the compostable plastic straw:

a) Straw specification:

A standard 7 ¾”, clear, unwrapped, compostable straw from Eco-Products, Inc. is selected for this study.

b) Straw manufacturing materials:

The manufacturer reported the use of 0.9 g polylactide (PLA) per straw as the primary material.

Calculating quantity of PLA for the functional unit:
= (0.9 g PLA / straw) * (584 single-use straw/person/year)
= 525.6 g

c) Straw manufacturing process:

The manufacturer reported extrusion has the main process in the manufacture of the compostable straws. However, as literature reports the use of a twin-screw extruder in the production of compostable straws (a process known as compounding) before the actual extrusion process (Boonniteewanicha et al., 2014), the study assumes the process of extrusion to happen twice.

d) Straw packaging:

Given the assumptions above, the amount of corrugated cardboard used is 70.08 g.

g) Straw distribution (transport):

The leading U.S. manufacturer of plastic straws is Eco-Products, Inc., based in Boulder, Colorado (Eco-Products, 2019).
Distance between Boulder, CO and Plato, MO = 1,327.71 km
Therefore, transport associated with straw distribution for the functional unit
= (weight of straw + packaging) * distance covered
= (0.52560 kg + 0.07008 kg) * 1,327.71 km
= 790.89 kgkm

e) Straw disposal:

The study assumes a landfill scenario for the disposal of used compostable straws and its associated packaging. Literature has constantly reported compostable plastic will not break down any faster than regular plastic unless it is disposed of in a proper commercial composter. There are only over 100 qualified composting centers that can process this type of plastic in the U.S. As a result, most compostable straws end up as regular waste. Since SimpaPro8.5 does not have an eco-profile for the disposal of PLA to landfill, the used compostable straws are treated as regular (mixed) plastic with respect to their biodegradability in this study.

The life cycle inventory of the bioplastic/compostable plastic straw is summarized in Table 3.4 below.

Life Cycle Stage	Inputs (Functional Unit Equivalence)		
	Materials	Unit	Process
Straw manufacturing	Polylactide, granulate, at plant/GLO US-EI U	525.60 g	Extrusion, plastic pipes/US- US-EI U (x 2)
Straw packaging	Corrugated board, recycling fibre, double wall, at plant/US-US-EI U	70.08 g	N/A
Straw distribution (transport)	N/A	790.89 kgkm	Transport, combination truck, average fuel mix NREL/US U
Disposal after use	Disposal, plastics, mixture, to US sanitary landfill/US US-EI U	88.2%	N/A
	Disposal, packaging cardboard, 19.6% water, to inert material landfill/US* US-EI U	11.8%	N/A

Table 3.4. Life cycle inventory of the bioplastic / compostable plastic straw (functional unit equivalence)

3.1.3.5 Input Data for (Reusable) Metal Straw

The reusable metal straw manufacturers that were contacted are: (a) Simply Straws (Simply Straws, 2019); and (b) Mulled Mind (Mulled Mind, 2019). As replies were not received from either of the manufacturers, the life cycle inventory of the metal straw had to be constructed using the following information and assumptions:

a) Straw specification:

An 8.5”, stainless steel (silver) straw which comes with a metal cleaning brush and a cloth storage pouch is selected for this study.

b) Straw manufacturing materials:

Most metal straws are made of the 18/10 food-grade stainless steel (as found on the websites of many metal straw manufacturers and retailers). The quantity of stainless steel per straw is assumed to be the weight of the straw. Using a weighing scale, the weight of the straw = 11.0 g.

c) Straw manufacturing process:

Based on the selected manufacturers' websites, it is assumed that the only process involved in the manufacturing of a metal straw is cutting of the straws to the desired length as most metal straws are made from metal pipes of size similar to the desired metal straw. Yet, the process of making metal pipes is factored in this study as the eco-profile "Drawing of pipes, steel/US- US-EI U" being the closest to it. For the sake of this study, the energy usage and global warming potential of the cutting process is considered negligible.

d) Straw packaging:

Most metal straws come with a cleaning brush and a textile storage pouch. This is assumed to be the straw packaging. A standard metal straw cleaning brush is made of stainless steel and nylon bristles. For the sake of this study, the weight of the nylon bristles is considered negligible and found to be 2.96 g using a weighing scale. Burlap (jute) is assumed to be the primary material used in the manufacture of a standard textile reusable straw storage pouch.

Calculating the average weight of a textile straw storage pouch:
Given dimensions of a cloth straw storage pouch to be 25cm x 9cm (Strawtopia, 2018);
Assuming storage pouch to be made of burlap weighing 18 lb for a roll of 12" x 100 yard (Uline, 2019);
43,200 inches^2 (or 278,709.12 cm^2) weighs 18 lb (or 8,164.66 g)
Therefore, (25 cm x 9 cm) weights (8,164.66 g / 278,709.12 cm^2) x 225 cm^2 = 6.59 g
An average textile straw storage pouch = 6.59 g

e) Straw distribution (transport):

The leading U.S. manufacturer of metal straws is Steelys Straws based in San Francisco, California (Eco Imprints Inc., 2019).
Distance between San Francisco, CA and Plato, MO = 3,196.157 km
Therefore, transport associated with straw distribution for the functional unit
= (weight of straw + packaging) * distance covered
= (0.011 kg + 0.00659 kg + 0.00296) * 3,196.157 km
= 65.68 kgkm

f) Straw use/maintenance:

It is assumed that an average person will use hot water to wash dishes, including a metal straw, and hand washing dishes uses more hot water than dishwashers (Ji et al., 2017). Using the instructional video from Strawtopia (a manufacturer of metal straws) on how to clean a metal straw, the study assumes that an average metal straw wash lasts around 20 seconds (Strawtopia, 2014).

Calculating the amount of water used per metal straw wash:
Studies show that on average people open the faucet to a flow rate between 1.0 GPM and 1.5 GPM (Jan, 2018). The study assumes an average faucet flow rate of 1.25 gallons per minute (or 4.73 L per minute). Therefore, the average amount of hot water used per wash is (4.73 L / 60 s) x 20 s = 1.58 L / wash.

For the functional unit, this equates to (1.58 L / wash) x 584 washes = 920.77 L.

Given that a single study source is not a sufficient basis for the water used per metal straw and that the study also examines the influence of human behavior on environmental impact, the study employs multiple scenarios whereby cold water is used instead of hot water, the washing time is cut to half (for e.g. by closing tap when rubbing the brush inside the straw before rinsing), and washing it in a dishwashing machine instead.

The life cycle inventory of the (reusable) metal straw is summarized in Table 3.5 below.

Life Cycle Stage	**Inputs (Functional Unit Equivalence)**		
	Materials	**Unit**	**Process**
Straw manufacturing	Steel, stainless 304, flat rolled coil/kg/RNA	11.0 g	Drawing of pipes, steel/US- US-EI U
Straw packaging	Textile, jute {GLO}| market for | APOS, S	6.59 g	N/A
	Steel, stainless 304, flat rolled coil/kg/RNA	2.96 g	N/A
Straw distribution (transport)	N/A	65.68 kgkm	Transport, combination truck, average fuel mix NREL/US U
Straw use / maintenance			
Scenario 1: hot water wash @ standard wash time	Washing, hot water, 48 C/US	920.77 L	N/A
Scenario 2: cold water wash @ standard wash time	Washing, cold water/US	920.77 L	N/A
Scenario 3: hot water wash @ half wash time	Washing, hot water, 48 C/US	460.40 L	N/A
Scenario 4: cold water wash @ half wash time	Washing, cold water/US	460.40 L	N/A
Scenario 5: use of a dishwasher	Dishwashing, automatic, utensil/US	365 units	N/A

Table 3.5. Life cycle inventory of the (reusable) metal straw (functional unit equivalence)

3.1.4 Life Cycle Impact Assessment

Using the SimaPro8.5 LCA software, an impact assessment was performed for the categories of global warming potential (GWP) (IPCC 2007 GWP 100a v1.03) and cumulative energy demand (CED) (Cumulative Energy Demand v1.08). These two methods were chosen because the carbon footprint of a product is often a key measure of its environmental performance and, thus, commonly used when comparing similar products. In addition, these methods allow for the comparable measurements of materials used versus processes used to manufacture the product, thus enabling insights on which aspect of the product design has a higher footprint, needs a better material, and/or needs to become more efficient. By way of background, IPCC 2013 GWP 100a V1.03 method inventories the total equivalent greenhouse gas emission in kilograms (kg CO_2 equivalent) and specifically uses a 100-year global warming potential definition. Meanwhile, the Cumulative Energy Demand method compares energy consumption in Mega joules (MJ). These two comparable methods are linked in that an excess dependency of energy for production increases the model's overall greenhouse gas emissions, while separate modeling provides definitive quantities for both values.

For each of the single-use straws, a single LCA model was created using the LCA inventory data and all assumptions listed in this report. However, four LCA models were created for the reusable metal straw to cater for the influence of human behavior on the use of these straws: (1) hot water washing at standard washing time; (2) cold water washing at standard washing time; (3) hot water washing at half of the standard washing time; (4) cold water washing at half of the standard washing time; and (5) dishwater washing.

3.2 Results, Interpretation and Discussion

3.2.1 Results of the Life Cycle Impact Assessment

The network models for the Cumulative Energy Demand and the IPCC 2013 GWP 100a V1.03 method assessment, for all four straw types, are documented in Appendix B.1 and Appendix B.2, respectively. The major contributing materials and processes to the energy demand and greenhouse gas emissions for each straw type is summarized (in order of magnitude) in Tables 3.6, 3.7, 3.8 and 3.9 below.

Standard (Single-Use) Plastic Straw		
Material or Process	**Energy Demand**	
	MJ	**% of total**
Polypropylene (base material of the straw)	18.4	82.0
Extrusion (primary process used to manufacture the straw)	2.07	9.21
Corrugated cardboard (key packaging material)	1.49	6.64
Transport related to distribution of straws	0.386	1.72
Disposal to landfill (used straws and associated packaging)	0.116	0.516
Total	***22.5***	***100***

Standard (Single-Use) Plastic Straw		
Material or Process	**GWP**	
	kg CO_2 eq	**% of total**
Polypropylene (base material of the straw)	0.5	58.4
Extrusion (primary process used to manufacture the straw)	0.114	13.3
Disposal of packaging (corrugated carboard) to landfill	0.107	12.4
Corrugated cardboard (key packaging material)	0.0798	9.31
Transport related to distribution of straws	0.0289	3.37
Disposal of used straws to landfill	0.0278	3.24
Total	***0.857***	***100***

Table 3.6.a. Major contributing materials for the energy demand of the standard plastic straw (functional unit equivalence); and
Table 3.6.b. Major contributing materials for the GWP of the standard plastic straw (functional unit equivalence)

Paper Straw		
Material or Process	**Energy Demand**	
	MJ	**% of total**
Kraft paper (base material of the straw)	43.9	78.5
Production process of the straw	9.3	16.6
Corrugated cardboard (key packaging material)	1.49	2.67
Transport related to distribution of straws	0.849	1.52
Disposal to landfill (used straws and associated packaging)	0.398	0.712
Total	***55.9***	***100***

Paper Straw		
Material or Process	**GWP**	
	kg CO_2 eq	**% of total**
Kraft paper (base material of the straw)	0.842	35.1
Disposal of used straws to landfill	0.834	34.7
Production process of the straw	0.474	19.8
Disposal of packaging (corrugated carboard) to landfill	0.107	4.45
Corrugated cardboard (key packaging material)	0.0798	3.33
Transport related to distribution of straws	0.0635	2.65
Total	***2.4***	***100***

Table 3.7.a. Major contributing materials for the energy demand of the paper straw (functional unit equivalence); and
Table 3.7.b. Major contributing materials for the GWP of the paper straw (functional unit equivalence)

Bioplastic / Compostable Plastic Straw		
Material or Process	**Energy Demand**	
	MJ	**% of total**
Polylactide (base material of the straw)	41.6	78.3
Extrusion (primary process used to manufacture the straw)	8.88	16.7
Corrugated cardboard (key packaging material)	1.49	2.81
Transport related to distribution of straws	1.01	1.9
Disposal to landfill (used straws and associated packaging)	0.141	0.265
Total	***53.2***	***100***

Bioplastic / Compostable Plastic Straw		
Material or Process	**GWP**	
	kg CO_2 eq	**% of total**
Polylactide (base material of the straw)	1.96	73.4
Extrusion (primary process used to manufacture the straw)	0.489	18.3
Corrugated cardboard (key packaging material)	0.0798	2.99
Transport related to distribution of straws	0.0757	2.84
Disposal to landfill (used straws and associated packaging)	0.0648	2.43
Total	***2.67***	***100***

Table 3.8.a. Major contributing materials for the energy demand of the bioplastic/compostable plastic straw (functional unit equivalence); and
Table 3.8.b. Major contributing materials for the GWP of the bioplastic/compostable plastic straw (functional unit equivalence)

(Reusable) Metal Straw *Scenario 1: Hot water washing at standard washing time*				
Material or Process	**Energy Demand**		**GWP**	
	MJ	**% of total**	**kg CO_2 eq**	**% of total**
Washing of straw after use	551	99.7	35.85	99.8
Metal straw manufacturing (including packaging)	1.52	0.275	0.0447	0.124
Transport related to distribution of straw	0.0863	0.0156	0.00646	0.018
Total	***553***	***100***	***35.9***	***100***

(Reusable) Metal Straw *Scenario 2: Cold water washing at standard washing time*				
Material or Process	**Energy Demand**		**GWP**	
	MJ	**% of total**	**kg CO_2 eq**	**% of total**
Washing of straw after use	20.5	92.7	1.17	95.8
Metal straw manufacturing (including packaging)	1.52	6.86	0.0447	3.66
Transport related to distribution of straw	0.0863	0.38	0.00646	0.515
Total	***22.1***	***100***	***1.22***	***100***

(Reusable) Metal Straw *Scenario 3: Hot water washing at half of standard washing time*				
Material or Process	**Energy Demand**		**GWP**	
	MJ	**% of total**	**kg CO_2 eq**	**% of total**
Washing of straw after use	275	99.4	17.9	99.7
Metal straw manufacturing (including packaging)	1.52	0.548	0.0447	0.248
Transport related to distribution of straw	0.0863	0.0307	0.00646	0.0354
Total	***277***	***100***	***18***	***100***

(Reusable) Metal Straw *Scenario 4: Cold water washing at half of standard washing time*				
Material or Process	**Energy Demand**		**GWP**	
	MJ	**% of total**	**kg CO_2 eq**	**% of total**
Washing of straw after use	10.3	86.5	0.585	92.0
Metal straw manufacturing (including packaging)	1.52	12.8	0.0447	7.03
Transport related to distribution of straw	0.0863	0.708	0.00646	0.989
Total	***11.9***	***100***	***0.636***	***100***

(Reusable) Metal Straw *Scenario 5: Use of a dishwasher*				
Material or Process	**Energy Demand**		**GWP**	
	MJ	**% of total**	**kg CO_2 eq**	**% of total**
Washing of straw after use	17.1	91.4	0.984	95.1
Metal straw manufacturing (including packaging)	1.52	8.1	0.0447	4.31
Transport related to distribution of straw	0.0863	0.448	0.00646	0.607
Total	***18.7***	***100***	***1.04***	***100***

Table 3.9. Major contributing processes for the energy demand and GWP of the reusable metal straw (functional unit equivalence) for (a) scenario 1; (b) scenario 2; (c) scenario 3; (d) scenario 4; and (e) scenario 5

A comparative summary of the total energy demand and GWP of all the straws for all metal straw washing scenarios is provided in Table 3.10.

Straw Type	Energy Demand MJ	GWP kg CO_2 eq
(Reusable) Metal Straw		
Scenario 1: hot water wash @ standard wash time	553	35.9
Scenario 2: cold water wash @ standard wash time	22.1	1.22
Scenario 3: hot water wash @ half wash time	277	18
Scenario 4: cold water wash @ half wash time	11.9	0.636
Scenario 5: use of a dishwasher	18.7	1.04
Standard (single-use) Plastic Straw	22.5	0.857
Bioplastic/Compostable Plastic Straw	53.2	2.67
Paper Straw	55.9	2.4

Table 3.10. Comparative summary of the total energy demand and GWP of all straws for all scenarios (functional unit equivalence)

3.2.2 Interpretations and Discussions of Results

The results from the life cycle impact assessment conducted for the selected four straw types demonstrate several significant findings. First, when comparing all four straws, the (reusable) metal straw has the least environmental impact in terms of both energy demand and global warming potential, provided that the metal straw is washed using cold water at half of the standard washing time. This could mean closing the tap when rubbing the brush inside the straw before rinsing.

When comparing only the three single-use straws, the standard plastic straw has the least environmental impact in terms of both energy demand and global warming potential. In fact, the energy demand of a standard plastic straw is less than half of that of a paper straw and a bioplastic/compostable plastic straw. In terms of global warming potential, the standard plastic straw is nearly one-third of that of a paper straw and a bioplastic/compostable plastic straw.

The result that plastic straws fare significantly better than paper straws and bioplastic/compostable plastic in terms of their energy demand and global warming potential can come as a surprising result to many, especially to an average consumer. This is contrary to popular belief of what we know about the environmental impact of plastic. On one hand, plastics are known to have significant negative impacts on the environment, especially when it comes to marine pollution. On the other hand, both paper and bioplastics appear to be environmentally-friendly materials to their plastic counterparts when their origin and biodegradability are compared. Nevertheless, when doing comparative life-cycle assessment studies between plastic products and their paper and/or compostable plastic counterparts, most of the literature has proved plastic products to be better. Examples of these include comparative studies between plastic bags and paper bags by Muthu et. al (2009) and between bioplastic straws and the standard petroleum-based plastic straws by Boonniteewanicha et al. (2014). Reasons for this could include the higher number of wastes generated in the manufacture of bioplastic straws (Boonniteewanicha et al., 2014), the lower weight of a plastic straw (0.42 g) versus 0.9 g and 1.2 g for bioplastic straws and paper straws, respectively, and the high efficiency of plastic production (which plastic producers have worked to improve over time).

The use/maintenance stage of a metal straw's life-cycle contributes to over 85% of the environmental impact for the functional unit equivalence used in this study. This means that the way in which a reusable metal straw is washed could greatly impact its energy demand and global warming potential, with the potential to outweigh any environmental benefit of using one instead of a single-use plastic, paper, or bioplastic straw. Using hot water to wash the metal straw consumes nearly 25 times more energy and has a global warming potential 41 times higher than using plastic straws over one year. Cutting down the washing time to half still produces a significantly higher impact, while using cold water instead of hot water cuts down the energy demand and global warming potential by over 25 times. The use of a dishwasher further cuts down the energy demand and global warming potential. However, based on the five scenarios, a reusable metal straw is seen to have an overall lower environmental impact than the other single-use straws when cold water is used instead of hot water and the washing time is cut to half.

It is important to acknowledge the choice of the electricity production mix and the role which it plays in determining the (reusable) metal straw's life-cycle for the scenarios that use hot water and/or the dishwasher. This study assumed a default average electricity production mix for the U.S. which is largely fossil-fuel based in the SimaPro8.5 database. Changing the electricity mix to other fuel sources such as natural gas or renewable energy (for e.g. using solar water heater) would yield different results and could significantly reduce the carbon footprint (global warming potential) of the reusable straw. Similarly, a variation of electricity production mix in the straw manufacturing process (for all straws) could also yield different results and would be worth considering as alternate scenarios in a future work of this study.

For all three single-use straws, the biggest energy demand and global warming potential comes from the base/primary material used in the straw. This implies that if straw manufacturers wish to reduce their product's environmental impact, the choice of base/primary material will be the key factor.

The disposal life-cycle stage had more impact on the product's global warming potential than its energy demand. The disposal of the used plastic straws and used bioplastic straws to the landfill had minimal impact (less than 3.5%) on the overall global warming potential of the products. This number was higher for the paper straws. Nearly 35% of the paper straws' global warming potential came from its disposal to landfill after use. The fact that paper straws cannot be recycled does not help. The feasibility of composting the used paper straws could be looked into to mitigate this impact.

Similarly, when it came to the disposal of associated packaging (made of corrugated cardboard), this life-cycle stage contributed to 12% of the global warming potential of a plastic straw. This could be mitigated by ensuring all food service places have a recycling program in place to recycle all packaging that comes with the straws. However, it does prove that paper, as a whole, has a significant global warming potential when disposed of to landfill, considerably higher than plastic.

4 Environmental Sustainability Assessment of the Seaweed-Based Drinking Straw

4.1 Methods

This chapter assesses the environmental sustainability of the seaweed-based drinking straw. For the purposes of this study (and in order to keep the comparison consistent with other drinking straw types assessed in this study), a U.S. based straw manufacturer was identified and contacted to collect the relevant data needed to conduct an environmental sustainability assessment of the seaweed-based straw. LOLIWARE Inc. was identified to be the sole producer of seaweed-based straws in the U.S. (LOLIWARE, 2020). Given that the straw is still in its pilot phase of production, this study chose to not include this straw in the limited LCA conducted for other straws in Chapter 3. Instead, the blue carbon assessment method was chosen as a preliminary form of environmental sustainability assessment. As discussed in Chapter 2, section 3 of this study, the seaweed (whether naturally grown or cultivated) captures carbon through photosynthesis and is thus considered a "blue carbon" ecosystem.

The seaweed that is used as raw material in the manufacture of the seaweed-based straw is derived from cultivated (farmed) seaweed crops. As such, this study uses the methodology from Sondak et al. (2017) of calculating the carbon dioxide mitigation potential of seaweed aquaculture beds. This methodology has also been used in studies like Duarte et al. (2017) and Froehlich et al. (2019) to assess the potential of seaweed farming in mitigating climate change. Using this methodology, this study first calculates the blue carbon of the seaweed-based straw, followed by the amount of CO_2 sequestered per straw. To recall, blue carbon refers to the amount of carbon assimilated by the seaweed biomass during photosynthesis.

For the purposes of this study, the following assumptions are made:

- Approximately 176 kg of CO_2 is emitted per metric ton of seaweed harvested (dry weight) during the seaweed production (including transportation and maintenance) due to the consumption of fuel and electricity (Alvarado-Morales et al., 2013).
- The seaweed is harvested at the canopy, thereby not disturbing the seabed and carbon sediment deposits.
- The seaweed (including the carbon captured and stored in it) is harvested before the biomass decays. This ensures that the carbon is not redeposited in the water.
- The seaweed harvested gives a 100 percent yield.
- The carbon content in harvested seaweed dry weight is assumed to be an average of 30 percent. By way of background, the percentage carbon content in harvested seaweed dry weight varies among and within species. The average range of carbon content is between 20 to 40 percent in various literature (Sondak et al., 2017).
- The carbon content in the harvested seaweed dry weight is maintained throughout the life cycle of the straw, including during the manufacturing process and the final disposal of the straw (assuming that the straw is composted after use).
- The seaweed-based straw is a single-use straw.

The blue carbon and CO_2 sequestered per straw is calculated as shown in Table 4.1.

Description	Value	Unit	Note(s)	Source(s)
Mean carbon content of seaweed (dry weight)	30	percent	-	(Sondak et al., 2017)
Seaweed input (dry weight)	1.5	g per straw	-	LOLIWARE Inc.
Blue carbon	0.45	g C per straw	= seaweed input (dry weight) x mean carbon content of seaweed (dry weight) = 1.5 x (30/100)	
Conversion of blue carbon to CO_2 of 1 g of dry matter seaweed	11/3	conversion factor	-	(Sondak et al., 2017)
CO_2 sequestered	0.00165	kg CO_2 per straw	= (blue carbon x conversion factor) / 1000 = (0.45 x (11/3)) / 1000	(Sondak et al., 2017)
CO_2 emitted during seaweed production (seaweed farming)	176	kg CO_2 per ton seaweed (dry weight)	-	(Alvarado-Morales et al., 2013)
Conversion of CO_2 emitted during seaweed production from kg CO_2 per ton dry weight to kg CO_2 per straw	0.000264	kg CO_2 per straw	= (CO_2 emitted per ton seaweed) x seaweed input) / (1000 x 1000) = (176 x 1.5) / (1000 x 1000)	(Alvarado-Morales et al., 2013)
Net CO_2 sequestered	0.00139	kg CO_2 per straw		(Alvarado-Morales et al., 2013)

Table 4.1. Blue carbon and CO_2 sequestration data for the seaweed-based drinking straw

4.2 Interpretation and Discussion of Results

As per the assessment conducted in this Chapter, each seaweed-based drinking straw has a blue carbon value of 0.45 g and a CO_2 sequestration value of 0.00165 kg. This means that the dry seaweed biomass used as raw material for each straw captured 0.45 g of carbon (or 0.00165 kg CO_2) during the seaweed farming stage. That carbon is stored in the biomass (and eventually the straw) until the straw's end of life provided that the straw is composted after use. After factoring in the CO_2 emissions from the seaweed production (seaweed farming), the net CO_2 sequestered comes to a value of 0.00139 kg per straw. It is important to note that these values are only an approximation based on the assumptions listed in the first section of this Chapter. These values can be validated by (a) sending samples of the dry seaweed biomass used as raw material to a laboratory for carbon content analysis; and (b) conducting a life cycle assessment of the farm where the seaweed is sourced from.

When comparing the seaweed-based straw's CO_2 sequestration potential to the global warming potential of the other single-use straws assessed in Chapter 3 (as summarized in Figure 4.1 below), the seaweed-based straw holds potential to fare significantly better than the other straw types. The net CO_2 sequestration potential of the seaweed-based straw is around 95 percent of the standard plastic straw, 34 percent of the paper straw, and 30 percent of the bioplastic/compostable plastic (PLA) straw. This means that what the seaweed-based straw removes from the atmosphere in terms of CO_2 (during the seaweed farming and harvest stages) is 95 percent of what a standard plastic straw emits throughout its life cycle in this study.

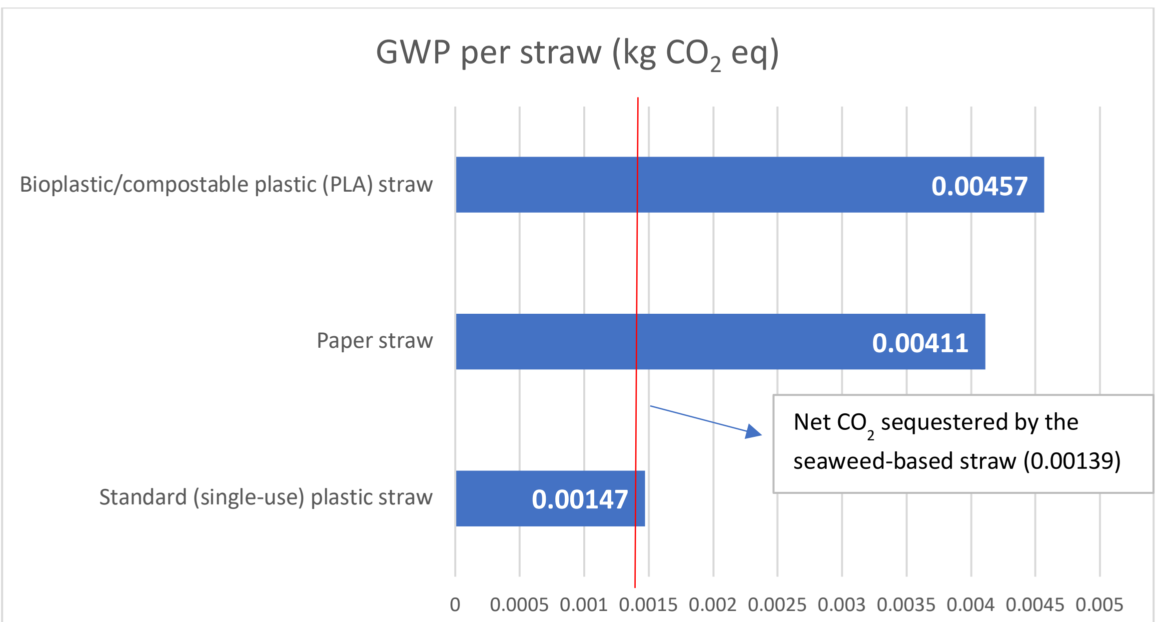

Figure 4.1. GWP comparison of the standard plastic straw, paper straw and PLA straw versus the net CO_2 sequestration potential of the seaweed-based straw (adapted from Table 3.10)

Using the life cycle assessment methodology to calculate the seaweed-based straw's GWP (kg CO_2 eq emitted per straw) could be the next key step in completing the straw's environmental sustainability assessment. The LCA could use a similar system boundary applied to the assessment of other single-use straws in Chapter 3, but include the seaweed farming and harvest stages. The blue carbon (CO_2 sequestered per straw) can then be subtracted from the global warming potential of the straw to calculate its net global warming potential. Given that the largest share of the global warming potential for the three single-use straw types calculated in Chapter 3 came from the base/primary material used in the straws (between 35 to 73 percent), the use of a carbon capturing raw material could be a game-changer in the drinking straws and alternatives to plastics markets. Additionally, if the product's life cycle is factored in the straw's design and manufacture, as well as other stages of its life cycle, the seaweed-based straw holds potential to be a carbon neutral straw or even a carbon negative straw. This could mean ensuring optimal production efficiency, powering part of the production plant using renewable energy, using efficient transportation modes to distribute the straws, and minimizing or eliminating waste.

Given the carbon content of the seaweed-based straw, it is important to highlight that the straw's end-of-life scenario is a key determinant in the straw's carbon footprint. As with the case of organic materials, landfill disposal of the used straw could result in the emission of greenhouse gases like carbon dioxide and methane through biogas produced during anaerobic decomposition (Michalak et al., 2017). This could eliminate the benefits of the blue carbon stored in the straw. A good disposal scenario for the seaweed-based straw could be composting. When biodegradable materials coming from plants are composted and applied to the soil, especially in agricultural practices, they may result in net CO_2 removals from the atmosphere whilst providing necessary nutrients to the soil (Paustian et al., 2016). In fact, recent studies prove that seaweed fertilizers could be better than other conventional fertilizers in terms of higher crop yields (Packiasamy & Govindasamy, 2018). Additionally, by replacing synthetic fertilizer to some extent, seaweed compost could avoid greenhouse gas emissions related to the production of those fertilizers. Nevertheless, some studies have highlighted concerns over the relatively low carbon to nitrogen (C/N) ratio of algae. These studies recommend that the seaweed material be measured for its C/N ratio before composting and be complemented with other supplements such as sawdust, if needed, to convert them into a valuable product for use in agriculture (Cole et al., 2015; Eyras et al., 2013). In either case, the effective collection of used straws will need to be ensured for composting and/or any other end-of-life use case(s) deemed viable and sustainable upon further study.

5 Linking Policy Instruments to Consumer Preferences and Willingness to Pay: A Review and Roadmap for Policy Assessment in the U.S. Context

5.1 Methods

This chapter conducts a comprehensive review of the literature to identify public policy instruments that may reduce the consumption of single-use plastic straws. Where literature is limited, it extends the scope to cover public policy instruments that have been developed and used to reduce the consumption of other single-use plastic products such as plastic bags, plastic bottles, etc. Whilst the focus is on identifying effective policy instruments for the U.S., relevant literature is included from across the world. In a sense, this study updates and upgrades the work by Wagner and Toews (2018), which merely addresses five public policy instruments available to reduce the consumption of single-use plastic straws and is focused on the U.S. alone. Moreover, based on the information retrieved from a review of the literature conducted on consumer preferences and willingness-to-pay in chapter 2, section 6 of this study, this chapter expands this literature review to conduct a limited meta-analysis of willingness-to-pay for more "sustainable" alternatives to single-use plastic straws. Three existing similar studies were chosen as they apply to other single-use plastic products.

5.2 Overview of Policy Instruments Available to Reduce Consumption of Single-Use Plastic Straws

Policy instruments are a means by which a desired goal under a public policy is achieved. Policy instruments may take different forms when applied to environmental policies. Cocklin (2009) identify the main categories of policy instruments as regulation (command-and-control), market-based (economic) instruments, voluntary approaches, and education and information. Policy instruments can also vary based on the type of government intervention. Fung et al. (2007) identify standards, market-based incentives, and targeted transparency as the three forms of government intervention in advancing public priorities. Targeted transparency is a policy mechanism which mandates disclosure by corporations and/or other actors regarding specific products or practices to a broad audience, usually the user (Fung et al., 2007). Very often, a combination of policy instruments are used to achieve an environmental policy.

When it comes to reducing the consumption of plastic straws, Wagner & Toews (2018) point out five primary public policy instruments available: (1) a ban; (2) default choice modification; (3) a tax or fee; (4) education; and (5) voluntary actions. Other policy instruments aimed at reducing the consumption of single-use plastic products reported in literature include extended producer responsibility (EPR), which mandates producers to assume responsibility for the postconsumer stage of the product's lifecycle (Abbott & Sumaila, 2019), the provision of green subsidies to bring down the cost of sustainable alternatives to plastic (Blackman, 2000), deposit refund schemes (for e.g. on plastic bottles) (Filho et al., 2019), and public financing and investment to incentivize R&D in alternatives to plastic products and/or set up a better waste management infrastructure for plastic waste and its alternatives (Watkins et al., 2019). Given that this study focuses on single-use plastic straws, EPR and deposit refund schemes are not considered due to the challenge in designing and implementing these schemes for small individual items such as drinking straws (Carbonnel, 2020).

Based on the above information, the public policy intruments available to reduce the consumption of single-use plastic straws can be categorised as per the degree of government intervention needed. As summarized in Table 5.1 and explained below, these policy instruments also vary in terms of the enforcement difficulty and effectiveness, amongst others.

5.2.1 Command-and-Control

Command-and-control are regulatory policy instruments which require a high (direct) degree of government intervention. There are two major types of command-and-control policy instruments available to reduce the consumption of single-use, plastic straws. These instruments, bans (prohibitions) and partial bans, are described below.

5.2.1.1 Ban

A ban prohibits the use and/or distribution of plastic straws at specified businesses, properties, or even nation-wide. While they are the strongest possible regulatory action to eliminate the use of plastic straws and are relatively easy to enforce, they require regular monitoring to ensure compliance, especially at smaller food establishments (Wagner & Toews, 2018). A ban on plastic straws is also made feasible with the increasing availability of non-plastic alternatives, however, these alternatives cost more and their "sustainability" can be dubious.

In the U.S., California became the first state to ban plastic straws at sit-down eateries starting January 2019, whilst at least sixteen local ordinances adopted by local governments such as the city of Seattle constituted full bans on plastic straws. Country-wise, Costa Rica and Great Britain, amongst other countries, announced their intentions to ban the sale of plastic straws and other single-use plastics by 2020 and 2021, respectively (Mosquera, 2019).

As per Wagner and Toews (2018), bans eliminate the consumption of plastic straws. However, there exists little to no literature on the effectiveness of plastic straw bans on reducing plastic pollution, probably because of how recent these bans are. The literature on the effectiveness of bans on a similar counterpart – plastic bags – report mixed results. In the U.S., a 75 percent reduction in the number of plastic bags in collected litter was reported in Austin since the plastic bag ban was introduced in 2013 (Gibbens, See the complicated landscape of plastic bans in the U.S., 2019). Yet, a plastic leakage equivalent to a 12-million-pound increase in trash bags was reported as an offset to the statewide ban on plastic carryout bags that led to a 40-million-pound reduction in plastic carryout bags in California (Taylor, 2019). The paper, instead, recommends imposing bag fees.

Internationally, Taiwan retracted its 2003 ban on the distribution of plastic bags because of evidence that the policy was ineffective (Ritch et al., 2009). Meanwhile, China and South Africa reported success (40-60 percent drop in bag use in supermarkets, and 70-90 percent drop in bag demand, respectively) when the ban on a stipulated thickness of bag was combined with a levy (Xanthos & Walker, 2017; Nhamo, 2005). Nevertheless, the need for strict enforcement is reiterated as Block (2013) report that the use of plastic bags continues to remain prevalent amongst street vendors and smaller stores in China.

5.2.1.2 Default Choice Modification (Partial Ban)

By default, plastic straws are provided with the purchase of a beverage at most food service establishments, whether the customer desires it or not. A default choice modification would imply that straws be provided to customers only upon request. This policy approach modifies the choice architecture without banning the behavior. An example of default choice modification is the "straw only upon request" law for full-service restaurants enacted by the state of California in 2018. The default choice modification ordinance can vary in terms of the choice of straw available upon request:

a) providing plastic straws and/or non-plastic straw alternatives depending on what the customer specifically requests for, as in the case of the newly adopted federal bill entitled "Break Free From Plastic Pollution Act of 2020"; (H. R. 5845, 2020); and
b) providing only acceptable single-use straws such as paper straws, except when a customer specifically requests a plastic straw to accommodate a disability or medical need, as in the case of San Francisco's "Single-Use Foodware Plastics, Toxics and Litter Reduction Ordinance" (SF Environment, 2020).

In terms of effectiveness of this policy instrument, only one study was identified. Wagner and Toews (2018) report an average decrease of 32 – 41 percent in straw consumption, with no impact to business and a small decrease in costs for some businesses, for the 133 affected businesses surveyed in their study. However, this policy instrument can be difficult to enforce as it often requires the involvement of the establishment to provide the straws.

5.2.2 Market-Based

Market-based policy instruments are economic instruments which require a moderate (mixed) degree of government intervention. There are two major types of market-based policy instruments available to reduce the consumption of single-use, plastic straws. These policy instruments, a tax/fee and a subsidy, are described below.

5.2.2.1 Tax/Fee

This policy instrument takes the form of a visible, separate tax or fee levied on single-use plastic straws at the point of sale. This sends a strong market signal to producers, food service establishments and consumers to reduce the use of plastic straws. Very often, the tax collected is invested in a related environment fund. While this policy instrument is relatively easy to enforce, an increased (but avoidable) cost is transferred to consumers who expect free straws at food service establishments. These consumers often fail to see the social and/or environmental cost of that plastic straw. This policy instrument may also require an increased administrative cost for regulation and establishment (Wagner & Toews, 2018).

This policy instrument can be effective in reducing the consumption of plastic straws because when a consumer is presented with an additional cost to participate in an avoidable action such as the use of drinking straw, consumption tends to decrease (Wagner & Toews, 2018). There is no documented evidence of a tax/fee applied to plastic straws. Yet, they have been successfully applied to single-use plastic bags in the U.S. and other countries (Wagner, 2017). A study by Williams et al. (2012) analyzed three cases studies from Washington D.C., Ireland, and Shanghai. While a tax/levy applied to plastic bags saw mixed success in Shanghai, it was difficult to gauge success for Washington D.C. and Ireland due to lack of monitoring of pre-policy and post-policy use of plastic bags. Nevertheless, the study highlighted the need for pre-policy intensive public outreach campaigns to educate retailers and consumers and gain public acceptance of the policy. The study also recommended introducing economic incentives and providing free product alternatives to low-income populations to mitigate increased costs from a fee-based policy.

5.2.2.2 Subsidy

Subsidies are economic incentives often used to promote more sustainable behaviors and can take the form of a payment or tax concession to producers of non-plastic alternatives to single-use plastic straws. The cost of such a subsidy is often met through the equivalent taxation of an alternate polluting product. This sends a strong market signal in support of more sustainable alternatives to plastic straws. Alternatively, subsidies which promote plastic production and trade can also be removed to increase the cost of single-use plastic and make non-plastic alternatives more competitive on the market.

While there is no documented evidence of a subsidy specifically applied to alternatives to single-use plastic straws, nor of the effectiveness of subsidies on alternatives to plastic products, there exists sufficient literature in support of subsidies applied to green products. In general, when compared to ordinary products, green products are more expensive to produce. This is also true in the case of plastic straws and its alternatives. Consequently, consumers either choose to pay a premium for these green products or are discouraged to buy it if cost is a priority for the consumer. As most businesses are risk-averse, limited companies would invest in producing green products if the perceived profits are low. As such, financial subsidies have proven to become an effective way for the government to encourage the development and consumption of green products. Nevertheless, the subsidy policy has to be scientific and reasonable to avoid excessive reliance on subsidies to sell green products (Zhao & Chen, 2019). Additionally, subsidies are often more politically palatable than taxes and the economic benefits that we derive from preventing plastic pollution often outnumber the fiscal resources needed to fund them (Blackman, 2000).

5.2.3 Financing and Investment

Financing-and-investment-based policy instruments are economic instruments which require a moderate (mixed) degree of government intervention as financial investments are made by both public and private entities. In the case of reducing consumption of single-use plastic straws, these investments are key to support the implementation of regulative instruments and/or development and uptake of market-based instruments (Watkins et al., 2019). Additionally, these investments directly facilitate the development of more sustainable alternatives to plastic straws throughout its lifecycle. There are two major types of financing-and-investment-based policy instruments available to reduce the consumption of single-use plastic straws: investments improving waste management infrastructure and R&D investment.

5.2.3.1 Waste Management Infrastructure

This policy instrument directly targets alternatives to single-use plastic straws by providing the necessary waste management infrastructure needed to make their end-of-life more sustainable. Bioplastic/compostable plastic straws and paper straws are the two most commonly used alternatives to single-use plastic straws. Nevertheless, literature has constantly reported that most bioplastic/compostable plastic straws and paper straws end up as regular waste. Compostable plastic will not break down any faster than regular plastic unless it is disposed of in a proper commercial composter and there are only over 100 qualified composting centers that can process this type of plastic in the U.S. Similarly, most paper straws are chemically treated to make them stronger, and therefore, cannot be recycled (Mosquera, 2019). As such, this policy instrument could take the form of investment in more commercial composters and qualified composting centers to facilitate its access to food service establishments and increase the recovery of waste straws for composting. Such a configuration of waste management infrastructure could also have a ripple effect by indirectly influencing the design of bioplastic products to ensure a higher biodegradability.

While there exists no documented evidence of investments in waste management infrastructure specifically related to plastic straws, similar investments have been deemed necessary to increase the recycling rates of plastics in general. An example of this is the “plastic recycling investment tax credit” initiated by the State of Colorado which gives a tax credit of 20 percent of the first USD 10,000 invested in new plastic recycling facilities in the state (Watkins et al., 2019).

5.2.3.2 R&D Investment

This policy instrument involves funding, in the form of public and private grants and investments, for research and development of more sustainable alternatives to plastic straws. The recipients could include small and medium enterprises (SMEs) developing products and services in the field of alternatives to plastic straws. It could also include research institutions who wish to understand and tackle the sustainability risks associated with bio-based and biodegradable plastic materials. Funding could also be provided for services which help reduce the consumption of plastic straws.

R&D investments in the alternatives to plastics sector could boost interest in this sector and aid the development of new products, especially by SMEs. The advantage is its applicability to other alternatives to plastic products, beyond plastic straws. An example of this is the New Plastics Economy Innovation Prize led by the Ellen MacArthur Foundation which offered USD 2 million in prizes to new materials, designs and business models relevant to plastics in 2017. Examples of winners included a seaweed-based packaging company (Evoware) in Indonesia, and the MIWA app which facilitates the use of reusable packaging during grocery shopping in Czech-Republic (Watkins et al., 2019).

5.2.4 Education and Transparency

Education and transparency are information tools that can be classified as policy instruments requiring little to no government intervention. They facilitate communication that supports the reduction in consumption of plastic straws in both a top-down and bottom-up approach for all stakeholders involved. These information tools may be voluntary or compulsory in nature and are often applied in a wider mix of regulatory and market-based interventions (Watkins et al., 2019). There are two major types of education and transparency policy instruments available to reduce the consumption of single-use plastic straws: campaigning, and certification or environmental labeling.

5.2.4.1 Campaigning

Campaigning includes communication tools that educate retailers, food service establishments, and consumers on the need to reduce the consumption of plastic straws. An example of this is mandatory signage placed at self-serve plastic dispensers. Wagner and Toews (2018) report that while there have been numerous resolutions passed by local governments in the U.S. encouraging businesses to reduce the consumption of plastic straws, they are mainly suggestive and not compulsory.

While educational campaigns seem to be the first obvious step to reduce the consumption of plastic straws, this policy instrument has seen limited success in reducing the consumption of single-use plastic products (Wagner & Toews, 2018). That said, literature has often reported that public awareness campaigns have proven to be a very beneficial tool when used in conjunction with other policy instruments such as bans and tax/levies (Williams et al., 2012).

5.2.4.2 Certification and Environmental Labeling

These interventions, often voluntary, can enable producers of single-use plastic straws and its various alternatives to provide credible information about the environmental impact of their product. This can be done in several ways, such as by choosing to comply with certain criteria in an environmental certification scheme, conducting life cycle assessments of their products, using product labels, and producing Environmental Product Declarations (EPDs) to provide information about product composition and lifecycle. This information can then be communicated and used by retailers, food service establishments, and consumers to enable them to assess any potential environmental impact and consume sustainably.

An example of certification and environmental labeling used in reducing the consumption of plastic straws are compliance claims by paper straws and bioplastic straws manufacturers. Paper straw manufacturers can use the Forest Stewardship Council and Sustainable Forestry Initiative to certify the sustainable sourcing of the raw material used. Meanwhile, bioplastic/compostable plastic straw manufacturers can use the Biodegradable Products Institute (BPI) certification to certify its product as compostable in large scale composting facilities.

5.2.5 Voluntary Action

Voluntary actions are primarily cooperative efforts undertaken by private institutions, without any government intervention, to reduce use of plastic straws. While most of these actions rely mainly on social and corporate responsibility, economic benefits and perceived image also come to play (Wagner & Toews, 2018). Multinational companies which announced the elimination of single-use plastic straws includes Starbucks, the Walt Disney Company, Mc. Donald, American Airlines and Royal Caribbean cruise lines (Mosquera, 2019).

Voluntary actions are good in that they provide flexibility for the government and target population. However, its impact of plastic straw consumption levels remains variable depending on the extent and duration of adoption, as well as customer feedback. Nevertheless, when applied to general environmental policies, Chang (2018) reports a substantial and growing body of literature supporting the view that voluntary actions are indeed more efficient and effective than regulatory instruments because they minimize the negative political and legal consequences of regulatory failure.

Level of Government Intervention	Policy Intrument	Summary	Enforcement Difficulty	Effectiveness
High (direct)	**Command-and-control (regulatory)**			
	1. Ban	Prohibits the use and/or distribution of plastic straws	Relatively easy, provided there is regular monitoring for compliance, especially at smaller food establishments	Eliminates consumption of plastic straw, but mixed results reported in plastic bag bans
	2. Default choice modification (partial ban)	Covered establishments to provide straw to customer only upon request	Somewhat difficult as it requires increased involvement of establishment	Proven to reduce consumption of plastic straw with minimal impact to businesses
Moderate (mixed)	**Market-based**			
	3. Tax/fee	Visible, separate tax or fee levied on plastic straws at the point of purchase	Relatively easy to enforce	- No evidence of application on plastic straws. - For plastic bags: mixed results, but mostly effective if accompanied by pre-policy public outreach campaigns and economic incentives for lower income populations
	4. Subsidy	Payment or tax concession to producers of sustainable alternatives to plastic straws to bring down the cost of the product	Relatively easy to enforce	- No evidence of application on plastic straws or nonplastic products. - For green products: mostly effective if subsidy is reasonably designed and used in conjuction with a tax/fee applied to an alternate polluting product

	Financing and investment			
	5. Waste management infrastructure	Investment in commercial composters and composting facilities to increase recovery/composting of bioplastic/paper straws.	Difficult to enforce	Impact on consumption of plastic straws uncertain but could indirectly increase the consumption of bioplastic and paper straws by increasing their composting rates.
	6. R&D investment	Funding for R&D of sustainable alternatives to plastic straws and related services	Difficult to enforce	Effective in boosting innovation and increasing availability of sustainable alternatives to plastic straws.
Low (light)	**Education and transparency**			
	7. Campaigning	Educating retailers, food establishments and consumers on the need to reduce straw use	Difficult to enforce	Not likely to be effective in having an appreciable impact on consumption of straws, especially if used alone.
	8. Certification and environmental labeling	Encouraging plastic/non-plastic straw manufacturers to provide information on product's sustainability through certifications, labels, EPDs, etc.	Difficult to enforce	Impact on consumption of plastic straws uncertain, but has potential to increase consumption of sustainable alternatives to plastic straws.
None (cooperation-based)	**Voluntary action**			
	9. Voluntary approaches	Voluntary actions and commitments by estabalishments to reduce use of straws	Cannot be enforced	Impact on consumption uncertain, variable on breadth and duration of adoption and customer feedback.

Table 5.1. Major public policy instruments available to reduce the consumption of single-use, plastic straws

5.3 Limited Meta-Analysis of the Linkage between Policy Instruments and Consumer Willingness-to-Pay

Literature suggests that contingent valuation and conjoint analysis are useful tools to quantify consumer preferences and willingness-to-pay for various forms of alternatives to plastic. A study by Barnes et al. (2011) conducted in the urban center of Honolulu, Hawaii, employed conjoint choice experiment to reveal that 81 percent of respondents were in favor of a ban on expanded polystyrene takeout food containers and 66.49 percent of respondents preferred a container constructed out of sugarcane material. Another study by Yue et al. (2010) utilizes and compares hypothetical conjoint analysis and non-hypothetical experimental auctions to show that participants were indeed willing to pay a price premium for biodegradable plant containers versus standard plastic ones in the floriculture industry. Finally, a study by Dunn (2012) uses a dichotomous-choice contingent survey and interval regression analysis to estimate the mean willingness to pay for continued use of plastic grocery bags and a mean willingness to accept to use reusable bags for all grocery shopping trips. The study concluded that a small tax on plastic grocery bags provides tremendous consumptive declines, while people who use reusable bags for some trips would switch to using reusable bags for all trips if they were paid $0.12 per reusable bag that they brought from home.

The information gathered from the aforementioned studies is combined with findings of the study by Wagner and Toews (2018) and applied to the nine policy instruments identified for reducing consumption of single-use plastic straws in the previous section of this chapter (and table 5.1). Table 5.2 below summarizes the linkage between the nine policy instruments, whether or not they retain consumer choice, whether or not the cost is borne by consumers (including food service establishments who are often the intermediate customer and provider), and willingness-to-pay, if relevant.

Policy Instrument	Consumer Choice	Cost Implications	Consumer Willingness-to-Pay
Command-and-control (regulatory)			
1. Ban	Eliminates consumer choice	Non-plastic alternatives cost more; cost often borne by food service establishment unless consumer buys their own straw	- 81% of respondents in favor of a ban on expanded polystyrene takeout food containers and 66.49% of respondents preferred a container constructed out of sugarcane material (Barnes et al., 2011) - Participants willing to pay a price premium for biodegradable plant containers versus standard plastic ones in the floriculture industry (Yue et al., 2010)
2. Default choice modification (partial ban)	Retains consumer choice	- Small cost decrease reported for food service establishments - No cost borne by consumer.	N/A
Market-based			
3. Tax/fee	Retains consumer choice	Increased cost (but avoidable) borne by consumer	A small tax on plastic grocery bags provides tremendous consumptive declines while people who use reusable bags for some trips would switch to using reusable bags for all trips if they were paid $0.12 per reusable bag that they brought from home (Dunn, 2012)
4. Subsidy	Retains consumer choice	Decreased cost borne by consumer if selecting non-plastic straw	
Financing and investment			
5. Waste management infrastructure	Retains consumer choice	No cost borne by consumer or food service establishment	N/A
6. R&D investment	Retains consumer choice	No cost borne by consumer or food service establishment	N/A

Education and transparency			
7. Campaigning	Retains consumer choice	- Low to no cost to consumers - May impose some cost to food service establishments	N/A
8. Certification and environmental labeling	Retains consumer choice	- Low to no cost to consumers - May impose some cost to food service establishments for those who pick non-plastic straws based on labels	N/A
Voluntary action			
9. Voluntary approaches	Limits consumer choice	- No cost to consumers - Could imply cost decreases to food service establishments if straws eliminated or cost increases if shift to non-plastic straws	N/A

Table 5.2. Linkage between major public policy instruments, consumer choice, and consumer willingness-to-pay to reduce the consumption of single-use, plastic straw

5.4 Proposed Policy Roadmap to Link Policy Options with Consumer Willingness-to-Pay

Based on the analysis of the literature review conducted on the nine major public policy instruments available to reduce the consumption of plastic straws and keeping in mind reported consumer preferences and willingness-to-pay, a comprehensive policy solution package combining four policy instruments is being proposed, as depicted in Figure 5.1 below. A default choice modification (straw upon request) framework combined with certification and environmental labeling, and investments in both waste management infrastructure and R&D will arguably prove to be the most successful set of policies to reduce single-use plastic straw consumption in the U.S. These policy instruments will address both producer and consumer sides of the problem and take into consideration the entire product lifecycle. Moreover, these policy instruments retain consumer choice, prevent "greenwashing," provide flexibility to food service establishments, and may even reduce their costs.

This study also highlighted that the end-of-life scenario of a used straw is a key determinant of the straw's carbon footprint and that the current waste management infrastructure does not fully cater for the recycling and/or composting needs of used bioplastic/compostable and paper straws. In fact, much of the problem linked to plastic pollution has been a result of the poor management of plastic waste. As such, an investment in the waste management infrastructure will help facilitate (and increase) the recycling and/or composting of used straws, where the material allows for it. This will, in turn, contribute to a circular economy. An investment in the waste management infrastructure will also be a proactive measure in encouraging SMEs to invest in new recyclable and/or compostable materials for future straw types.

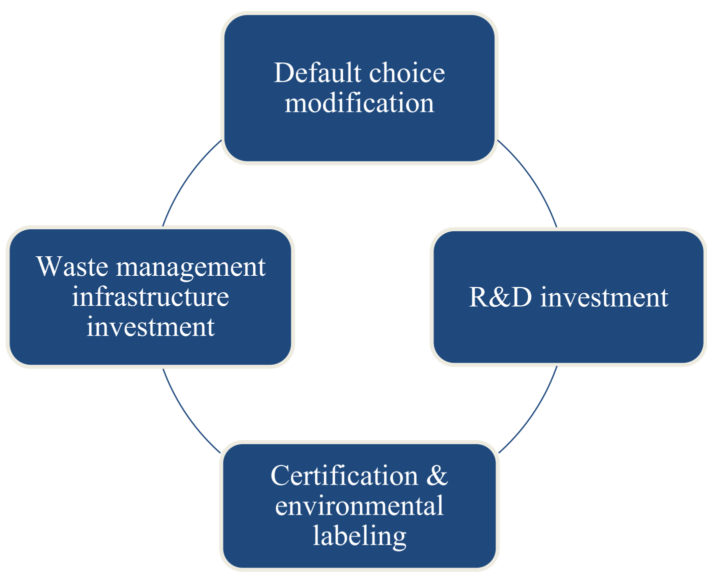

Figure 5.1. Proposed policy package to reduce the consumption of plastic straws

6 Conclusion and Future Work

The use of a (reusable) metal straw has a significantly lower overall environmental impact than that of the use of plastic straws, paper straws, and bioplastic straws over a year, provided that the metal straw is washed using cold water and the standard washing time is cut to half. Therefore, if a person wishes to reduce their environmental impact in terms of drinking straw usage, a switch to the (reusable) metal straw should be made and this metal straw should be carried and used by the person every time a straw is needed. That said, human behavior has a big influence on the environmental impact of a reusable metal straw. Over 85 percent of the environmental impact reported from the use of a metal straw over a period of one year comes from the washing of the straw. As such, how a user decides to wash their straw is a key determinant of the product's environmental sustainability. The use of hot water should be avoided or reduced to only the soap wash phase (and combine with cold water rinse) at all costs. Additionally, the standard washing time should be cut into half. In reality, a thorough study of washing behaviors of the metal straw is recommended, with sanitation considerations to be included as a study component.

There is also the promise of the seaweed-based straw. Given that the largest share of carbon footprint came from the base/primary material used in single-use straws, the use of naturally occurring and carbon dioxide capturing materials could be a game-changer in the drinking straws and alternatives to plastics markets. This study estimates the blue carbon and a CO_2 sequestration values of the seaweed-based straw to be 0.45 g and 0.00165 kg per straw, respectively. However, these values are only a preliminary approximation. A complete life-cycle analysis of the straw, coupled with lab-tested samples of the dry seaweed biomass and the straw for carbon content is needed to validate these results. Nevertheless, the net CO_2 sequestration potential of the seaweed-based straw is shown to be around 95 percent of the standard plastic straw, 34 percent of the paper straw, and 30 percent of the bioplastic/compostable plastic (PLA) straw in this study. This means that if the product's life cycle is factored in the straw's design and manufacture, as well as other stages of its life cycle, the seaweed-based straw holds potential to be carbon neutral or even carbon negative.

This switch to (reusable) metal straws (or seaweed-based straws in the future) will only be fully effective if food service establishments make key policy changes. Significant reductions in the consumption of single-use plastic straws can be achieved by addressing both the production decisions of producers and the consumption decisions of consumers in a way that does not economically affect the "middle guy" – food service institutions. The surging demand for sustainable alternatives to plastic straws, coupled with the growing number and variety of these alternatives, do suggest an increasing consumer preference for non-plastic straws. Public policy instruments, as well as voluntary actions from businesses, continue to play a substantial role enable this the switch to sustainable alternatives to plastic straw.

By default, plastic straws are provided with the purchase of a beverage at most food service establishments, even when customers do not need it. As such, the default choice modification policy instrument has been the most successful in reducing the consumption of plastic straws while minimizing impacts to businesses. Yet, it does not specifically promote a switch to non-plastic straws, nor addresses the high costs of these alternatives. It also does not address the issue of potential "greenwashing" and misinformation by alternative straw companies who may falsely market their as "green" or "biodegradable" without considering the entire lifecycle of the straw. As such, this study recommends a default choice modification (straw upon request) framework combined with investments in the upgrade of the waste management infrastructure and R&D, and certification and environmental labeling as the most effective policy to reduce single-use plastic straw consumption in the U.S. This could be complemented by food service establishments running customer awareness programs and providing incentives for customers to use their own reusable metal straws.

This study also debunks some popular beliefs around paper and bioplastic straws (and products). Both paper and bioplastics appear to be environmentally friendly materials when compared with their plastic counterparts in terms of their origin and biodegradability. As such, both paper straws and bioplastic straws manufacturers aggressively market their products as environmentally-friendly, and almost every food service establishment that has eliminated plastic straws has substituted with either paper straws or bioplastic straws. However, the environmental impact of plastic straws (in terms of energy demand and global warming potential) is less than half of that of paper straws and bioplastic straws. This lower carbon footprint has been consistently proved by similar studies done between plastic products and their paper/bioplastic counterparts, even when using the Eco-Indicator 99 impact assessment method (Muthu et al., 2009). In addition, paper straws are not recyclable and bioplastic straws are not biodegradable unless composted in an industrial composting facility. Consumers should be made aware of these facts to protect them from misinformation and potential "greenwashing."

The results of this study can be used to determine the most environmentally sustainable straw option between the standard plastic straw, the paper straw, the bioplastic straw, and the reusable metal straw. It can also be used to understand the environmental sustainability of a newer straw: the seaweed-based straw. Nevertheless, this remains a limited life-cycle assessment with certain hypothesis and assumptions. This study calls for future research in the following areas to increase its scope and accuracy. This additional research can then feed into important legislative, corporate and consumer decisions related to plastic products and their alternatives, including the plastic straw.

a) *Ecotoxicology of marine plastics integrated into life cycle assessment*

There needs to be progress on the study of the ecotoxicology of marine plastics (Abbott & Sumaila, 2019). Even if plastic straws (and products) have a lower energy demand and global warming potential than their paper and bioplastic counterparts, the biggest environmental issue associated with the use plastics remains plastic pollution, especially marine litter and its threat to marine biodiversity. A review of the literature shows that impact indicators for major drivers of marine biodiversity loss are currently lacking from sustainability assessment approaches such as the LCA (Woods et al., 2016), including tools to assess the potential ecosystem damage from plastic waste. As such, the application of

LCA to assess the relative sustainability of different options has drawn criticism. Recognizing this limitation, the LCA community released the Medellin declaration on marine litter in life cycle assessment and management to call for impact assessment model development to account for potential ecosystem damage caused by marine litter (Woods et al., 2019). A study by Civancik-Uslu et al. (2019) also introduced a Littering Potential indicator to allow a comparison of the risk of littering of different carrier bag options in marine environment. Future research could be done on this indicator, especially when applying it to other traditionally plastic products such as the straw.

b) Life cycle assessment of other drinking straw types

This study identified nearly ten types of drinking straws, including the standard plastic straw, and conducted a comparative LCA on the four most commonly used straws. The study also estimated the net CO_2 sequestration potential of the seaweed-based. The study could be extended to include LCAs of the other straw types, including the seaweed-based straw. For instance, bamboo straws are directly cut from the bamboo plant and hay straws are made from natural wheat. Polyhydroxyalkanoate (PHA) bioplastic straws are also starting to hit the market and provide promising results given their ability to biodegrade in marine and soil environments (bioplastics MAGAZINE, 2019). Finally, as demonstrated in this study, the seaweed-based straw has the potential to be a carbon neutral or even a carbon negative straw.

c) A comprehensive economic assessment of plastic pollution

It has been reported that plastic costs $13 billion in economic damage to marine ecosystems each year (Avio et al., 2017). There is also growing literature on the negative impacts of plastic debris on human health (Vethaak & Leslie, 2016). Besides this small literature on the lost welfare from marine debris, there has been little research on the broader economic damages from plastic pollution, especially single-use straws. First, there needs to be progress on the study of the ecotoxicology of marine plastics (Abbott & Sumaila, 2019). Then, there needs to be research done on the effects of plastic use and plastic pollution on human health. Further research is then needed to quantify market and nonmarket welfare effects, and socio-economic costs (for e.g. reduced tourism, litter clean-up costs, etc.), of the use of single-use plastic straws (and single-use plastic products as a whole). Finally, these welfare effects and costs have to be effectively communicated to both consumers and policymakers.

d) The development of a new Sustainability Index

An increasing number of consumers are now concerned with the socio-economic impacts of a product, rather than just its environmental impact. For a drinking straw, this could translate into indices related to the welfare of employees working in the straw manufacturing company, as well as the product's price, amongst other socio-economic indicators. The current LCA assessment methods do not cater for these socio-economic aspects. Therefore, a new Sustainability Index which considers all the three core aspects of sustainability needs to be developed. This Index should comprise of environmental (including ecotoxicology of marine pollution and blue carbon), social and economic indicators, allocating a fair and appropriate weightage to them. This Sustainability Index should be represented by a simple rating score from 1 to 10 to make it easy for a consumer to understand. Finally, manufacturers should be encouraged to calculate their product's Sustainability Index and readily provide that information to consumers.

e) *Cost comparison and Conjoint Choice Analysis to assess consumer willingness-to-pay*

A review of the literature, including market research data cited in this paper, suggests that there are several important areas where economic research can help determine consumer preferences and willingness to pay for non-plastic straws. A conjoint choice analysis (CCE) can be used. CCE has consistently proven to be a useful economic analysis tool in quantifying consumer preference and willingness to pay for plastic alternatives. An appropriate sample size can be determined using the Johnson & Orme (2003)'s formula for sample size for CCE. The data, once collected, can then be analyzed using Latent Class Analysis (Barnes et al., 2011). The proposed survey questionnaire design is as follows:

Part 1: Information on preferences and habits related to use of drinking straw of respondents

a) The frequency of straw use
b) The frequency of recycling or composting
c) The respondent's decision to avoid straws altogether if not automatically provided one with their beverage
d) The respondent's decision to recycle or compost their drinking straw if provided with that option
e) The respondent's decision to eat their drinking straw if straw is edible
f) The respondent's support for a local ban on single-use plastic straws.

Part 2: Socio-economic profile of respondents

a) Gender
b) Age
c) Educational attainment
d) Yearly income

Part 3: Preference for sustainable alternatives to plastic straws

Here, the respondents are forced to make tradeoffs between product attributes when picking their choice of non-plastic alternatives. Following the stages of CCE design summarized by Chan-Halbrendt et al. (2010), the attributes are selected and the attribute levels assigned, followed by the construction of choice sets. The selected attributes are based on current market options for sustainable alternatives to plastic straws with an assumption that food service establishments will only serve single-use non-plastic straws. All reusable straw options are put under one category "reusable" and assumed to be carried by the respondent when consuming at the establishment. The personal comfort scale levels, Sustainability Index Score levels and additional price per straw per usage levels are hypothetical for the sake of this proposed design, based on the review of literature on this topic.

The product attributes and their levels are shown in Table 6.1 below.

Attributes	**Choice Set and Levels**				
Type of Material	A. Paper	B. Compostable / bioplastic	C. Seaweed-based	D. Hay straw	E. Reusable
Use in both hot and cold beverages	No	No	No	Yes	Yes
Amount of uses	Single	Single	Single	Single	Multiple
Convenience of use	High	High	High	High	Low
Personal comfort, feel and taste (Scale: 1 – 5)	1	4	3	2	3
Sustainability Index Score (Scale: 1 – 5)	2	2	5	4	5
Additional price per straw per usage ($) (compared with single-use plastic straw)	0.02	0.03	0.04	0.07	-0.04

Table 6.1. Example of a choice set including sustainable alternatives to plastic straws attributes and level

Currently, there exists no complete study which analyses the costs of the various sustainable alternatives to plastic straws which exist on the U.S. market. The proposed CCE study can also look into conducting a comprehensive cost analysis and comparison. The results of this cost analysis can then be applied to upgrade the proposed CCE questionnaire design and calculate a more accurate consumer willingness-to-pay for non-plastic straws. Such a cost comparison study can also highlight the price differences to legislators and policy-makers who can then see the benefit in applying green subsidies to sustainable alternatives to plastic straws. The proposed "Sustainability Index Score" comprising of environmental, social and economic indices can then be calculated for each straw type and green subsidies can be allocated based on that score.

Overall, this study makes a strong case for the need of science-based policy making. This is demonstrated by the fact that many countries and establishments chose to impose a ban on single-use plastic straws with the intention of reducing and/or eliminating its use. However, these bans automatically led to the replacement of plastic straws by paper straws and/or bioplastic (PLA) straws. While these alternatives have been widely assumed to be more "sustainable", the LCA results from this study show that these alternatives have a significantly higher energy demand and carbon footprint than the plastic straw. Thus, in trying to eliminate one problem (plastic pollution), a new problem may have been unintentionally created. This study also reminds us of the age-old 3Rs (reduce, reuse, recycle) hierarchal concept of dealing with waste. Given that drinking straws are automatically provided with beverages in majority of restaurants, the first policy approach should be to reduce the use of drinking straws as a whole, irrespective of the material.

The results of this study aim to add to the literature of science-based policy making, plastic pollution, and LCA methodologies, amongst others. It is hoped that the proposed areas for future research work are implemented by researchers and scholars from all across the world, with this study serving as a basis. It is also hoped that this study is used by policy-makers when designing policies relating to plastic pollution and product sustainability, by manufacturers of alternatives to plastic products when designing their products, and by businesses, food service establishments and individual consumers when deciding on the most sustainable drinking straw policy and option.

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A LCA of Drinking Straw Types: Data Source

A.1 Datasheet Shared with Straw Manufacturers

[The following datasheet was sent to all selected straw manufacturers in an email requesting them to participate in this study]:

1. Straw type
(a) Which straw type sells the most from your company
(b) What is the packaging type of that straw type?

For that straw type:
2. Raw materials
(a) What raw materials go into the production of the straw and in what quantity?
(b) Where are the raw materials sourced from?
Optional: Is there any transportation involved? If yes, what's the approximate distance?

3. Packaging materials:
(a) What packaging materials are used and in what quantity?
(b) Where are the packaging materials sourced from?
Optional: Is there any transportation involved? If yes, what's the approximate distance?

4. Production and assembly of straws:
(a) What processes are used to produce the straw?
(b) How much energy / electricity is used in the production? (either as a whole or per process) (if possible, give amount per unit of production)
Optional: What other resources are used and in which quantity? (e.g. water)

5. Disposal of used straws and associated packaging:
What is the recommended disposal route of
(a) your straw; and
(b) its associated packaging?

A.2 Responses Received from Straw Manufacturers

- The response received from **OKSTRAW Paper Straws** is found below:

1. Straw type
(a) Which straw type sells the most from your company?
Black jumbo straws
(b) What is the packaging type of that straw type?
Wrapped and unwrapped, pack of 6000 straws or 3600 straws

For that straw type:
2. Raw materials
(a) What raw materials go into the production of the straw and in what quantity?
Food grade white kraft paper (1.2g/straw)
(b) Where are the raw materials sourced from?
Purchase
Optional: Is there any transportation involved? If yes, what's the approximate distance?
Around 800km

3. Packaging materials:
(a) What packaging materials are used and in what quantity?
Corrugated cardboard (1.2kg/10000 straws)
(b) Where are the packaging materials sourced from?
Purchase
Optional: Is there any transportation involved? If yes, what's the approximate distance?
Around 8km

4. Production and assembly of straws:
(a) What processes are used to produce the straw?
Printing, slitting, straw making, drying, packaging
(b) How much energy / electricity is used in the production? (either as a whole or per process) (if possible, give amount per unit of production)
n/a
Optional: What other resources are used and in which quantity? (e.g. water)

5. Disposal of used straws and associated packaging:
What is the recommended disposal route of
(a) your straw; and
Selling them as scrap
(b) its associated packaging?
Selling them as scrap

- The response received from **Eco-Products, Inc.** is found below:

1. Straw type
(a) Which straw type sells the most from your company?
Wrapped Clear PLA straw – EP-ST770
(b) What is the packaging type of that straw type?
It is wrapped in paper and then packaged in a paperboard box of 400, then in a cardboard carton of 9600 total straws

For that straw type:
2. Raw materials
(a) What raw materials go into the production of the straw and in what quantity?
PLA - 0.9 grams of PLA

(b) Where are the raw materials sourced from?
Our PLA is sourced from the NatureWorks facility in Blair, NE. They source their corn from local farmers. The PLA goes from NE to China where it is extruded into straws.
Optional: Is there any transportation involved? If yes, what's the approximate distance?

3. Packaging materials:
(a) What packaging materials are used and in what quantity?
Paper wrap for the straws, paper board with 400 straws, then corrugated cardboard with 9600 straws
(b) Where are the packaging materials sourced from?
Sourced locally at the manufacturing facility
Optional: Is there any transportation involved? If yes, what's the approximate distance?

4. Production and assembly of straws:
(a) What processes are used to produce the straw?
Extrusion
(b) How much energy / electricity is used in the production? (either as a whole or per process) (if possible, give amount per unit of production)
Energy Demand (Total Life Cycle): 0.061655 MJ
Energy Demand (Production only): 0.00924825 MJ
Optional: What other resources are used and in which quantity? (e.g. water)

5. Disposal of used straws and associated packaging:
What is the recommended disposal route of
(a) your straw; and
Commercial compost
(b) its associated packaging?
The paper, paperboard, and cardboard should be recycled (highest, best use), but can also be composted.

B LCA of Drinking Straw Types: Network Models

B.1 Network Models for Cumulative Energy Demand

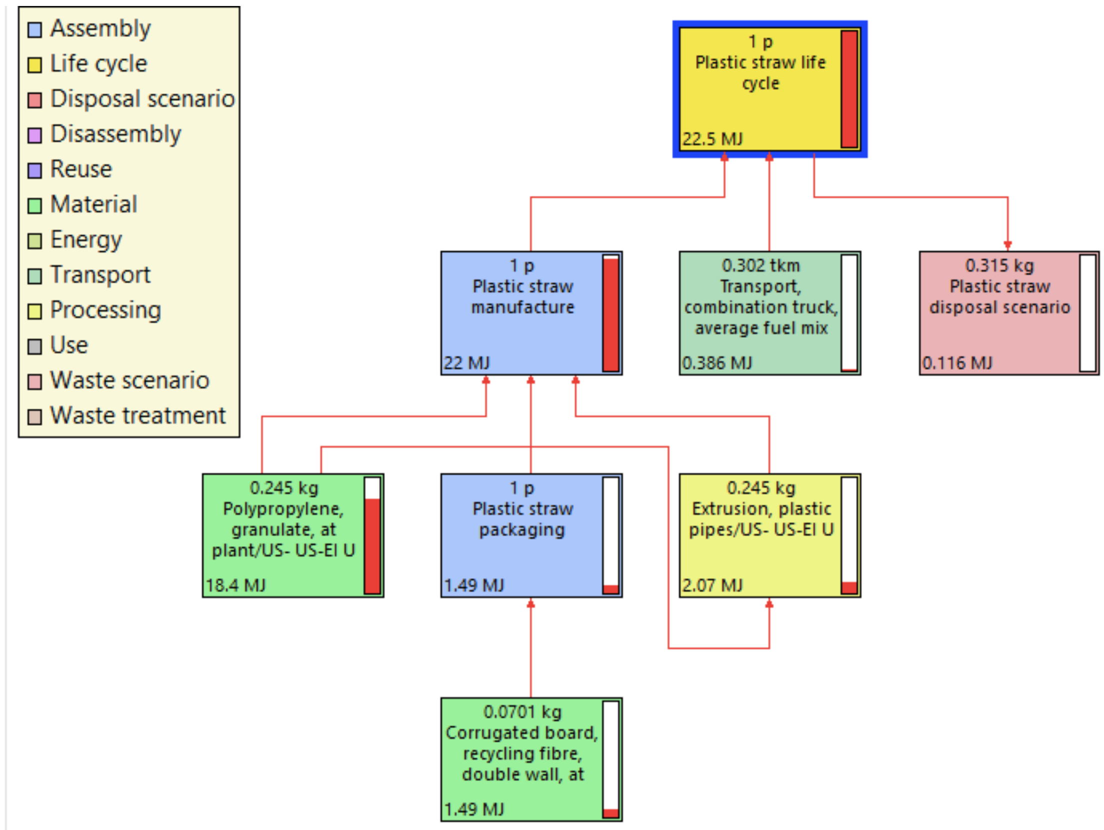

Figure B.1. Network model for Cumulative Energy Demand of the standard (single-use) plastic straw (functional unit equivalence)

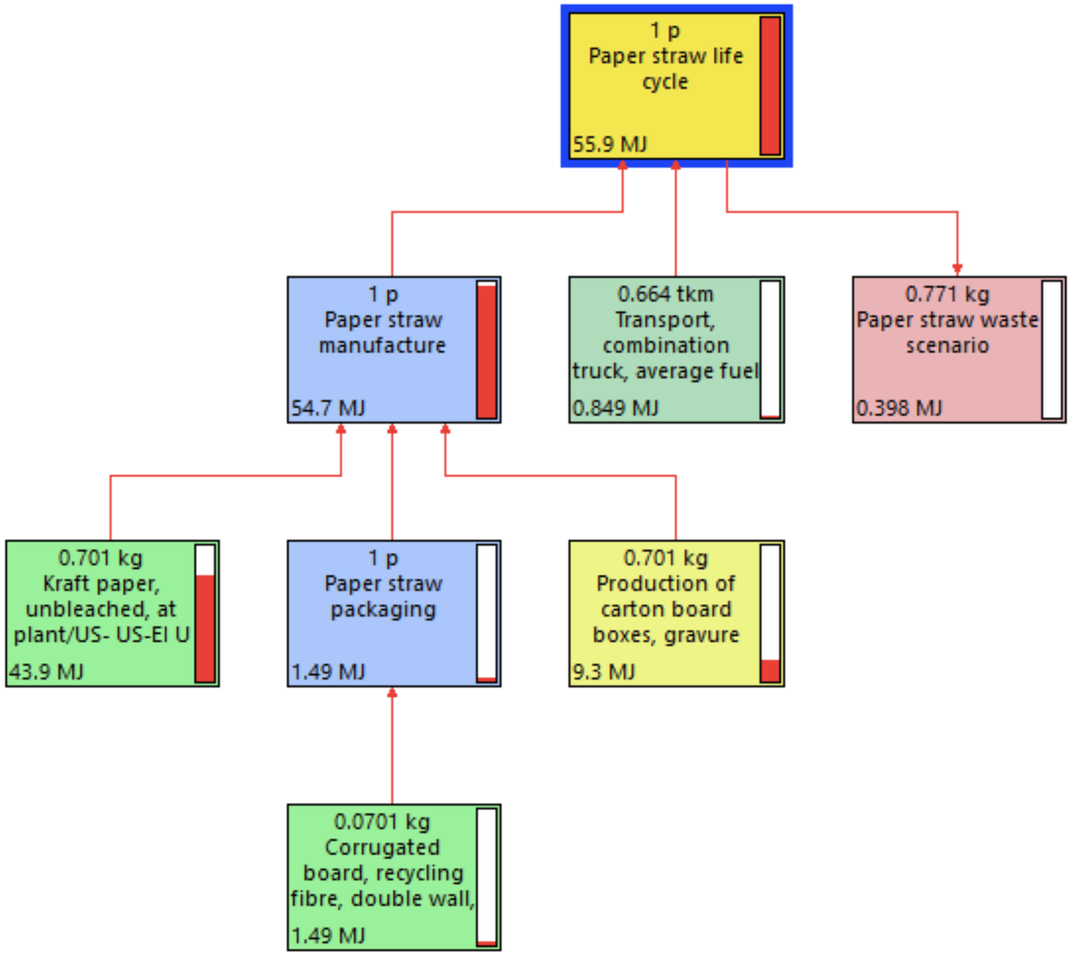

Figure B.2. Network model for Cumulative Energy Demand of the paper straw (functional unit equivalence)

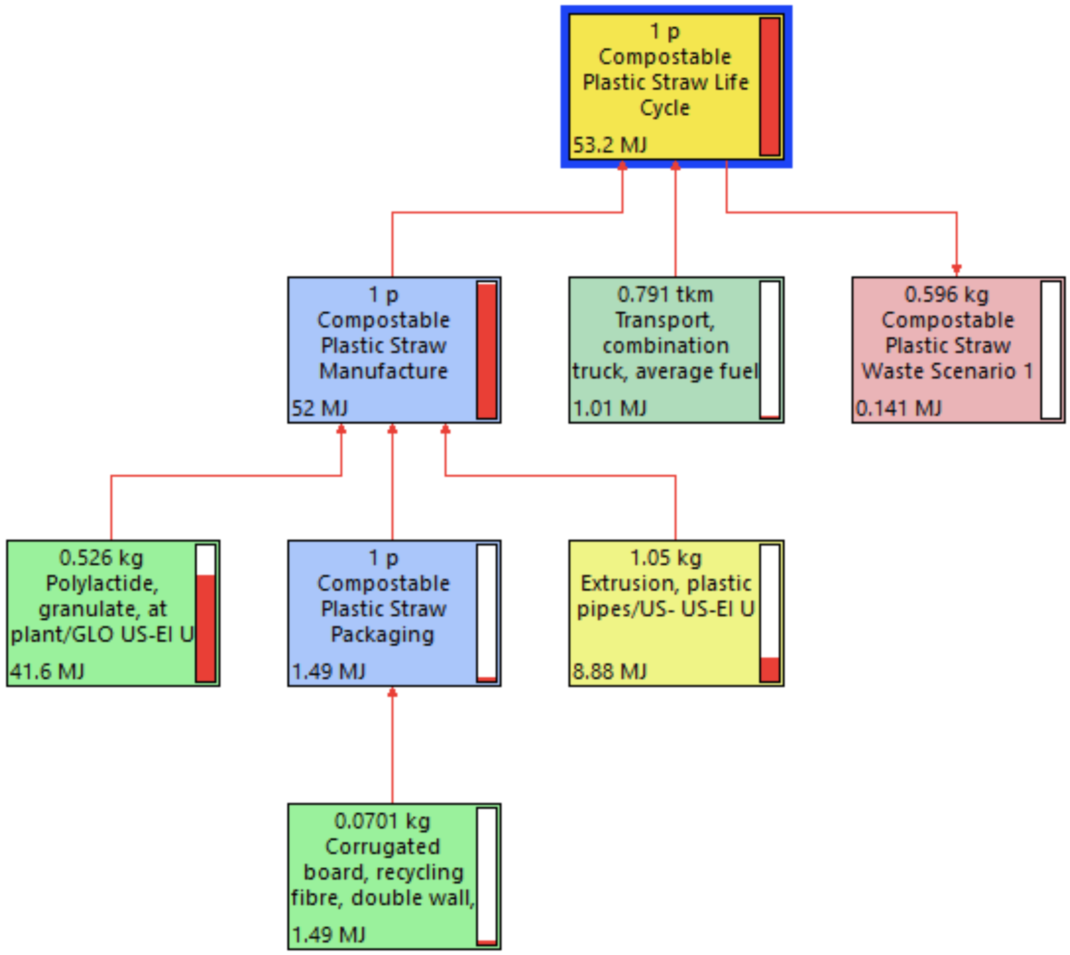

Figure B.3. Network model for Cumulative Energy Demand of the bioplastic/compostable plastic straw (functional unit equivalence)

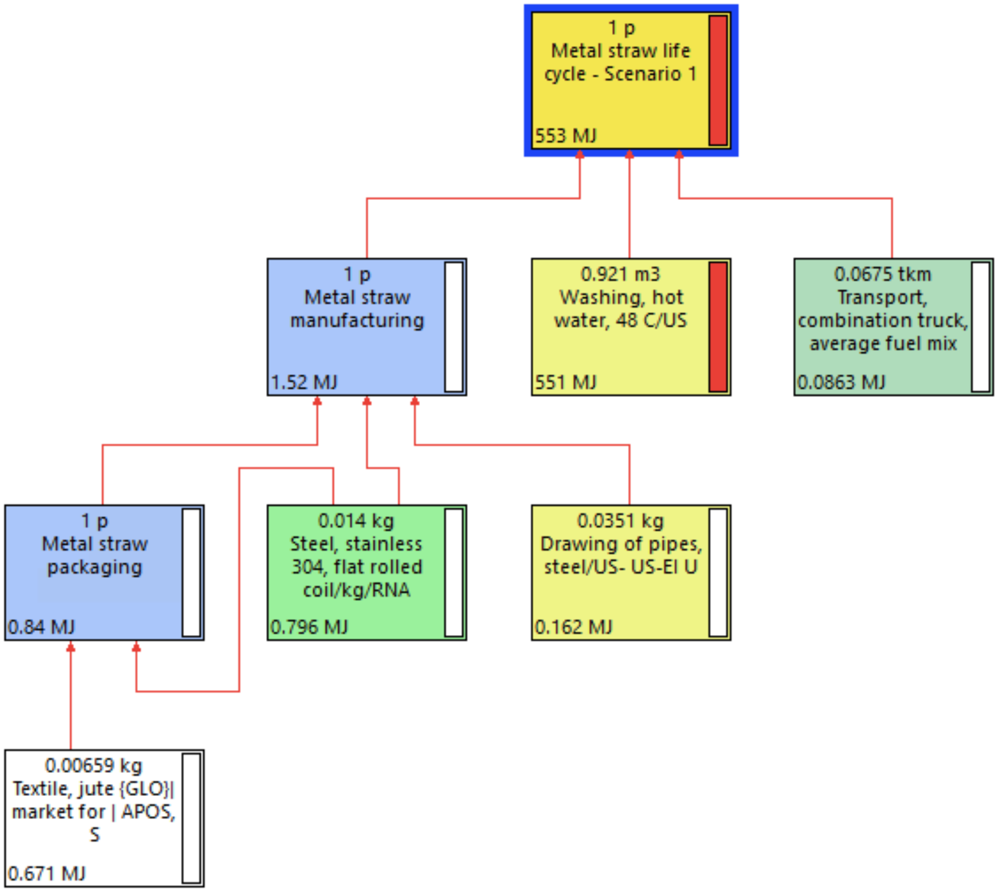

Figure B.4. Network model for Cumulative Energy Demand of the (reusable) metal straw for Scenario 1 – hot water washing at standard washing time (functional unit equivalence)

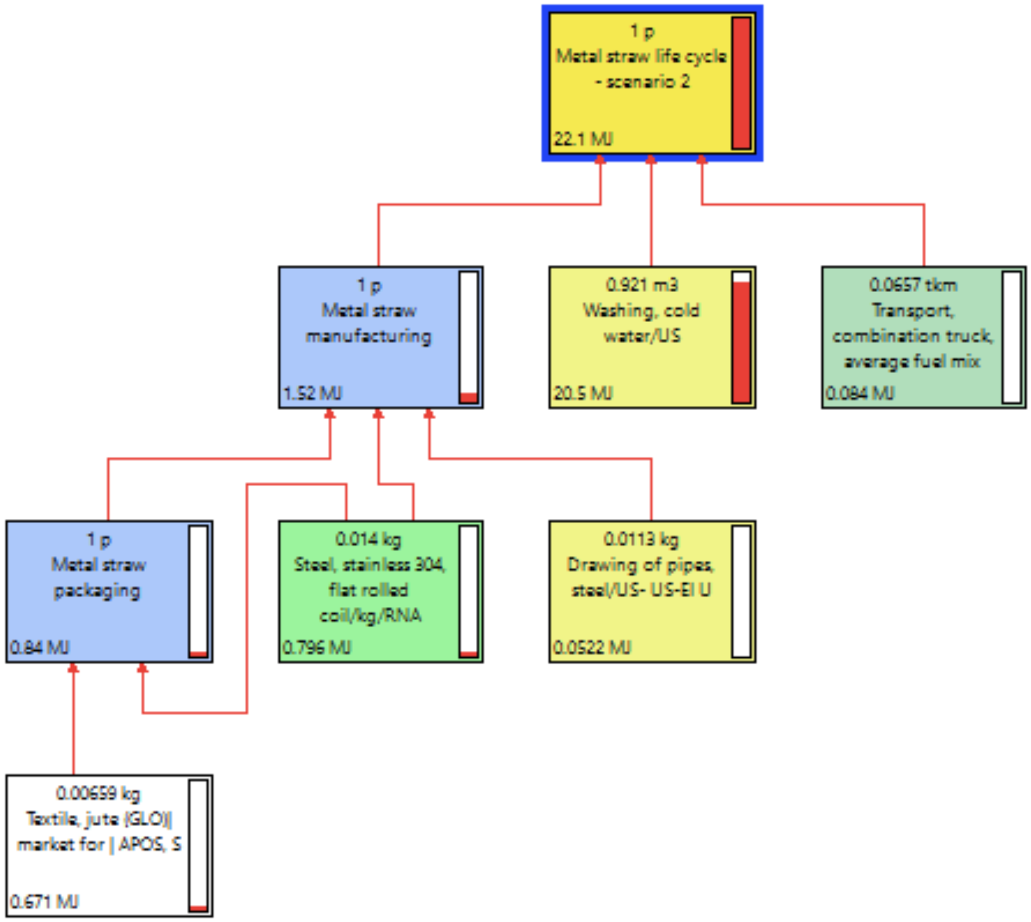

Figure B.5. Network model for Cumulative Energy Demand of the (reusable) metal straw for Scenario 2 – cold water washing at standard washing time (functional unit equivalence)

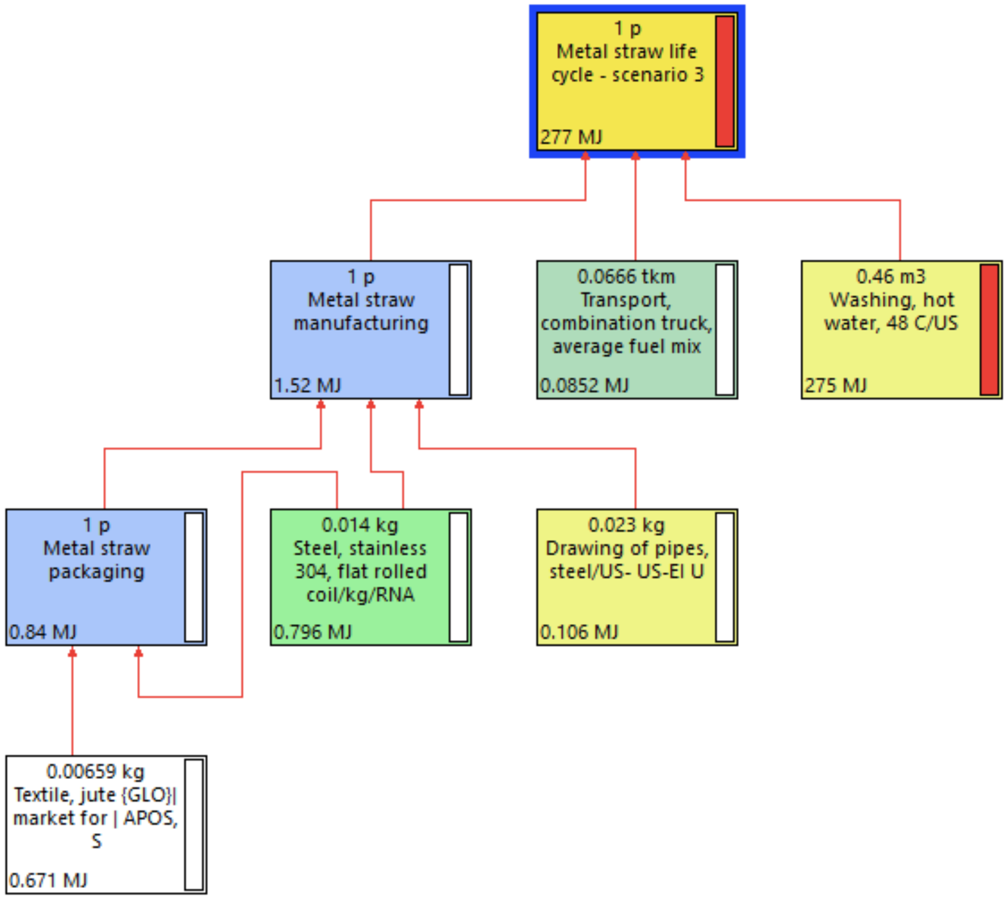

Figure B.6. Network model for Cumulative Energy Demand of the (reusable) metal straw for Scenario 3 – hot water washing at half of standard washing time (functional unit equivalence)

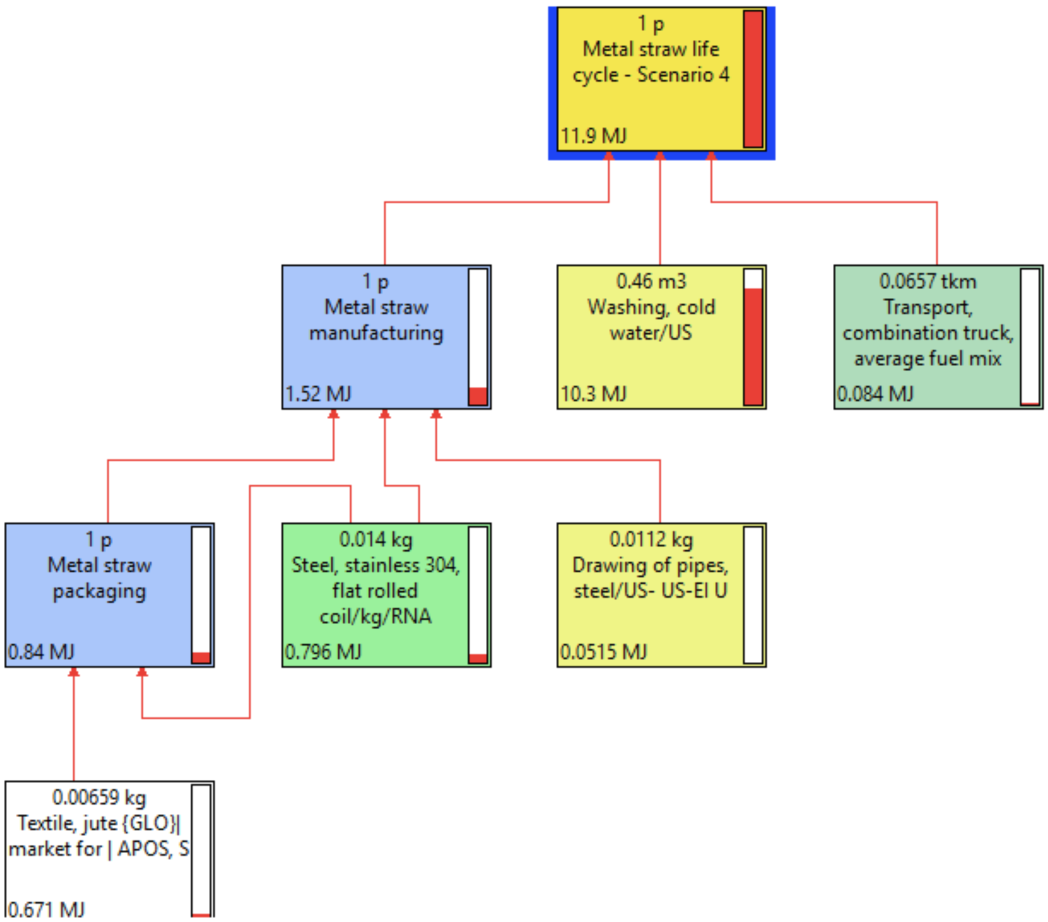

Figure B.7. Network model for Cumulative Energy Demand of the (reusable) metal straw for Scenario 4 – cold water washing at half of standard washing time (functional unit equivalence)

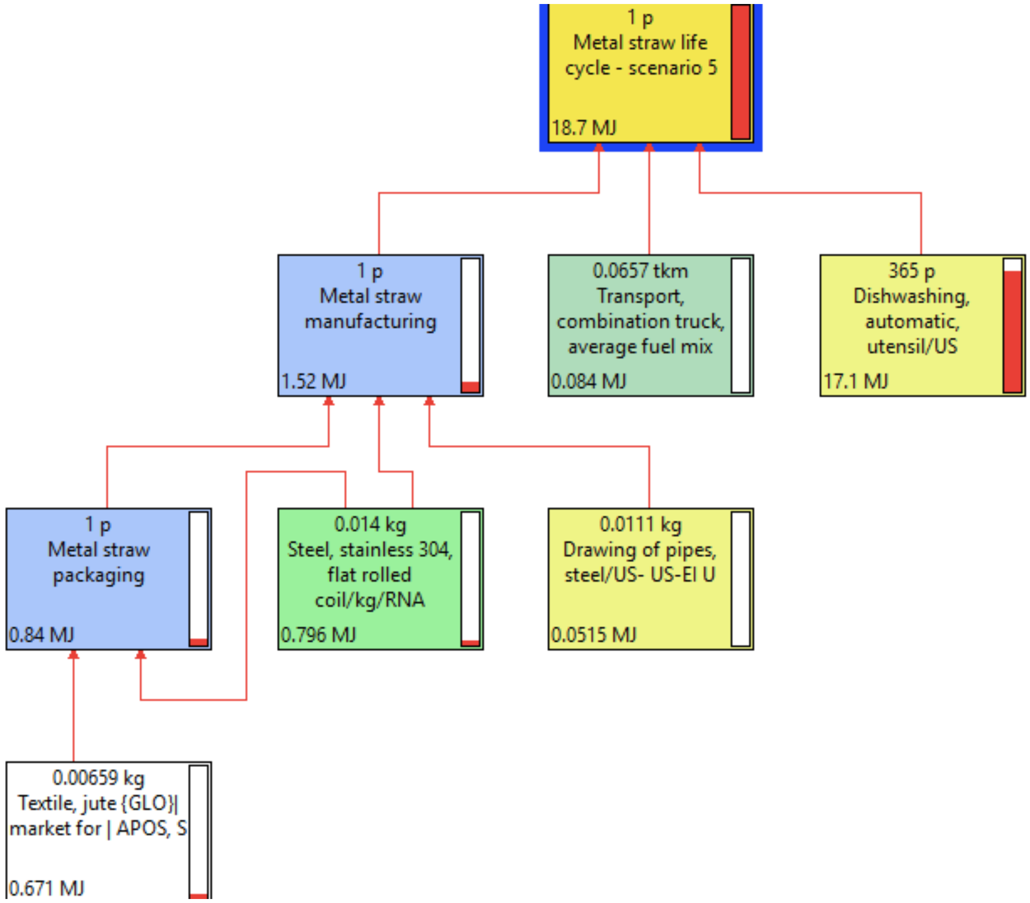

Figure B.8. Network model for Cumulative Energy Demand of the (reusable) metal straw for Scenario 5 – use of a dishwasher (functional unit equivalence)

B.2 Network Models for Global Warming Potential (IPCC 2013 GWP 100a V1.03)

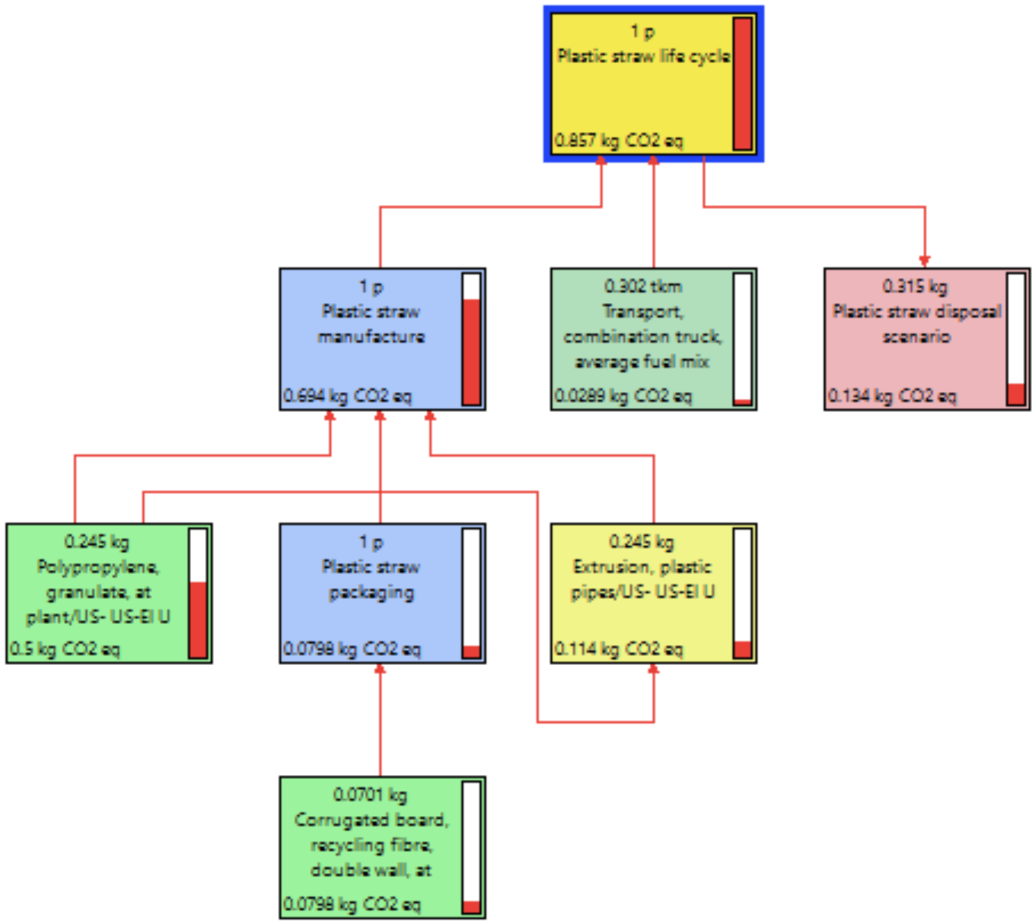

Figure B.9. Network model for Global Warming Potential of the standard (single-use) plastic straw (functional unit equivalence)

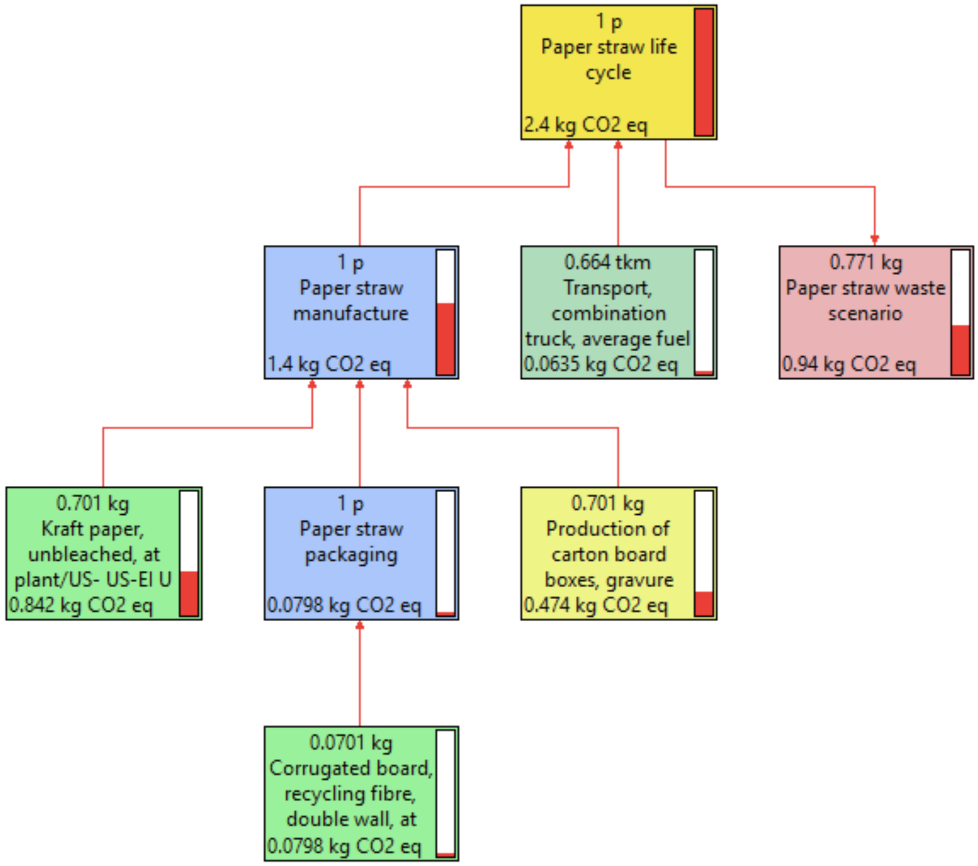

Figure B.10. Network model for Global Warming Potential of the paper straw (functional unit equivalence)

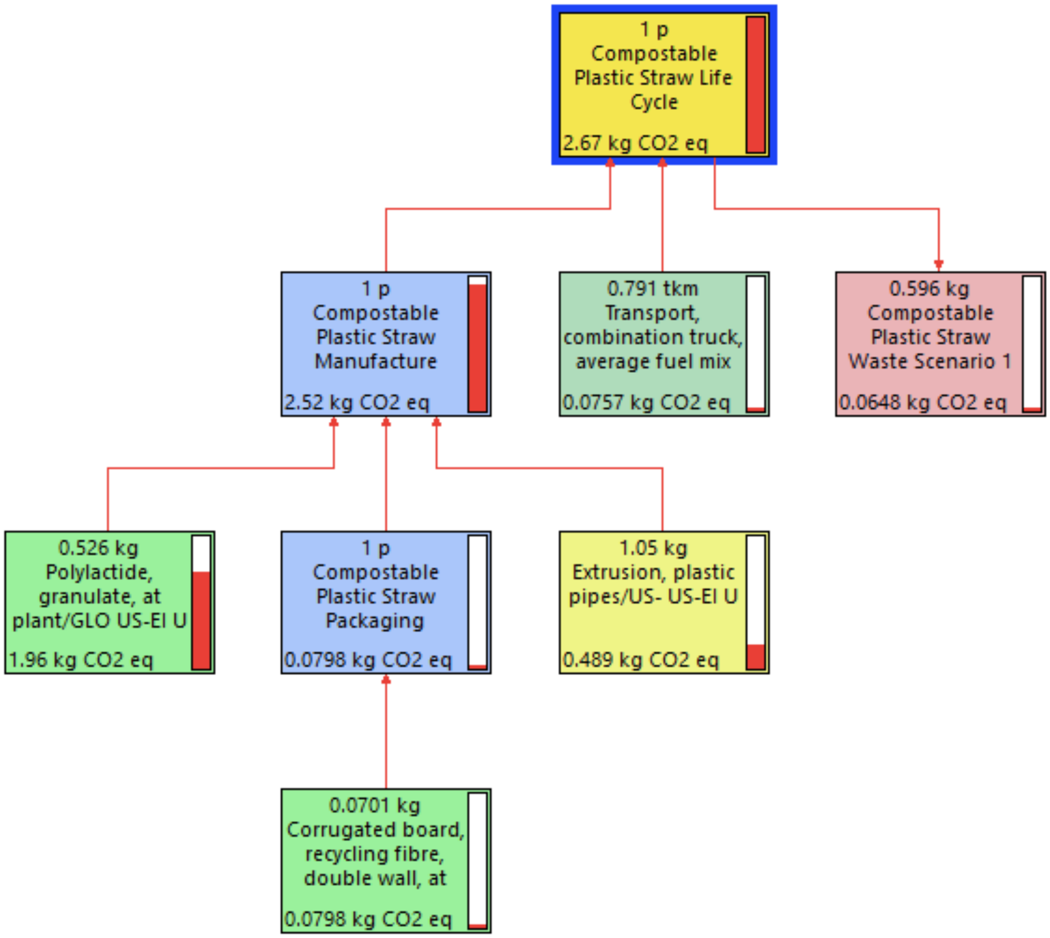

Figure B.11. Network model for Global Warming Potential of the bioplastic/compostable plastic straw (functional unit equivalence)

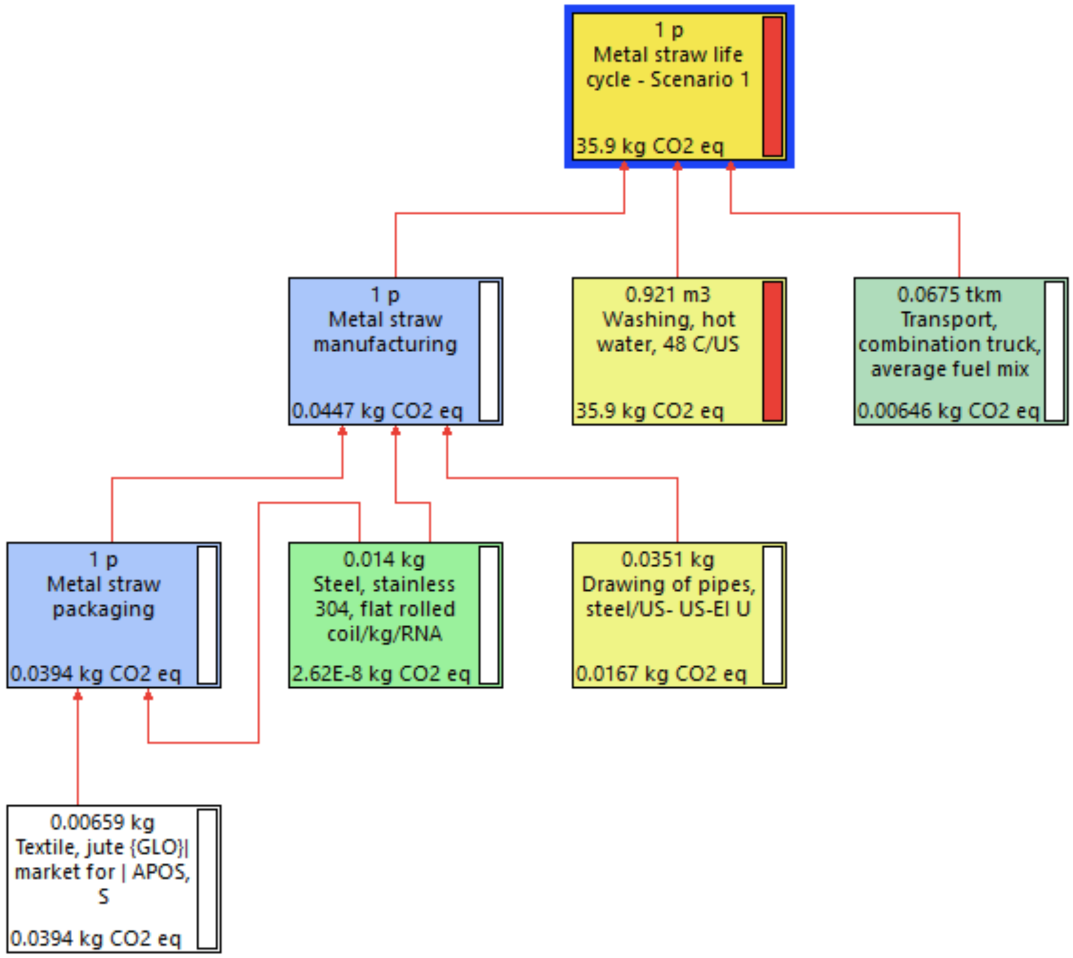

Figure B.12. Network model for Global Warming Potential of the (reusable) metal straw for Scenario 1 – hot water washing at standard washing time (functional unit equivalence)

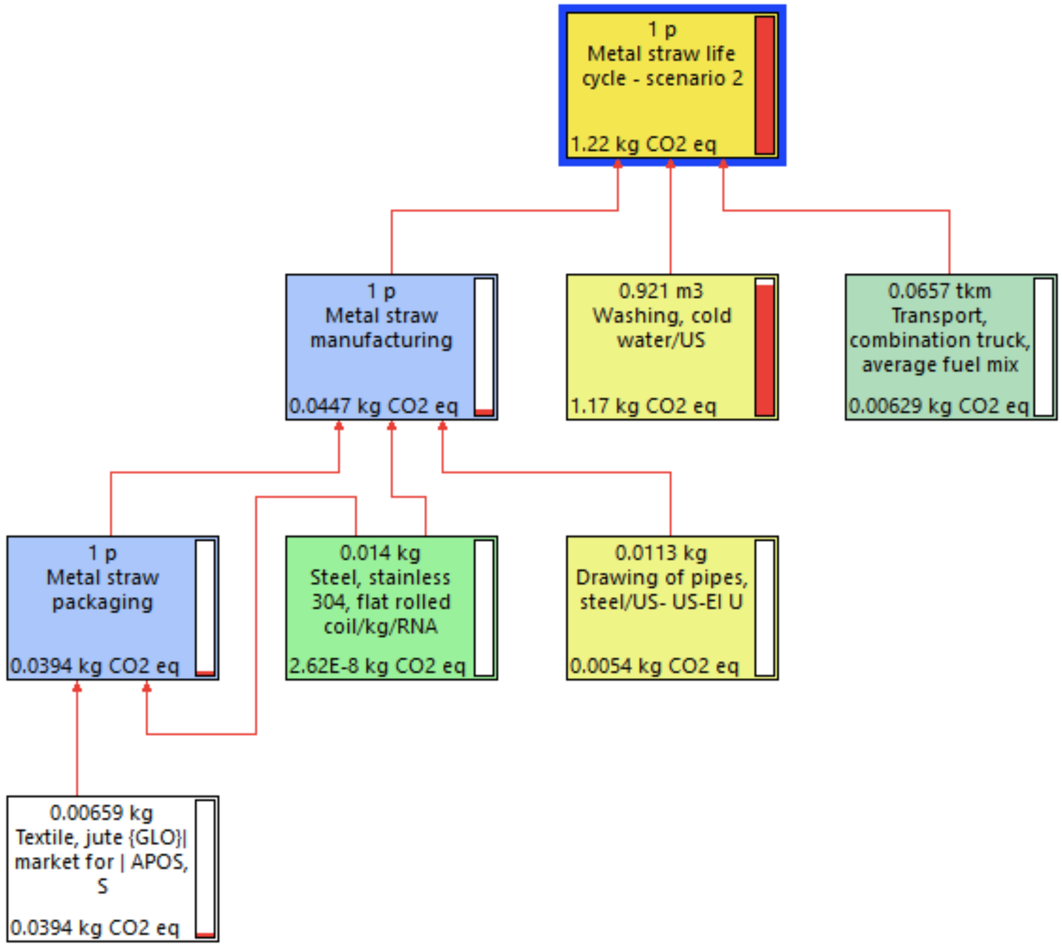

Figure B.13. Network model for Global Warming Potential of the (reusable) metal straw for Scenario 2 – cold water washing at standard washing time (functional unit equivalence)

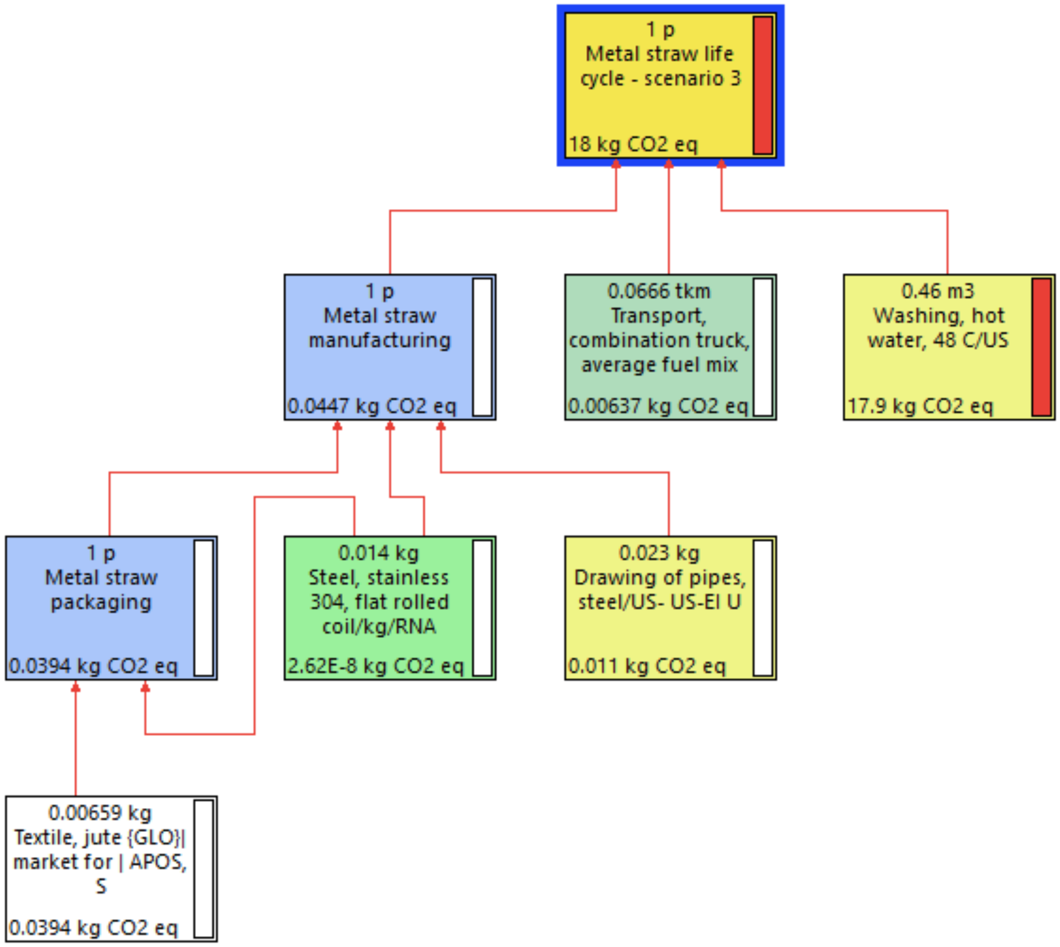

Figure B.14. Network model for Global Warming Potential of the (reusable) metal straw for Scenario 3 – hot water washing at half of standard washing time (functional unit equivalence)

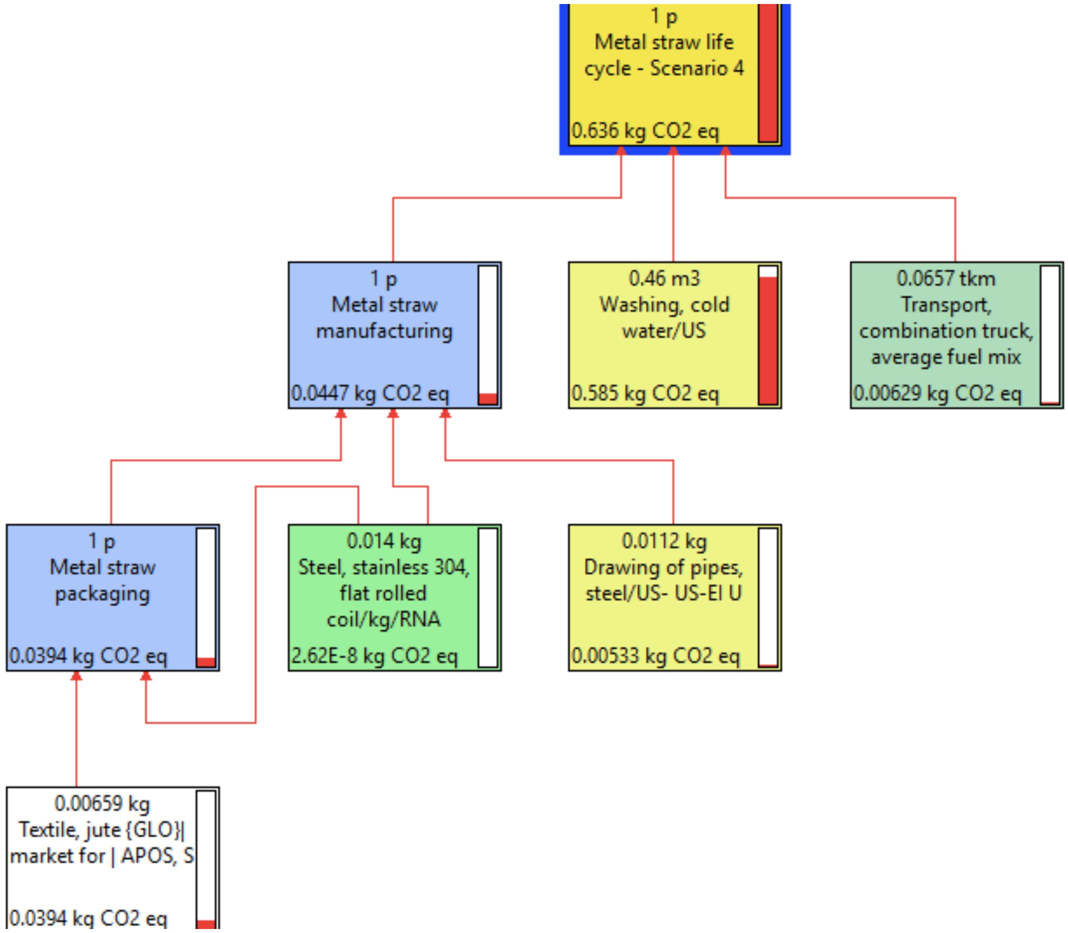

Figure B.15. Network model for Global Warming Potential of the (reusable) metal straw for Scenario 4 – cold water washing at half of standard washing time (functional unit equivalence)

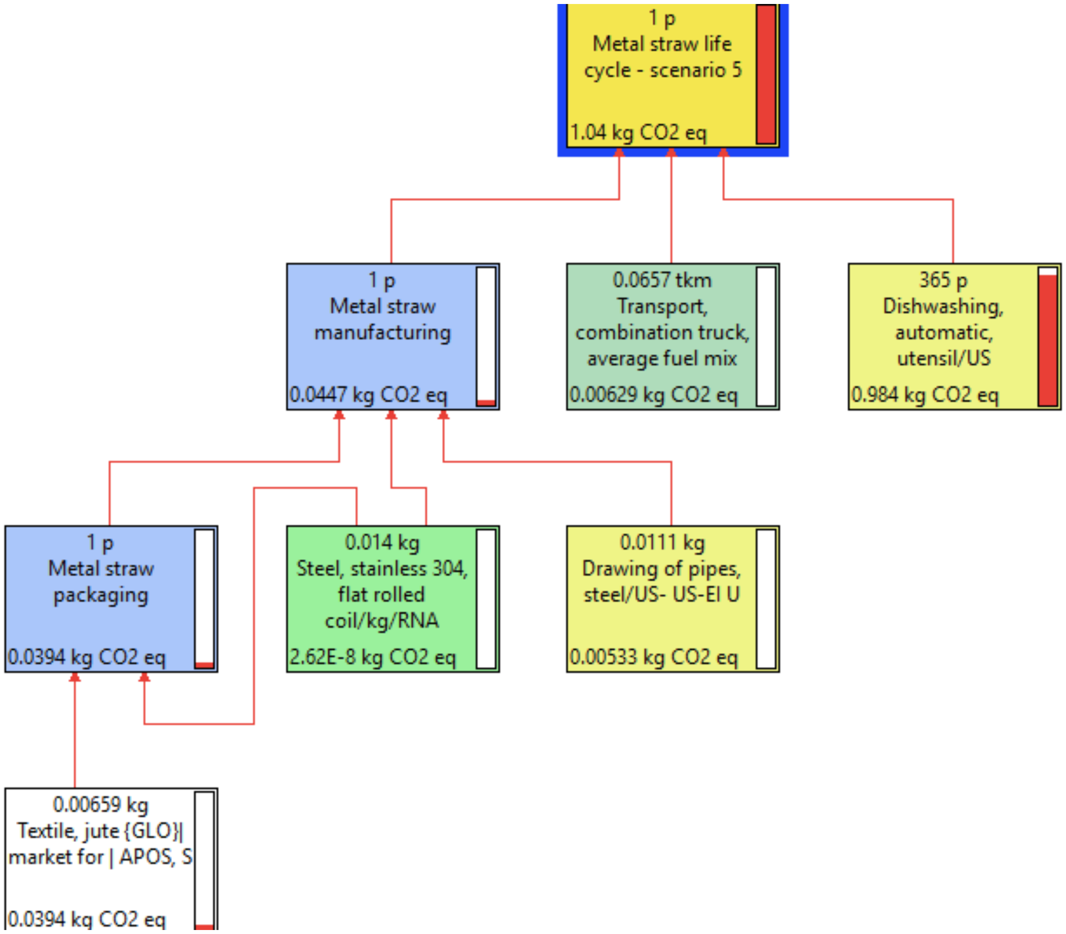

Figure B.16. Network model for Global Warming Potential of the (reusable) metal straw for Scenario 5 – use of a dishwasher (functional unit equivalence)