Assessing the Feasibility of Chemical Recycling for Plastics in Copenhagen

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Abstract

The incineration of plastic waste releases substantial amounts of CO_2 and terminates the plastic's lifespan, both of which are counter to Copenhagen's carbon-neutral or circular economy goals. Our project team, partnering with Copenhagen Solutions Lab and Amager Resource Center, investigated and analyzed chemical recycling processes in order to develop more circular and sustainable practices for waste plastics in Copenhagen. The results show that pyrolysis is the most technically and operationally feasible process considering the city's plastic waste streams, waste processing system, stakeholder perspectives, and consumer participation.

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Executive Summary

Introduction

In response to the challenge of climate change, the city of Copenhagen developed the CPH 2025 Climate Plan to strategically reduce CO_2 emissions across the municipality. This plan, set in motion in 2012, included the ambitious goal of becoming the world's first carbon-neutral city by 2025. Currently, the city incinerates residual waste to produce heat and electricity for use in the municipality. Unfortunately, plastic waste can be incorrectly placed among residual waste bins by consumers, consequently causing the plastic waste to be incinerated. The incineration of plastic releases substantial amounts of CO_2 and terminates the plastic's lifespan, which counters Copenhagen's goals for carbon neutrality and a circular economy of plastics.

The concept of chemical recycling offers a potential solution to reduce the carbon footprint and improve the lifespan of plastic waste. Chemical recycling is defined as the recovery of a plastic's chemical constituents in monomers, oligomers, or other intermediates such as fuels or waxes, through a depolymerization process. This depolymerization allows for the outputs of chemical recycling to be used to make new virgin-like plastics. In addition, chemical recycling does not release the drastic amount of CO_2 that incineration does, as it is not a combustion-heavy process. These features prompted an exploration into the opportunity chemical recycling presents for Copenhagen.

Goals and Objectives

In collaboration with Copenhagen Solutions Lab (CSL) and the Amager Resource Center (ARC), this project aimed to investigate plastic chemical recycling processes that could serve as an alternative to incineration, and to produce a feasibility study on implementing chemical recycling within Copenhagen. This feasibility study considered factors such as environmental impact, circularity, and compatibility with the current waste processing system in order to help Copenhagen reach its goal to become carbon neutral by 2025.

Investigating Chemical Recycling

The investigation of existing chemical recycling processes was completed through both preliminary research and semi-structured interviews of five private firms that actively implement chemical recycling processes. The team reviewed Copenhagen's current waste processing system with an environmental manager at ARC, which provided an understanding of how chemical recycling could become part of Copenhagen's sustainability infrastructure. This helped the team pose effective inquiries to chemical and mechanical recycling professionals.

Assessing the Societal Impact

The infrastructure surrounding recycling continues to reflect Denmark's commitment to sustainability and improving consumer recycling. The team therefore considered changes that the city would need to undergo in order to adopt chemical recycling to the current infrastructure. To be conscious of the social impact chemical recycling would pose to consumers and stakeholders alike, the team conducted interviews with non-governmental organizations and other stakeholders based in or around Denmark. Local perspectives regarding Copenhagen's current waste processing system were vital in understanding the acceptance of a new recycling method.

Comparing the Technical Feasibility of Chemical Recycling Processes

Life cycle assessments (LCA) were conducted on different chemical recycling processes to assess the environmental impact of implementing each one within the current system. This was the most crucial component of the project for CSL and ARC. With the information gathered from our investigation and life cycle assessments, the team created a decision matrix to directly assess the technical extent to which each chemical recycling process was able to address Copenhagen's plastics issue.

Three main criteria were established as prerequisites to assess the existing chemical recycling processes. To be considered for implementation in Copenhagen, a process was required to take in mixed plastic waste as input because individual polymer sorting and multiple plastic recycling facilities would be expensive. A process must also produce plastic feedstock as an output in order to help Copenhagen progress toward the goal of material circularity. Finally, a process must provide a net reduction in carbon dioxide emissions compared to that of the current waste processing infrastructure. Four different chemical recycling processes were investigated to evaluate their compatibility based on these criteria. The advantages and disadvantages of each of these methodologies are detailed with respect to their fit for Copenhagen's goals.

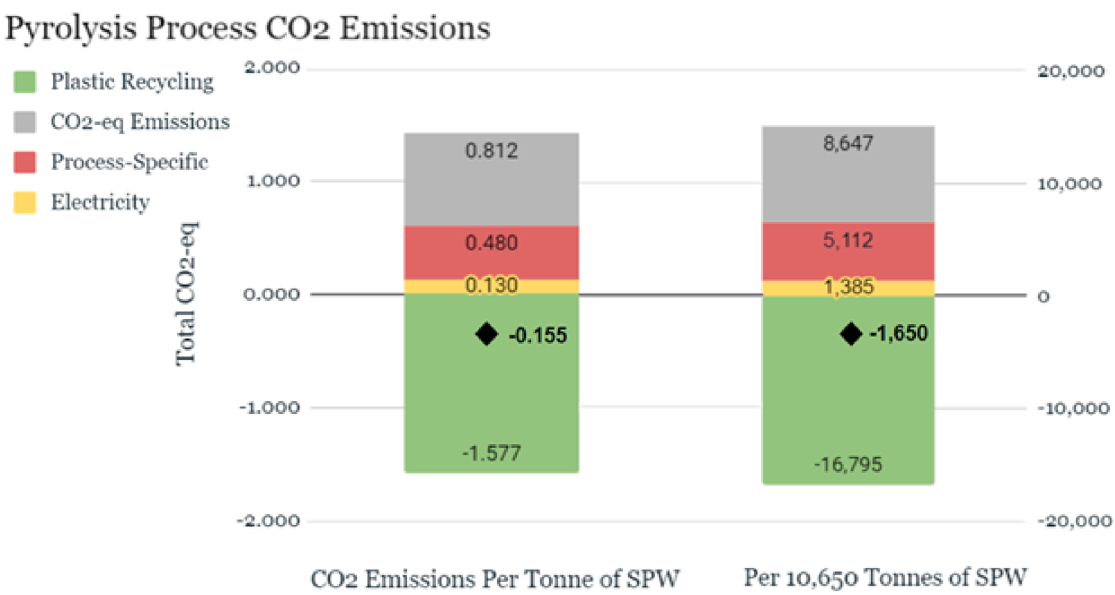
Out of the four processes investigated, pyrolysis was determined to be the most technically feasible chemical recycling process to implement within Copenhagen. It can take in the mixed plastic waste from the sorting facility and create fuels and feedstock for new plastic at a significantly low emissions cost.

How Pyrolysis Fits Copenhagen's Plastic Puzzle

Pyrolysis, a thermolysis process, met the three established criteria for chemical recycling in Copenhagen. Pyrolysis heats mixed plastic waste at high temperatures to melt and break apart the chemical bonds in plastic polymers, yielding hydrocarbon oils that can be used as fuels or plastic feedstock. Pyrolysis is primarily effective for ASTM International plastic types 4-7, but it can process smaller percentages of types 1-3. The Copenhagen residual waste stream contains a heavy distribution of types 4-7 with lower percentages of types 1-3, and thus it was determined that pyrolysis could process an average mix of this plastic waste. In the near future, these plastics will be sorted out of the residual waste stream by a sorting facility. The facility was estimated to be about 80% efficient. This means that for the annual waste stream which contains 12,505 tonnes of mixed plastic, around 10,650 tonnes of plastic will be sorted to be chemically recycled. This total does not account for polyvinyl chloride (PVC) or certain other types of plastic in the waste stream.

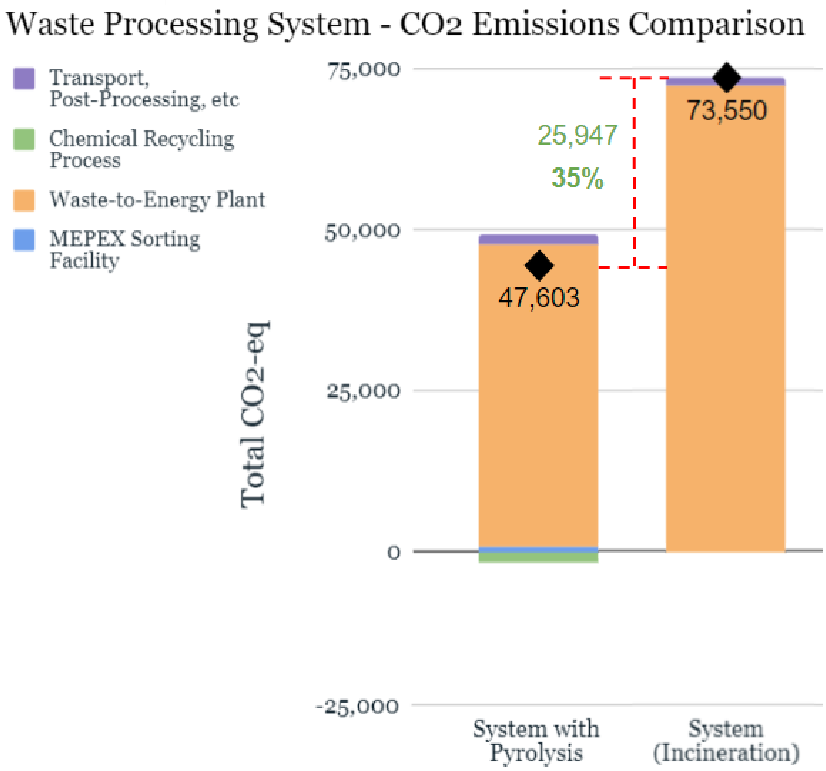
The primary output of pyrolysis is hydrocarbon oil, consisting of carbon and hydrogen molecules linked together in long chains. Depending on the pyrolysis operating parameters, the types and lengths of yielded hydrocarbon chains can differ. After studying the outputs of multiple pyrolysis processes, it was determined that a majority of the hydrocarbon oils produced can be considered as diesel fuel. However, 10% to 25% of the oils can be classified as naphtha, which is a light oil that serves as the primary feedstock for plastic production around the world. Producing naphtha from plastic waste, as opposed to the traditional way from mined crude oil, allows plastic to be reused in a circular fashion.

Pyrolysis also allows for a reduction in CO_2 emissions. The net CO_2 emissions from pyrolysis were calculated to be about -0.155 tonnes of CO_2 emitted per tonne of solid plastic waste processed. This total incorporates the process-specific CO_2 emissions, CO_2-equivalent emissions, electricity consumption, and reduction from recycling the plastic waste. When applied to Copenhagen's 135,000 tonnes of residual waste in 2019, of which about 10,650 tonnes is plastic, the pyrolysis process itself would remove approximately 1,650 tonnes of CO_2 from the atmosphere. This breakdown of emissions can be viewed in the figure below.



The waste processing system with pyrolysis was modeled in the EASETECH life cycle assessment application, developed at the Technical University of Denmark, where the system's impact on global warming was examined in a full-scale sense. Considering the emissions from the pyrolysis process, waste-to-energy plant, sorting facility, and other factors like transport vehicles, the waste processing system with pyrolysis accounted for about 47,603 tonnes of CO_2 emissions. The current waste processing system, which only includes the waste-to-energy plant and transport vehicles, accounted for about 73,550 tonnes of CO_2 emissions.

When all these factors are considered, a transition to chemical recycling in the waste processing system would achieve a reduction of about 26,000 tonnes of CO_2 emissions. This reduction can be visualized in the figure below.



While pyrolysis was shown to be technically feasible, the team wanted to ensure that pyrolysis would not pose any drastic social implications. Considering stakeholders, the team was able to identify the change resistance towards chemical recycling as well as attitudes towards Copenhagen's current recycling initiatives. The team also contemplated how a proposed process could impact the existing recycling habits and duties of consumers.

Despite some concerns about some negative attitudes towards chemical recycling, the team is confident in pyrolysis as a feasible methodology to save material from incineration, substitute the demand for producing new resources with the recycling of existing materials, and decrease carbon dioxide emissions; all while having little to no need for additional consumer participation.

Conclusion

The team's analysis suggests that pyrolysis is the most technically and operationally feasible chemical recycling process for Copenhagen to pursue. Pyrolysis converts a mixed plastic waste input into feedstock for new plastic material, addressing the need for a more ethical usage of the world's existing resources through circularity. It also helps Copenhagen move closer to the environmental goals outlined in the CPH 2025 Climate Plan by potentially reducing CO_2 emissions from the waste processing system by about 35%. As we address the evolving issue of climate change, we must always consider that it is our responsibility to protect and manage the world's natural resources more ethically.

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CHAPTER 1
Introduction

The evolution of climate change and its potential for irreversible environmental damage catalyzed an international movement, which called for a more ethical usage of the world's existing resources. In 2015, multiple nations drafted the Paris Agreement to formally address the demand for more sustainable practices. The agreement's articles especially urged ratifying nations to reduce greenhouse gas emissions, like CO_2, to keep the increase in global temperature below 2°C more than pre-industrial levels (Paris Agreement, 2015).

The emphasis on emissions in the Paris Agreement reaffirmed Copenhagen's CPH 2025 Plan adopted in 2012, which included the ambitious goal of becoming the first carbon-neutral city in 2025 (Technical and Environmental Administration, 2012). The plan focused on developing emission-friendly alternatives that would also contribute to a circular economy. A circular economy is an economic system which asserts a holistic approach to optimizing the flow of materials and to prioritizing the reuse of resources. This is ideally achieved by repurposing resources already present in the system, while maintaining their value, integrity, and quality (Gray, 2019).

Copenhagen (CPH) has already integrated this concept into their waste processing system. In 2017, the city opened a new waste-to-energy plant known as Amager Bakke in its Amager Resource Center (ARC), shown in the illustration at the beginning of this chapter. This facility is capable of processing and incinerating over 450,000 tons of waste (Valence, 2019) while simultaneously generating heat for

160,000 homes and electricity for another 62,500 each year ("Case: Amager Bakke", n.d.). Although incineration is a strong first step in the pursuit of a circular economy, transforming waste into energy, there are two fundamental challenges with this practice that hinders Copenhagen's carbon-neutral plan.

The first challenge is the sheer volume of CO_2 created from waste incineration. ARC estimates that Amager Bakke produces about 160,000 tons of CO_2 each year (Amager Resource Center, n.d.). In particular, plastic waste (when compared to other waste items) disproportionately creates more CO_2 when burned. Due to difficult-to-recycle plastics and errors by consumers, plastic waste can be incorrectly placed among residual waste.

The second challenge incineration presents is downgrading. Downgrading occurs when a process diminishes the material properties of a recycled plastic, such that the output of the process is of lower quality compared to the original material (Lesli, 2016). In this context, downgrading prevents recycled plastic from being used as an input to make its original product. And so, incineration downgrades plastic to a single-use fuel to produce energy. In an ideal process, waste plastic reprocessing would create a product with equivalent properties for reuse (Gaia, 2019).

Both challenges involving the incineration of plastics have prompted investigations into alternative methods to recycle plastic waste. In collaboration with Copenhagen Solutions Lab (CSL) and the Amager Resource Center (ARC), this project aims to investigate plastic chemical recycling processes, that could serve as an alternative to incineration, and to produce a feasibility study on the implementation of new methodologies. This feasibility study will consider factors such as environmental impact, downgrading and circularity, compatibility in the current waste processing system, and the reduction of plastic waste in order to help Copenhagen reach its goal to become carbon neutral.

CHAPTER 2
Background

In this chapter, Copenhagen's progress and initiatives towards carbon-neutrality, as established in the CPH 2025 Climate Plan, are further detailed. In order to understand the technical aspect of this project, an overview on how plastics can be recycled, including classifications, methods, and challenges is provided. Finally, the Danish consumer contribution and current perspective regarding recycling is discussed to create a frame of reference for recycling practices in Copenhagen.

2.1 CO_2 Reduction Efforts

The CPH 2025 Climate Plan targets carbon neutrality by stressing improvement in the following four pillars: energy consumption, energy production, green mobility, and city administration. The plan is split into three phases: Phase 1, from 2013-2016, Phase 2 from 2017-2020, and Phase 3 from 2021-2025 (Technical and Environmental Administration, 2012). Each phase sets milestones and addresses specific actions to be taken in the four pillars, such that progress towards carbon neutrality is continuous, as shown in **Figure 1**.

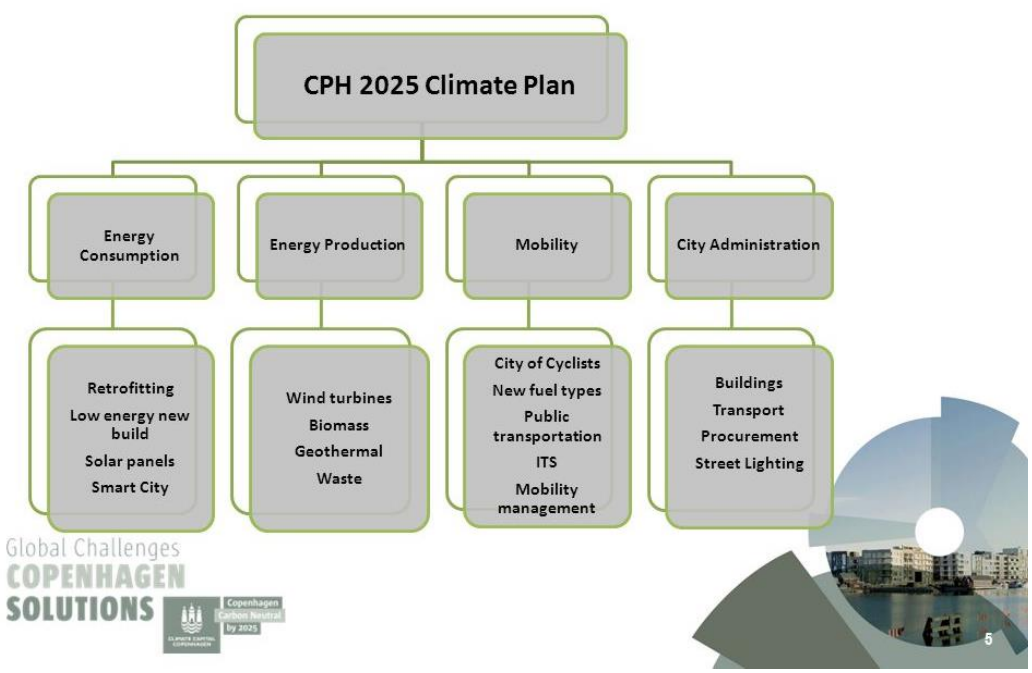

Figure 1: CPH 2025 Climate Plan Pillars (Abildgaard, 2017)

As of 2012, it was estimated that three of the four pillars would collectively account for just 20% of CO_2 reduction in the city. The remaining 80% was attributed to initiatives in the energy production pillar (Technical and Environmental Administration, 2016). In Phase 1 of the Climate Plan, considerable progress was made toward improving this pillar, as the foundations for key objectives were identified. These objectives include the installation of wind turbines in and around Copenhagen, and the transition from traditional coal-fired power plants to a new biomass-fueled heat and power plant. The channels through which energy is produced for the city, the resource used for the generation, and their relationship to one-another are shown in **Figure 2**.

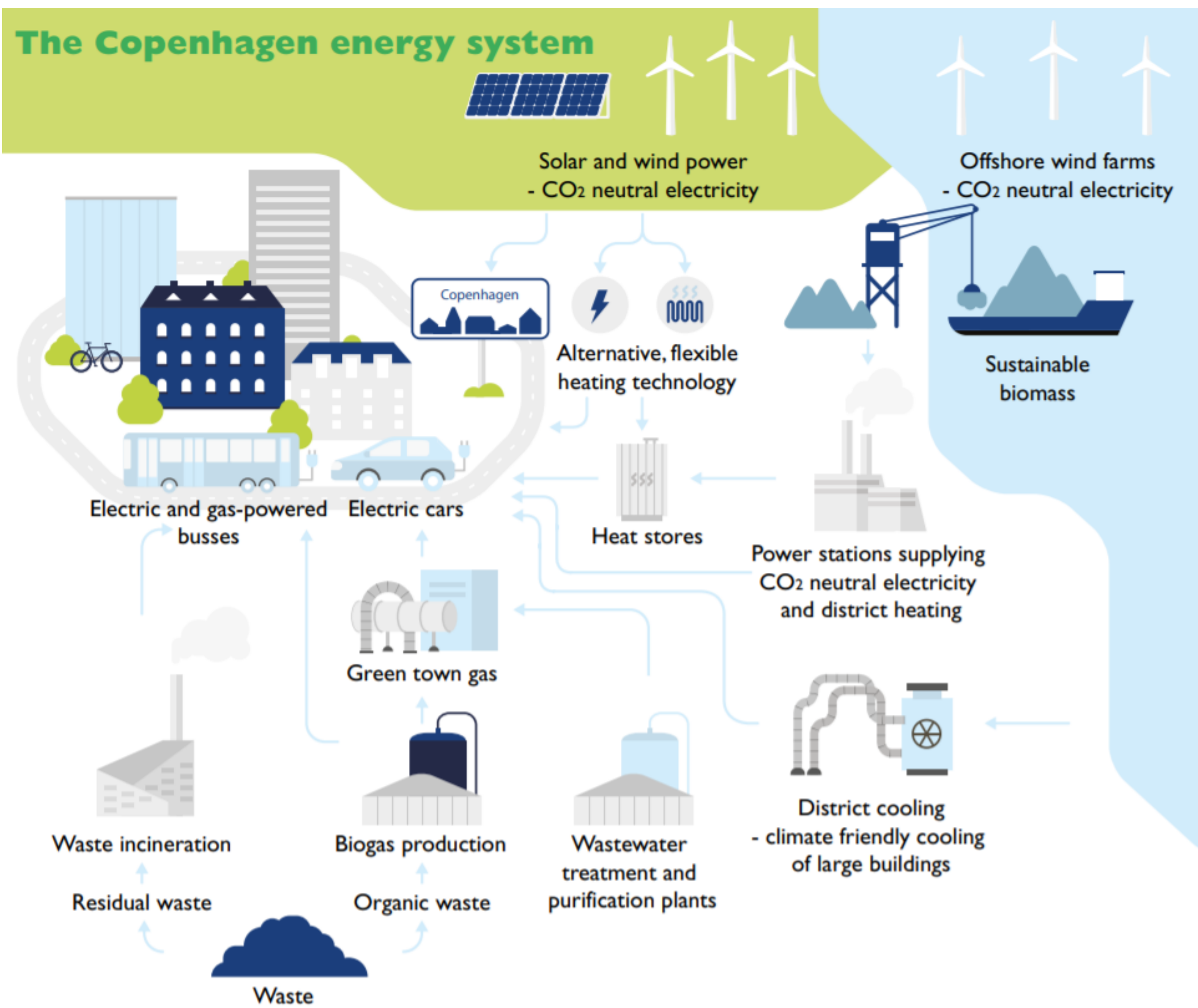

Figure 2: The Copenhagen Energy System (Technical and Environmental Administration, 2012)

Despite these alternative energy channels, the separation of plastics from other waste to be incinerated still accounted for nearly 102,000 tons of CO_2 generated from the energy production pillar as visualized in **Figure 3** (Technical and Environmental Administration, 2012).

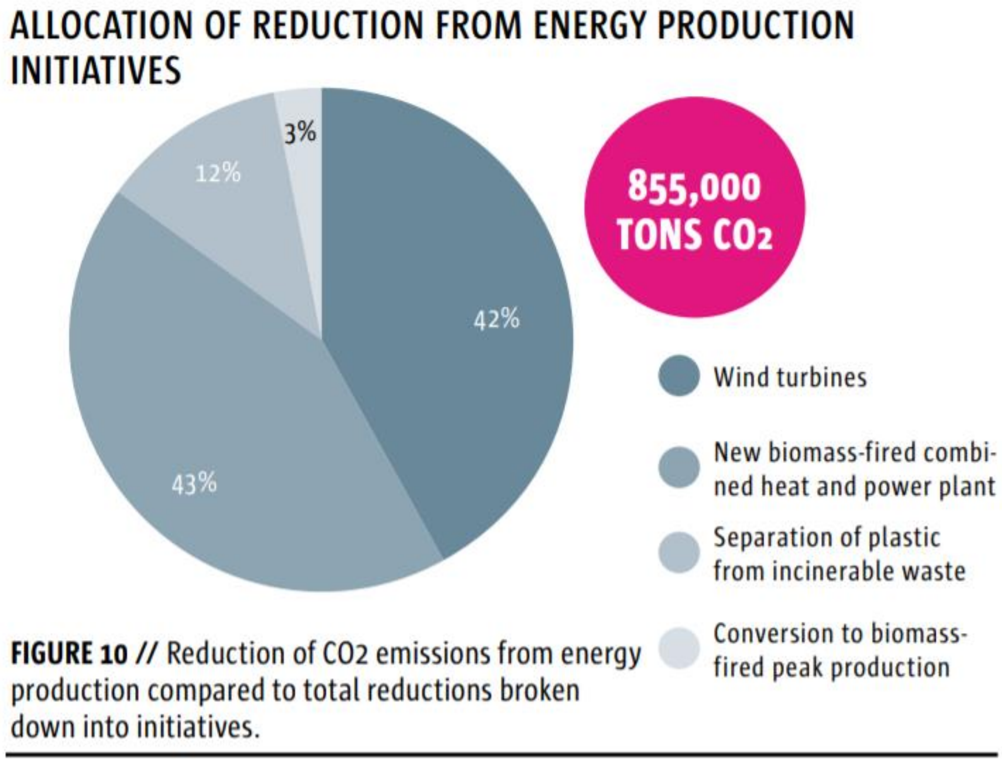

Figure 3: Allocation of Reduction from Energy Production Initiatives (Technical and Environmental Administration, 2012)

2.2 Recycling

Recycling includes various methods to reuse and preserve existing resources which can contribute to a circular economy by maintaining a sustainable outlook while actualizing a cyclic use of materials. Denmark has investigated tertiary recycling as a competitor to existing incineration, with a goal of introducing more environmentally conscious processes that ultimately reduce plastic waste. However, the actualization of various plastic recycling practices can introduce multiple challenges.

2.2.1 Recycling Classifications

In its simplest terms, recycling can be defined as the recovery and reprocessing of waste in order to regain material suitable for reuse in new products (The Editors of Encyclopedia Britannica, 2019). Within the discussion of plastics recycling, three classifications for relevant terminology can be made: the recycling activity, the recovery product, and the recycling stream(s).

For the first classification, recycling activities are organized into Primary, Secondary, Tertiary, and Quaternary levels of recycling.

Primary Recycling is the reuse of plastic in its original structure thus yielding a product with equivalent properties (Hopewell, 2009). Primary recycling can occur either through mechanical processes or personal consumer contributions. Mechanical processing includes but is not limited to activities such as sorting, grinding, melting, and reforming.

Secondary Recycling, commonly referred to as downgrading, also involves mechanical processing where the chemical polymer is not altered (Hopewell, 2009). Secondary recycling creates recycled plastics whose application is applied to products with lower properties. Downgrading is most commonly used to describe how the recycled plastic creates a product of both lesser material and monetary value compared to the product produced by the virgin plastic (Grigore, 2017).

Tertiary Recycling, also known as chemical recycling, is the recovery of a plastic’s chemical constituents (i.e. monomers, oligomers, or other intermediates such as oils or waxes) through a type of depolymerization process (Sharobem, 2010). It should be noted that biodegradable plastics fall into the tertiary recycling category due to their ability to be composted and return to their organic properties (Ragaert, 2017).

Quaternary Recycling is energy recovery where the processing of the plastic waste indirectly uses the heat byproduct to produce electricity (Sharobem, 2010).

For the second classification, the recycling recovery terms make comments on the lifecycle of a plastic from the virgin polymer to waste plastic and beyond.

Open Loop recycling describes waste plastic that is used for a different product than the one they were originally recovered from (Grigore, 2017). This does not necessarily imply that the different product is of lesser value than the original product. Examples include manufacturing textile fibers from PET bottles or forming printer components from polycarbonate water bottles (Ragaert, 2017).

Closed-Loop recycling describes recycled plastics that are used to produce the same product they were originally recovered from (Eriksen, 2019). The new product can be made entirely from recycled plastics or a combination of recycled plastic and virgin plastic (Ragaert, 2017).

For the final classification, the recycling stream(s) terms distinguish the measures the waste producer individually takes to source separate their recyclables.

Single Stream recycling is when multiple types of post-consumer recyclables are bundle-sorted from residual waste. For example, glass, paper, and plastic, would be placed into one recycling bin and to be sorted into their proper constituent types once collected (LeBlanc, 2020).

Multi-Steam recycling is when each type of post-consumer recyclable is source-sorted into their respective fractions (Here’s how to sort, n.d.). This is often encouraged by having recycling centers or multiple recycling bins for each stream or fraction such as glass, paper, plastic, metal, etc. (LeBlanc, 2020).

At the heart of a circular economy, plastics would ideally be transformed through either primary, secondary, or tertiary recycling in such a manner that they are recycled in a closed loop (Ministry of Environment and Food, 2018). The direct reuse of pre-existing plastics, through chemical recycling, while reducing the excess waste of recyclables, is the primary goal of this project.

2.2.2 Types of Plastics Recycled

Plastics or Polymers is a general category within the four classifications of all materials. However, plastics can be distinguished into the following groups: Thermoplastics, Thermosets, and Elastomers. For this discussion of plastics recycling, the project is solely concerned with the thermoplastic subcategory.

Thermoplastics are characterized by their chemical composition and material properties or processability. Due to their linear or branched structure, thermoplastics are the most favorable among manufacturers because they can be melted and reformed iteratively for potentially infinite cycles (Shivkumar, 2019). The reversible processability, without experiencing degradation, makes these plastics available for processes such as extrusion, injection molding, rotational molding, blow molding, calendaring, and thermofolding (Grigore, 2017). It should be noted that the recycling for thermoplastics will never reach 100% efficiency, however thermoplastics still provide an opportunity for the waste material to be used again as an input to the same or new process. This quality distinguishes thermoplastics from their constituents.

For manufacturers and designers, thermoplastics can be further stratified by their qualities, material properties, processability, and cost (Shivkumar, 2019). Due to their low cost, a large majority of consumer plastic products are sourced from Commodity Plastics. Within Commodity Plastics, amorphous plastics are particularly attractive as they are easier to process and are more readily available. Unfortunately, this contributes to the overwhelming presence of single-use products because amorphous plastics are more difficult to recycle as a result of contamination and chemical leaching (Eriksen, 2019).

Overall, consumer plastic products are categorized into seven different categories with products having a corresponding number identification. The identification serves to inform a consumer or recycling center of the plastic's composition for the purpose of effectively sorting the plastics. The seven categories and common products are described by **Figure 4**. It is important to recognize that the chemical differences of the plastics require them to be recycled separately in order to be completely recovered (Achilias et al.,2012).

Figure 4: The Different Grades of Recycled Plastics (Seaman, 2012)

2.2.3 Tertiary Recycling and Incineration

Within tertiary recycling, often referred to as chemical recycling, there are two categories in which plastics can be broken into their respective constituents: via thermolysis or chemolysis. A summary of the distinctions between incineration, thermolysis, and chemolysis are found in **Table 1**. It should be noted that incineration is considered a quaternary recycling method.

Table 1: Comparison of Energy Retrieval Methods (Baytekin, 2013)

Method of energy recovery	Incineration	Thermolysis (Thermal or "petrochemical„ routes)	Chemolysis (Chemical routes)
Description	Burning	Pyrolysis (cracking without oxygen) Gasification (cracking with low oxygen) Hydrogenation (cracking with hydrogen)	Hydrolysis, aminolysis, glycolysis, methanolysis etc.
Most suitable polymer type	All (risk of producing carcinogenic products for some polymer types)	Polyolefins	Condensation polymers
Main products	Heat	Lighter hydrocarbons, fuel, coke	Monomers

Incineration recovers energy by using the heat to generate steam which would drive a turbine to ultimately produce electricity (Case: Amager Bakke, n.d.). The indirect usage of the heat is what distinguishes incineration from tertiary recycling. The process produces ash, flue gases, and the highest CO_2 emissions compared to the other thermolysis processes (Muthu, 2015).

Thermolysis is defined as the treatment of plastic waste in the presence of heat in a controlled temperature environment, without additional catalysts, that produces an intermediate output such as gas, oils, or waxes (Baytekin, 2013). Some of these constituents can be processed to make plastic feedstock.

Gasification is a thermochemical process that converts the carbonaceous material to synthesis gas (syngas). Waste, steam, and oxygen are fed into a gasifier where heat and pressure break apart the chemical bonds of the waste to form syngas (Sharobem, 2010). This allows the breakdown of hydrocarbons into the gaseous mixture by carefully controlling the amount of oxygen available (Al-Salem, 2009). Syngas may be used directly in internal combustion engines or to make products that substitute for natural gas, chemicals, fertilizers, transportation fuels and hydrogen (Thermochemical conversion processes, n.d.). Pollutants are removed from syngas before it is combusted, so that it does not produce the high levels of emissions associated with other combustion technologies (Muthu, 2015).

Pyrolysis also turns waste into energy by heating under controlled conditions but involves thermal degradation in the complete absence of air (Sharobem, 2010). Pyrolysis typically occurs under pressure and at operating temperatures above 430ºC (800ºF) (Sharobem, 2010). Pyrolysis produces char, pyrolysis oil, and syngas, all of which can be used as fuels, and can tolerate mixed contaminated plastics as inputs.

On the other hand, chemolysis is the decomposition of plastic waste using chemical agents or catalysts. Some of the most common chemical decomposition methods include hydrolysis, glycolysis, and methanolysis which use water, glycol, and methanol respectively as the catalyst to depolymerize a plastic (Muthu, 2015). Although chemolysis can only occur with condensation polymers, it is suitable for contaminated plastics as depolymerization removes toxicities such as polyvinyl chloride, sodium hydroxide, acidic glues, and acetaldehyde (Muthu, 2015).

Additionally, Photodegradation is a form of natural degradation for plastics which can be achieved by landfilling. When the plastic is subjected to UV light, often from the sun, it is provided with the activation energy to initiate the incorporation of oxygen atoms into the polymer, known as thermo-oxidative degradation (Grigore, 2017). Consequently, the plastic becomes brittle and fractures into smaller pieces until the polymer chains reach sufficiently low molecular weight to be metabolized by microorganisms. The microorganisms convert the carbon of the polymer chains to carbon dioxide or incorporate it into biomolecules, but this process will take at least 50 years (Grigore, 2017).

2.2.4 Challenges of Plastics Recycling

Although the framework, as well as the technology, surrounding plastics recycling exists, its execution in both implementation and efficiency administers multiple challenges. Each broadened process type has its own benefits and drawbacks as shown in **Table 2**.

Table 2: Summary of Discussed Recycling Techniques (Grigore, 2017)

Technique	Advantages	Challenges
Mechanical recycling	Cost-effective, efficiency, well-known	Deterioration of product's properties, pre-treatment
Chemical recycling	Operational for PET, simple technology	Mainly limited to condensation polymers
Energy recovery	Generates considerable energy from polymers	Not ecologically acceptable

For mechanical recycling, degradation and downgrading are the primary process concerns. Degradation will always occur during the lifetime of a polymer from exposure to heat, oxygen, light, radiation, and moisture (DeAndrade, 2016). These environmental conditions, in high concentrations, will significantly weaken a plastic. When processing, stress and heat are often applied to grind, compound, and pelletize the waste plastic. In response to the shearing of the polymer during the melt process, the plastic undergoes thermal-mechanical degradation (DeAndrade, 2016). In this degradation, chain scission and chain branching ultimately separates the carbon bond which generates free radicals that can undergo some chemical reactions (DeAndrade, 2016).

For chemical recycling, the process is limited to condensation polymers. Due to the chemical variance in the different types of plastics, one chemolysis recycling method would not be suitable for all plastic types. The individual treatment of plastics can be attributed to the immiscibility of polymer blends as well as the distinct catalysts required to depolymerize each plastic. When developing infrastructure for this type of recycling, facilities may be limited by the processes they choose to implement or the plastics they prioritize. In addition, processing obstacles like contamination, chemical leaching, and thermal degradation make complete recycling and recovery difficult. Therefore, for any chemical recycling process to be successful, a mechanical recycling process must also be present.

For energy recovery, speaking only of the incineration of plastics, the environmental hazards outweigh the benefits of energy production. Besides emitting CO_2, incinerating plastics also releases toxic substances such as noxious dioxins, furans, acid gases, and particulate matter into the environment. (Ragaert, 2019). For example, Polyvinyl Chloride (PVC) and halogenated additives are typically present in mixed plastic waste leading to the risk of dioxins, chlorine gas, other polychlorinated biphenyls being released into the environment (Hopewell, 2009).

These byproducts are particularly harmful to humans when exposed under high concentrations. The United States EPA cites dioxins and furans to cause hormonal levels to fluctuate, the development of a skin disease called chloracne, and as substances likely to be a cancer-causing substance (US EPA, n.d.). **Figure 5** indicates that most plastics are disposed of in this manner, which raises major environmental and health concerns.

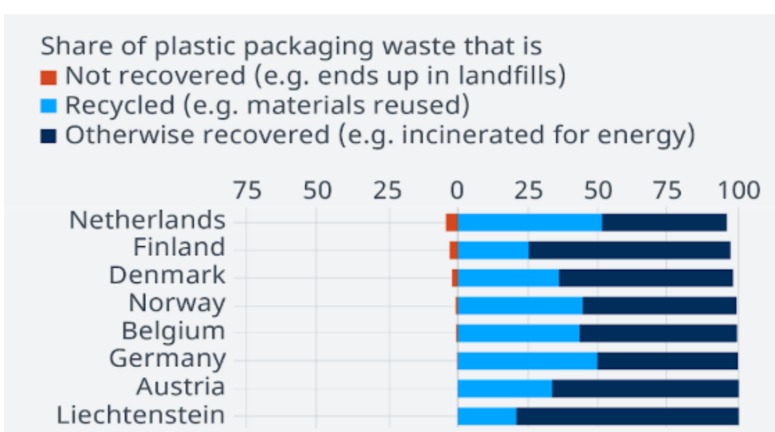

Figure 5: Summary of Plastic Recycling by Country (Eurostat, 2019)

For Denmark specifically, sorting errors are a primary culprit for the volume of plastic that is not recycled. Because Denmark participates in source-separation, it is ultimately the consumers' responsibility to properly recycle the plastic. As shown by **Figure 5**, about 50% of plastic waste is incinerated instead of being recycled which indicates that plastics are incorrectly being placed among residual waste. In addition, Denmark does not have the infrastructure to recycle their plastic waste. Currently, the plastic fraction is shipped abroad to places such as Germany and Sweden for processing. Although Denmark will be implementing a plastic sorting facility in 2021, this is only a preliminary step towards mechanical recycling.

2.3 Denmark's Consumer Contribution & Perspective

Denmark's attention and dedication towards environmental development has always been prominent. In 1978, Denmark introduced the world's first law on recycling, stating that at least 50% of all paper and beverage packaging should be recycled (Rosendal, 2014). Since then, further infrastructure has been created to support the recycling of 35 different waste fractions (Stefany, 2018). To become more flexible and experimental, Danish authorities also have legal ground for self-determination in relation to recycling - meaning that they have the right to take initiatives within the area of waste management as they see fit ("Reuse and recycling in Denmark," n.d.).

In 2013, the Danish government created the "Denmark without Waste" proposal which discussed necessary infrastructure for reducing waste and fulfilling another ambitious goal of recycling 50% of all household waste (Rosendal, 2014). With more attention to the diverse waste fractions, the government believed citizens could double their recycling rates for household waste, which would be a keystone in achieving this goal (The Danish Government, 2013).

This massive leap had two motivating factors: circular economy and incineration. A completely circular economy demands for the development of better waste processing and recycling practices ("Circular economy-definition," n.d.). Without these practices, the materials would only be utilized in one product cycle -- a neglectful manner to use existing resources in the eyes of the Danish (The Danish Government, 2013). Another motivating factor was the movement from incineration. Over recent decades, Denmark has been incinerating almost 80% of their household residual waste

(The Danish Government, 2015). While this process returns electricity and heating, other methods like biogas plants and wind energy were viewed as more effective in exploiting the energy received from waste (The Danish Government, 2015).

Currently, Denmark is diligent in making its recycling resources available to the consumer which include recycling centers, near-recycling stations (shown in **Figure 6**), trade centers, for public and private use. There are 10 recycling centers and 6 near-recycling stations are operating in the metropolitan area (Amager Resource Center, n.d.). The metropolitan centers alone have more than one million visitors each year with citizens and businesses delivering approximately 105,000 tons of waste per year (Amager Bakke waste-to-energy plant, n.d.).

Figure 6: Danish Recycling Center Drop-Off (Stefany, 2018)

Both the recycling centers and near-recycling centers serve as drop off points for the sorting of individual waste fractions. In recycling centers, waste can be distinguished into fractions that includes but is not limited to electronics, household appliances, metal, paper, glass, cardboard, PVC, wood, textiles, and hard plastic (Stefany, 2018).

The individual waste fractions, some shown in **Figure 7**, are characterized by having certain specific physical characteristics or qualities which make it economically, resource or environmentally advantageous to treat them separately (“Here’s how to sort,” n.d.). The waste that cannot be categorized by one of these fractions is regarded as residual waste and is collected curbside.

Figure 7: Danish Recycling Fractions (Here's how to sort, n.d.)

In alignment with a circular approach, the newest Sydhavn Recycling Center doubles as a classroom space, testing laboratory, gallery, and workshop space. To introduce recycling into the educational system, Sydhavn has developed a recycling curriculum with topics such as waste and sorting, the lifecycle of different types of waste, and waste travel (Copenhagen Municipality, n.d.). Often, there are partnership programs with local schools to visit both the recycling center as well as the incinerator at ARC (Copenhagen Municipality, n.d.). Moreover, to better inform all ages of recycling, Sydhavn hosts events such as debates, workshops, and presentations to reinforce the practice and importance of recycling (Copenhagen Municipality, n.d.). Finally, this recycling center has a laboratory partnership with the municipality as well as other entrepreneurs (Copenhagen Municipality, n.d.). The test laboratory specifically works with smaller organizations to better develop new material storage and recycling practices on tighter timelines.

In addition, the Rethink Plastic consortium, held by ARC, generated different 'design dogmas' with the hopes of influencing the way plastic products are made in order to make them recyclable (Eriksen, 2019). The established dogmas stressed that the product should be easy to separate for the consumer as well as use clear PET or mono materials to reduce contamination (Amager Resource Center, n.d.). Other specifications included suggestions on surface treatments, sealing, and labels. Ultimately, product design is key to enabling the circular economy by creating products of longer lifespan and greater recycling potential (Ellen Macarthur Foundation, 2013).

The existing efforts that Denmark has put forth are a strong reflection of the city's attempt to improve the recycling habits of consumers. The Danish public perception of recycling efforts has historically been positive, but it has wavered as of late September. In the fall of 2019, a 10-month investigation from Danish media companies concluded with a news story about Danish plastic waste that was supposedly exported for recycling found in dumps in Malaysia ("New discovery: Danish Waste," 2019). This has led to a slight distrust in the recycling and waste management systems in Denmark among the public (J. Nedenskov, personal communication, February 21, 2020). Near-future recycling systems will rely on the public trust of them, as consumers play a key role in ensuring plastics are source-segregated from other residual waste so that they aren't incinerated.

Overall, Danes share the same expectation, along with many Nordic countries, that it is a common responsibility to protect the world's natural resources. Denmark incentivizes and involves various groups of people from the common citizen, to up-and-coming organizations, entrepreneurs, and global partners in their recycling initiatives. By leading from example, as well as providing the necessary tools, the government has empowered the people to participate in pursuing sustainable outlooks.

CHAPTER 3
Methodology

This chapter describes the methods developed to achieve the mission of the project. The team's mission is to explore alternatives to the incineration of recycled plastics and to produce a preliminary feasibility study on the implementation of new chemical recycling technologies. From the project mission, the following objectives were created:

1. *To investigate selected existing commercial chemical recycling processes and to assess the efficacy of their outputs and input specifications.*

2. *To assess how the implications of a newly proposed process, compared to the existing waste processing system, would be perceived by stakeholders in Copenhagen.*

3. *To compare the environmental and operational aspects between each proposed chemical process.*

4. *To produce a preliminary feasibility study on implementing and integrating the chemical recycling processes with current incineration practices to propose the most viable alternative.*

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A roadmap of the project's methodology can be seen in **Figure 8** below.

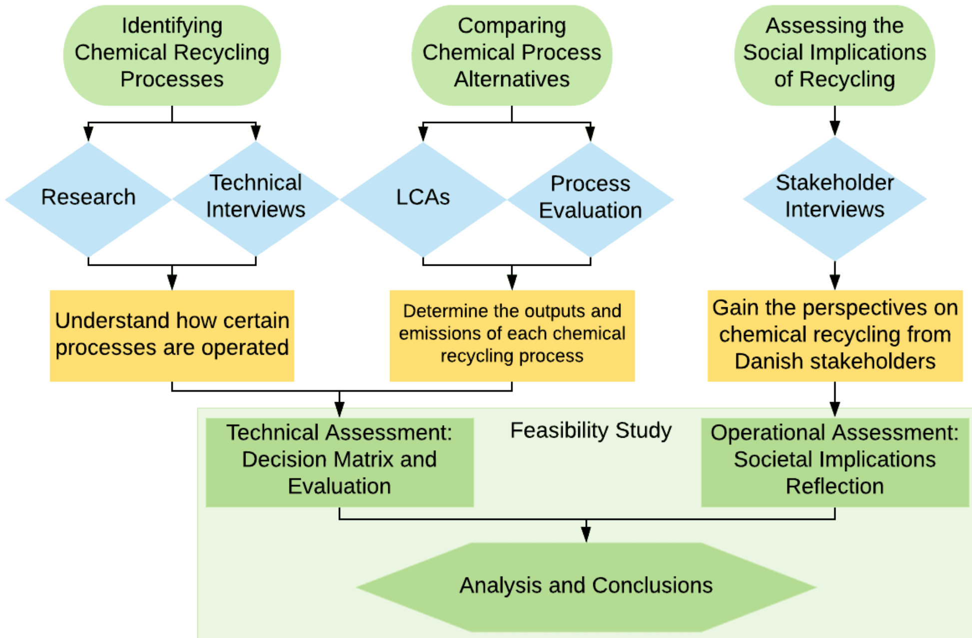

Figure 8: Project Methodology Road Map

The methodology roadmap demonstrates the objectives in green, the methods in blue, and the intended outcomes in yellow. The following sections in this chapter describe the methods used to complete the project objectives. The Gantt Chart in **Appendix 1** was created to outline the timeline of the project's completion. facility in 2021, this is only a preliminary step towards mechanical recycling.

3.1 Investigating Chemical Recycling Processes

The investigation of chemical recycling was completed through both preliminary research and semi-structured interviews of private firms that actively implement a chemical recycling process. Firms were selected to gather details on the deployment of chemical recycling processes executed on an industry/commercial scale. Information gathered from these interviews includes a general overview of the firms' processes, the input materials and energy required, and both desired and undesired outputs. The list of firms contacted can be found in **Appendix 2**.

Each of these firms were contacted through the email address listed on the corporation's website, the messaging portal on the website's contact page, or a personal contact at the corporation. Interviews were conducted virtually and lasted between 30 and 75 minutes. The responses to these questions were coded for analysis based on:

1. The type of chemical process;
2. The necessary systems prior, during, and after the chemical processing;
3. The desired versus realistic inputs and outputs; and
4. The impacts or nuances of the process.

3.2 Comparing Chemical Process Alternatives

The chemical processes investigated were compared to determine which process had the most effective balance of environmental impact and technical compatibility in Denmark. This comparison was made through a decision matrix, in which the benefits and drawbacks of each process were considered through the scoring and weighting of each process in four key criteria.

3.2.1 Life Cycle Assessment

A Life Cycle Assessment (LCA) was conducted on each chemical recycling process using the EASETECH application, provided by the Technical University of Denmark (http://www.easetech.dk/). From EASETECH, the team was able to more accurately model residual waste flows from residential homes in Copenhagen.

These diagrams modeled potential future waste processing systems in which a chemical recycling process is paired with standard waste incineration at Amager Resource Center (ARC). The data collected from preliminary research and technical interviews was compiled and used in the application to consider all inputs and outputs of a chemical recycling process integrated with ARC.

3.2.2 Process Evaluation

The technical evaluation of each chemical recycling process was conducted based on the following three criteria: 1) material inputs, 2) yield of product outputs, 3) net energy, and 4) emissions released. Quantities of all inputs and outputs into the waste processing system were tracked in EASETECH, and these values were separated in tables of specific chemical elements, compounds, and materials.

The data helped determine which processes minimize the impact on the environment from CO_2 emissions. Information collected from interviews with chemical recycling companies helped determine which processes create the desired outputs and utilized inputs most efficiently to operate. The team scored the chemical processes, where each criterion was weighted by importance to distinguish the strengths and weaknesses of each chemical recycling process investigated.

3.3 Assessing the Societal Impacts of New Methods

The team evaluated potential social implications of introducing a chemical recycling process into Copenhagen's current waste processing system through interviews with environmental non-governmental organizations (NGOs) and other stakeholders based in or around Denmark. The infrastructure surrounding recycling continues to reflect Denmark's commitment to sustainability and improving consumer recycling and, therefore, would be subject to change at the inclusion of chemical recycling. Collecting the opinions of stakeholders of this system, including environmental NGOs, contributes to assessing the operational feasibility of implementing chemical recycling in Copenhagen ("The feasibility study," 2017).

The team initially intended to understand citizen participation in recycling, as demonstrated by the citizen interviews in **Appendix 3**. However, because the team was unable to travel to Copenhagen, this section was adjusted to understand professional perceptions by conducting online interviews with stakeholders.

Stakeholders were interviewed in a semi-structured format to elicit their perceptions of Copenhagen's current waste processing system, recycling plastics, Danish recycling habits, incineration, environmental effects of different waste processing practices, and the opportunity of chemical recycling. Local perspectives on Copenhagen's system as well as the acceptance of a new recycling method were realized through these interviews. The list of contacted stakeholders and their status can be found in **Appendix 4**.

3.4 Preliminary Feasibility Study and Recommendation

A study on the feasibility of implementing a chemical recycling process in Copenhagen is the final deliverable of this project. A feasibility study focuses on the economic, technical, legal, operational and scheduling considerations of a proposed project. However, this preliminary feasibility study will only capture the technical and operational aspects of the project.

The Technical Aspect of feasibility aimed to assess if chemical recycling *could* be implemented into the Copenhagen waste processing system, and what measurable impacts it would have on the environment. It is assessed in the scores of each process in the decision matrix, with higher scores representing more beneficial qualities a process could offer to Copenhagen. A reflection on how well each process scored in each of the four technical criteria compliments each of the four criteria of the decision matrix.

The Operational Aspect of feasibility aimed to assess if chemical recycling *should* be implemented and what change resistance will exist in the stakeholders as a result. This was assessed in the reflection of opinions expressed in the interviews conducted with environmental NGOs, and partially in the potential impact on consumer citizens and their participation in cleaning plastic products before disposing of them.

The final recommendations to Copenhagen Solutions Lab and the Amager Resource Center were developed to include a realistic overview of the Copenhagen waste processing system, and a conclusion on whether implementing the chemical recycling process is technically and operationally feasible. It includes potential projections on how the environmental impact of the current waste processing system might change in the future.

CHAPTER 4

Investigating Chemical Recycling Processes

This chapter contains the results obtained from preliminary research into Copenhagen's waste processing system, as well as key findings from the technical interviews into chemical and mechanical recycling processes. Outlining the waste processing system allowed the team to pose inquiries on the technical professionals of chemical and mechanical recycling companies. With the information gathered from the interviews, the team assessed the extent to which each company was able to address Copenhagen's plastics issue.

4.1 Copenhagen's Waste Processing System

In order to effectively assess different chemical recycling processes that would best address the plastic recycling needs of Copenhagen, the team researched and created a representation of the Copenhagen waste processing system as seen in **Figure 9**. The blue box represents the system boundaries for a chemical recycling process when integrated into the system.

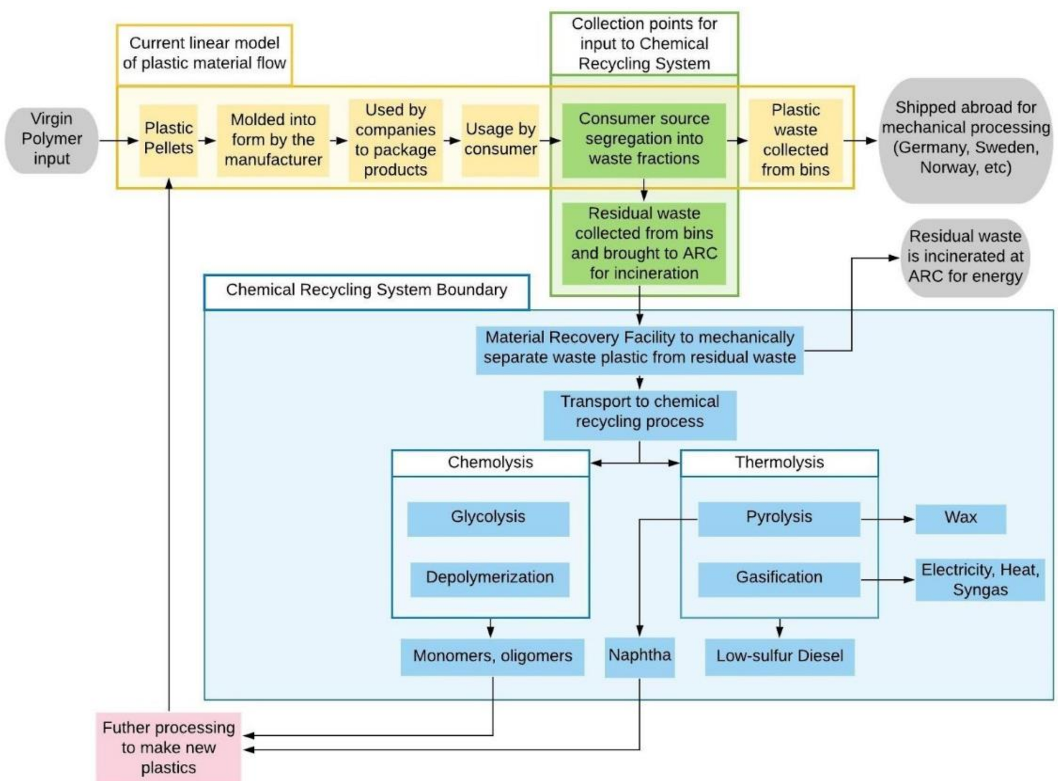

Figure 9: CPH Waste Processing with Chemical Recycling

After verifying the modeled system and consulting with Jonas Nedenskov, an Environmental Manager from ARC and project partner, it was established that the team was only focused on opportunities to chemically recycle the mixed plastics from household residual waste, instead of the source-segregated plastics. Mr. Nedenskov also informed the team that a material recovery facility (MRF) will be operational in Copenhagen by 2021, which will mechanically sort about 80% of plastics out of the residual waste stream which is represented within the proposed chemical recycling process (Fredriksen, 2017). Looking toward the future, Copenhagen would be interested in building infrastructure to optically sort the different polymer types (ideally through Fourier Transform near-infrared spectroscopy). With these key pieces of information, the team continued research and constructed **Table 3** to demonstrate the types of plastics compatible with each chemical recycling process.

Table 3: Compatibility of Plastics and Chemical Recycling Process

SEPARATE TREATMENT			CHEMICAL RECYCLING PROCESS						
			Chemolysis					Thermolysis	
			Hydrolysis	Glycolysis	Methanolysis	Ammonolysis	Unknown Catalyst*	Pyrolysis	Gasification
PLASTIC TYPE	1	PET(E)		Ioniqa			Loop Industries, Ioniqa		Powerhouse
	2	HDPE					N/A	JBI, Plastic En.	Powerhouse
	3	PVC					Vinyloop	BASF	Texaco
	4	LDPE					NA	BME, JBI, Veba	Powerhouse
	5	PP					NA	BME, JBI, Veba, Plastic E.	Powerhouse
	6	PS					Polystyvert, INEOS Styrosolution	Agilyx, BME, Plastic En.	Powerhouse
	7	OTHER	N/A	N/A	N/A	N/A	NA	BME	

*The following companies do depolymerize the respective polymers, but the composition of their catalyst is patented and not specified.

Process Compatibility	YES	NOT IDEAL	NO	Not Available

As plastics are immiscible, it was assumed that these processes would be implemented separately for each type of plastic. However, a company name that appears across multiple plastic types indicates that those plastics are processed as a mixed stream. This early research aided the team in identifying the prevalence of processes in the chemical recycling market and potential companies to interview.

For chemolysis, **Table 3** shows that many processes are not compatible with LDPE, HDPE, and PP. These polymers are commonly known as polyolefins and are produced mainly from oil and natural gas by a process of polymerization of ethylene and propylene. As polyolefins are vinyl polymers, it is difficult for them to be degraded with simple chemicals into their monomers.

Additionally, **Table 4** was created to represent the estimated distribution of plastic types in Copenhagen's household residual waste stream in 2019 using data from the 2017 MEPEX Sorting Plant for Residual Waste from Households report. The team received confirmation to exclude PVC. PVC should not be present in residual waste, but instead sorted in its own respective fraction to be landfilled, as thermal treatment of PVC releases hazardous gasses. To estimate the amount of each type of plastic in the waste stream in 2019, the team applied the percentage of plastic waste in the waste stream in 2016 to the total amount of residual waste incinerated at Amager Bakke in 2019 (Amager Resource Center, 2019). The assumption was made that the same percentage of each plastic type entered the waste stream in 2019 as in 2016.

Table 4: Estimated Distribution of CPH Plastic Waste in 2019

Estimated Distribution of Plastic Waste in 2019			
Year	**2016**	**2019**	**Percentage of Total Plastic**
Total Residual Waste (tonnes)	172,235[2]	134,796[1]	
Total Plastic Waste (tonnes)	15,978[2]	12,504.84*	100.0%
Total PET (1)	1,162[2]	909.4*	7.3%
Total HDPE (2)	740[2]	579.1*	4.6%
Total LDPE (4)	5,552[2]	4,345.2*	34.7%
Total PP (5)	2,819[2]	2,206.2*	17.6%
Total PS (6)	331[2]	259.0*	2.1%
Total Other (7)	2,269[2]	1,775.8*	14.2%
Total Black	2,279[2]	1,783.6*	14.3%
Other Plastic Products	827[2]	647.2*	5.2%

* Estimated based on the distribution of plastic waste in 2016.

Note 1: Data is from Amager Resource Center (2019).

Note 2: Data is from MEPEX (2017)

4.1.1 CO_2 Emissions from Incinerating Plastics

The team estimated the amount of CO_2 emissions from incinerating plastics in the Copenhagen waste stream by using the data on total tonnage of plastics in the Copenhagen waste stream from **Table 4**. The estimated total tonnage of each plastic type was multiplied by the amount of CO_2 emitted from incinerating each type of plastic in the United States Environmental Protection Agency's (EPA) 2015 Plastics report, as shown in **Table 5** below. The outcomes of total CO_2 emissions per plastic type were summed together, equating to about 41,048 tonnes of CO_2 emitted into the atmosphere from incinerating plastic waste.

Table 5: Estimated CO_2 Emissions from Incinerating Plastics in CPH

Estimated CO_2 Emissions from Incinerating Plastics in CPH					
Plastic Type in Residual Waste	**2019 Plastic Tonnes/Year**	**Percentage of Plastic**	**CO_2 Emissions / SPW (Tonne/Tonne)**	**CPH CO_2 Emissions (annual tonnes)**	**Output of CO_2**
PET (1)	909.4*	7.3%	2.28[1]	2073.432*	66.4% of burned CPH RW plastics yields 27,255.93 tonnes of CO_2
HDPE (2)	579.1*	4.6%	3.45[1]	1997.895*	
PVC (3)	0*	0.0%	1.41[1]	0	
LDPE (4)	4345.2*	34.7%	3.45[1]	14990.94*	
PP (5)	2206.2*	17.6%	3.35[1]	7390.77*	
PS (6)	259*	2.1%	3.1[1]	802.9*	
Other (7)	1775.8*	14.2%	--	--	33.6% of burned CPH RW plastics can be estimated as 13,792.16 tonnes of CO_2
Black	1783.6*	14.3%	--	--	
Other Plastics	647.2*	5.2%	--	--	
Total	**12505.5***	**100.0%**	**--**	--	**Approx. 41,048.09 tonnes**

*Estimated based on the distribution of plastic waste in 2016.
Note 1: Data is from the United States Environmental Protection Agency, Plastics WARM13 (2015).

Due to the fact that the MEPEX report specified more plastic fractions than those cataloged in the US EPA report, the CO_2 released from the remaining 33.6% of plastics not specified by the US EPA was estimated based on the CO_2 output of the 66.4% of plastics that were specified. Overall, it was estimated that 41,048 tonnes of CO_2, or 3.28 tonnes of CO_2 per tonne of solid plastic waste (SPW), were produced. Compared to the estimate of 102,000 tonnes of CO_2 estimated in the CPH 2025 Climate Plan, this is a conservative estimate, as it only accounts for the plastic from residual waste and no other fractions that are incinerated at Amager Bakke.

4.1.2 CO_2 Emissions Modeled by EASETECH

The Amager Bakke waste-to-energy incineration plant and the subsequent waste disposal processes were modeled in the EASETECH Life Cycle Assessment application to determine net CO_2 emissions of the current waste processing system. This model included the incineration of residual waste, transportation of residues to landfills, the production of heat and electricity, and the use of heat and electricity in Copenhagen. The input residual waste stream consisted of 134,796 tonnes of waste, 12,505 of which was plastic waste. Using the 2013 International Reference Life Cycle Data System Life Cycle Impact Assessment (LCIA) standard, the total amount of CO_2-eqivalent emissions produced in the system model was calculated to be 73,550 tonnes. Of this total, 70,240 tonnes of CO_2 were directly from incinerating residual waste at the Amager Bakke waste-to-energy plant. The model can be seen in **Figure 10** below.

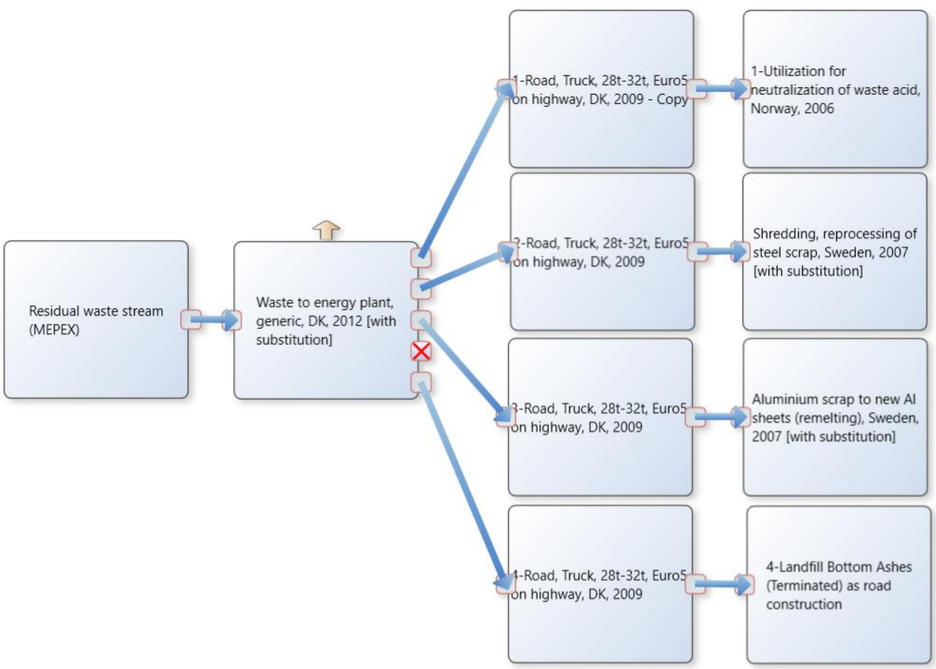

Figure 10: The EASETECH Incineration System Model

The sorting facility process was designed based on metrics specified in the MEPEX report (Fredriksen, 2017). The described facility was a two-stage sorting facility, with an estimated 90% efficient near infrared (NIR) optical sorting stage followed by a 90% efficient cleaning and washing stage (Mastellone, 2019). If each stage is 90% efficient, then the overall efficiency is 81%, meaning 81% of the plastics entering the facility will be sorted out and 19% will remain in the residual waste. This overall efficiency was used to create the sorting process in EASETECH. With 12,505 tonnes of plastic waste estimated to be in the residual waste stream in 2019, it is expected that about 10,650 tonnes would be separated and shipped to a chemical recycling process. This amount of plastic will be used for analysis in the following chapter.

Additionally, the facility was estimated to consume 3390 MWh at 160,000 tonnes of residual waste processed per year, which equates to about 21 kilowatt-hours per tonne of solid plastic waste (kWh/t) being consumed. This rate of electricity consumption was also captured in the sorting process in EASETECH. Electricity accounts for approximately 0.244 kilograms of CO_2 per kilowatt-hour consumed, and thus the total CO_2 emissions from the sorting facility are estimated to be 0.005 tCO_2/t, or 698 tonnes of CO_2 through the processing of 134,796 tonnes of residual waste.

4.2 Chemical Recycling Interviews

The following section describes key findings from the interviews with chemical recycling firms that were already operating on an industrial scale. Both chemolysis and thermolysis firms alike were sought after, with no geographical restrictions, as it was critical for the team to have a holistic perspective of all technologies readily available in the world. As a result, 19 companies internationally were contacted with a process distribution of: 9 pyrolysis, 1 gasification, and 9 chemolysis. Following outreach and additional follow-ups, the team had a 52% response rate and 26% interview rate.

The five firms interviewed were:

- **Brightmark Energy (USA)** | Pyrolysis | https://www.brightmark.com/
- **INEOS Styrolution (GER)** | Depolymerization | https://www.ineos-styrolution.com/
- **Ioniqa (NLD)** | Glycolysis | https://ioniqa.com/
- **Plastic Energy (UK)** | Pyrolysis | https://plasticenergy.com/
- **PowerHouse Energy Group (UK)** | Gasification | https://www.powerhouseenergy.net/

Prior to the interview, the interviewees were provided with statements of intent for the interview and data collected. The interview questions focused on the following categories: process, inputs/sourcing, outputs, and impacts. These questions can be found in **Appendix 5**. A summary of each chemical recycling interview, organized per firm, can be found in **Appendix 6**.

4.2.1 Benefits of Implementing Company-Specific Process

The unique qualities and interest in the company-implemented process, identified by the firm representatives, are summarized in **Table 6**. This table includes results from all interviews and establishes the operational reasoning behind a process being chosen.

Table 6: Chemical Recycling Justification and Benefit of Process

Company	Process	Why this Process?
Brightmark Energy	Pyrolysis	• BME can slightly adjust the output hydrocarbon mix for better market yield, has lower temperatures, and reuses released gas internally • Considered implementing gasification, but it requires a higher oxygenated environment, significantly more energy, and more capital
INEOS Styrolution	Depolymerization	• Easier plastic-to-plastic conversion with less CO_2 output, smaller market competition, and abundant sources of PS • Requires less heat than pyrolysis and is more circular
Ioniqa	Glycolysis	• Ioniqa's catalyst could speed up depolymerization and was able to take out waste stream impurities • 75% lower CO_2 footprint than oil-based plastics
Plastic Energy	Pyrolysis	• Pyrolysis has evolved significantly through developments in the last 10 years to produce usable outputs for the market
Powerhouse Energy Group	Gasification	• About 40% efficient in converting that gas into electricity • Recently able to generate clean gas from waste which is an additional benefit compared to other waste-to-energy systems

4.2.2 Required Plastic Inputs and Preparation

The plastic inputs used and internal preparation required by the company-implemented process are summarized in Table 7. This table includes results from all interviews and provides greater context to how the waste plastic streams must be modified internally to fit the needs of their process. It should be noted that some companies do not internally prepare their plastic and instead provide input guidelines to waste sorting groups, which often sort with material recovery facilities (MRF) that conduct mechanical recycling.

Table 7: Chemical Recycling Plastic Inputs and Processing

Company	Process	Plastic Inputs	Internal Preparation Required
Brightmark Energy	Pyrolysis	• Mainly mixed plastics types LDPE, PP, PS, OTHER (4-7) • Can handle PET (1) and HDPE (2), but large quantities of these aren't in the waste stream	• Separates out PVC (3); can process up to 8-9% • Shreds, dries, and pelletizes plastics to meet 8% max moisture and contamination content
INEOS Styrolution	Depolymerization	Requires clean and sorted PS (6) with 95% purity to ideally form food-grade plastic	None: Sourced from MRF where FT-NIR can detect PS at nearly 100%
Ioniqa	Glycolysis	Prefers a 90-95% shredded PET content for efficiency	None: Sourced from MRF
Plastic Energy	Pyrolysis	• Mixed plastics types L/HDPE, PP, PS, OTHER (2, 4-7) • Limit type 7 plastic to avoid contamination and impurities	• Optically sorts out PET (1) and PVC (3) due to oxygen content • Dries polymers to limit moisture
Powerhouse Energy Group	Gasification	• All colored mixed plastics, 1-7 and beyond • Can take 100% PVC, does a caustic wash to avoid chlorine gas	None

4.2.3 Process Outputs and Industry Use

The process outputs and their respective industry use from the company-implemented process are summarized in **Table 8**. This table includes results from all interviews and presents a range of outputs as well as products that have potential as plastic feedstock.

Table 8: Chemical Recycling Outputs and Industry Markets

Company	Process	Process Outputs & Industry Use
Brightmark Energy	Pyrolysis	• 751 L of fuel produced / tonne of solid plastic waste • Ultra-low Sulfur Diesel • Naphtha (blending for gasoline or plastic feedstock) • Paraffin Waxes (food-grade) • Char (construction, bricks, roads)
INEOS Styrolution	Depolymerization	• Styrene monomer (feedstock for ASN, ABS, and ASMA) • Palm oils (for food or fuel) • Undesired: lost PS from efficiency, Benzene, Alphumethastryene, charcoal residue
Ioniqa	Glycolysis	• BHET (astrofied form can be re-polymerized into PET resin) • At certain viscosities, polyester fibers or packaging are made
Plastic Energy	Pyrolysis	• 860 L of fuel / dry tonne of SPW • 70-75% TAC oil or hydrocarbon oil (feedstock plastic) • ~10% max char (construction, bricks, roads) • 15% syngas (used internally to keep ovens heated)
Powerhouse Energy Group	Gasification	• Based off of the 40 tonnes/day • 3.8 MWe Electricity (marketable) • 2.2 MWe (th) Heat (used internally) • 2 tonnes of 99.999% Hydrogen (for fuel cell vehicles) • Syngas (for industrial use)

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4.3 Mechanical Recycling Interviews

This section describes findings from the team's interview with a Material Recovery Facilities (MRF). Multiple chemical recycling firms cited that the success of MRFs directly correlated to the levels of contamination and internal preparation required in their incoming plastic stream, a common obstacle to their processes. As a result, the team reached out to three MRFs, and was able to successfully interview Waste Management, a company based in North America. The interview questions focused on the following categories: process, collection, sorting/separation, and outputs. These questions can be found in **Appendix 7**.

Waste Management described their process as separating single-stream recyclables which includes a mixed stream of plastic, paper, metal, glass, and cardboard. It should be noted that Denmark would not see a single stream of recyclables due to their multi-stream source separation. However, Waste Management's sorting of plastics from its single-stream constituents, even with the company's intake contamination levels at 30%, demonstrates that plastics can be successfully separated from a highly polluted stream.

Waste Management cited that unrecyclable materials incorrectly being placed in recycling bins accounted for a majority of the 30% contamination, a direct correlation to consumer understanding of recycling. Besides biowaste and wood, a primary culprit in the plastics realm are plastic bags and other films. These items become caught in the facility's separating barrels and require removal from the facility's operators, which is a dangerous and a time-consuming task.

In relation to plastics, optical sorters are used in the MRF to sort out specific polymers. Because of market value and interest from plastic reuse companies, Waste Management currently only sorts out PET (1), HDPE (4), and PP (5) from the waste stream, with the remaining types being landfilled.

CHAPTER 5

Comparison of Processes in a Technical Decision Matrix

This chapter elaborates on the technical feasibility of implementing four possible chemical recycling processes in Copenhagen. The processes were compared with each other, and with incineration, in a technical decision matrix to determine which best aligned with the goals and requirements of Copenhagen Solutions Lab and Amager Resource Center.

The matrix includes four domains: the plastic inputs to the process, the output products of the process, the net energy of the process, and the impact of the process on the environment. Each process was scored based on performance in the subdomains of each domain, relating to a scoring scale developed by the team to reflect the most desirable qualities. A 10 represents the most-desirable score, and a 0 represents the least-desirable score. Each subdomain and domain were weighted to reflect their relative importance to each other. The following sections will describe in detail the decisions on the scores given and the quantity of each weight set. The process data for pyrolysis, gasification, and chemolysis can be found in **Appendix 8**, **Appendix 9**, and **Appendix 10** respectively.

5.1 Plastic Inputs

The plastic inputs domain conveys the types of plastics that each process can handle, based on the distribution of plastic types in the Copenhagen waste stream. The plastic inputs domain will make up 20% of each process's final score. A process would not be successful if it cannot take in the mixed plastic input defined as the output of the sorting facility in the MEPEX sorting facility report (Fredriksen, 2017). The decision matrix will reflect each process's acceptance of different plastic types with a high weight.

The subdomains of this domain include the standard 1-7 plastics, black plastics, and unclassified plastics. The weights applied to each subdomain are the percentage of that type of plastic in the waste stream, as shown in **Table 4**, based on the fractions in the Copenhagen waste stream as defined in the MEPEX report (Fredriksen, 2017). A score of 0 indicates that a process can take 0% of that type of plastic, while a score of 10 indicates a process can take 100% of that type of plastic. The scores of the plastic inputs domain are shown in **Table 9** below. The total possible score that a process could achieve in this domain is 20.0, because the domain weight is 20%, as displayed in the rightmost column of the table.

Table 9: Plastic Inputs Domain Scores

Plastic Inputs									
Subdomain	1 PET	2 HDPE	3 PVC	4 LDPE	5 PP	6 PS	7 Other	Black/ Other	Grade out of: 20.0
Subdomain Weight	**7.3%**	**4.6%**	**0.0%**	**34.7%**	**17.6%**	**2.1%**	**14.2%**	**19.5%**	
Pyrolysis	10	10	1	10	10	10	7	0	**15.2**
Gasification	10	10	10	10	10	10	10	10	**20.0**
Depolymerization (PS)	0	0	0	0	0	10	0	0	**0.4**
Glycolysis (PET)	10	0	0	0	0	0	0	0	**1.5**
Incineration	10	10	10	10	10	10	10	10	**20.0**

Pyrolysis received a score of 19.1 because it can process 100% of PET (1), HDPE (2), LDPE (4), PP (5), and PS (6), as well as 70% of Other plastic (7), in the Copenhagen waste stream. Through interviews with the pyrolysis companies Brightmark Energy (BME) and Plastic Energy (PE), the team determined that pyrolysis favors plastic types 4-7 but experiences no difficulties processing PET (1) and HDPE (2). As PET and HDPE are less common in the Copenhagen waste stream at 7.3% and 4.6% respectively, the determination was made that pyrolysis could process the average tonne of mixed plastic with this composition of plastic waste. It should be noted that, while acknowledging PET and HDPE could be processed with pyrolysis, mechanically separating PET and HDPE would best utilize or recover these plastics instead of being an input to pyrolysis.

Gasification received a score of 20.0 because it can process 100% of all types of plastic in the waste stream. This was a key aspect of gasification that was gathered in the interview with PowerHouse Energy Group (PH). Gasification can also process a small percentage of other calorific material along with any composition of plastic, such as wood and tires.

Depolymerization and Glycolysis each received low scores of 0.4 and 1.5 respectively, as they each can only process one specific type of plastic. The depolymerization of PS and the glycolysis of PET are important engineering breakthroughs, but they will not be the best solution for Copenhagen. As the plastic input to a chemical recycling process has already been defined as mixed plastic waste. Incineration received a score of 20.0, as it takes in all types of plastic.

5.2 Product Outputs

The product outputs domain conveys the types of outputs that each chemical recycling process creates from plastic waste. The product outputs domain will make up 35% of each process's final score due to the importance for a process to produce a tangible output that allows the plastic waste to be reused.

The subdomains of this domain include plastic feedstock and fuels because they represent the two predominant product yields from the four chemical recycling processes analyzed. The ability for a chemical recycling process to produce feedstock material for new plastics is of high importance to Copenhagen Solutions Lab, and therefore that subdomain is weighted much higher than fuels. Fuel outputs allow plastics to be reused, but downgrading plastics to fuels so they can be burned for energy is not circular or sustainable. Therefore, this subdomain holds considerably less weight than plastic feedstock. The product outputs domain can be seen in **Table 10** below. The total possible score that a process could achieve in this domain is 35.0, as displayed in the rightmost column of the table.

Table 10: Product Outputs Domain Scores

Product Outputs			
Subdomain	Plastic Feedstock	Fuels	Grade out of: **35.0**
Subdomain Weight	**80%**	**20%**	
Pyrolysis	3	7	**13.3**
Gasification	0	1	**0.7**
Depolymerization (PS)	7	0	**19.6**
Glycolysis (PET)	10	0	**28**
Incineration	0	0	**0**

5.2.1 Plastic Feedstock

Plastic feedstock refers to the material produced from a chemical recycling process that can be used as a building block to create new plastics. The scores given to each process in this subdomain represent the percentage of the process's output that can be used as plastic feedstock.

Pyrolysis of mixed plastic waste produces a mix of oils, made up of hydrocarbon chains of different lengths. One grouping of the hydrocarbon chains is naphtha, which is the main ingredient of plastic products (Dean, 2013). Naphtha is acquired through distilling crude oils and is thermally cracked to produce shorter hydrocarbon chains, known as major intermediaries, that serve as the monomers for many plastics (Dean, 2013).

The average yield of hydrocarbon oils from six active pyrolysis companies was computed to be about 890 liters for every tonne of solid plastic waste processed. The companies and their yield amounts that were averaged can be found in **Appendix 8**. This yield is composed of hydrocarbon chains ranging from C_4-C_{30}. While naphtha is considered to be hydrocarbon chains of length C_4-C_{12} ("Petroleum hydrocarbon chains," n.d.). BME shared that they focus on hydrocarbon chains between C_4-C_{10} to make into naphtha and outsource. According to BME, the distribution of the hydrocarbon output from pyrolysis can be controlled based on the operating conditions of the process. This results in a range of naphtha hydrocarbons that can be produced from the pyrolysis process.

In a 2009 study on the pyrolysis of HDPE, PP, PS, and PVC, the percentages of different hydrocarbon chain lengths output from the process were reported (Miskolczi, Bartha, & Angyal, 2009). The gasoline portion of the process output was considered to include hydrocarbons C_5-C_{17} and small percentages of other oils ("Petroleum hydrocarbon chains," n.d.). Of this portion, 64.8% was composed of hydrocarbons C_5-C_{12}, while 48.8% was composed of hydrocarbons C_5-C_{10} ("Diesel and gasoline," n.d.). This would constitute pyrolysis receiving a score of 5-7 in the plastic feedstock domain, but there were other portions of the output reported in the study. These include light oil (C_{11}-C_{29}) and heavy oil (higher hydrocarbon ranges) ("Diesel and gasoline," n.d.). The percentage of each of the three portions of the total output was not reported, and therefore, it is difficult to quantify the total yield of naphtha for every tonne of plastic waste processed. The full breakdown of hydrocarbon yields from this study can be viewed in **Appendix 11**.

According to BME's pyrolysis process, the output of hydrocarbons follows a normal distribution curve similar to **Figure 11** shown below. It should be noted that the breakpoint between naphtha and diesel at C_{10} does not represent one standard deviation from the average of the graph. Based on the curve and the study, the estimation was made that naphtha comprised approximately 10%-25% of the 890-liter hydrocarbon oil output of pyrolysis. This equates to a range of 89-220 liters of naphtha.

The naphtha output can be treated in a steam cracker in the presence of water vapor at a high temperature (Lichtarowicz, 2014). This causes the hydrocarbons to split into their major intermediaries, olefins and aromatics (U.S. Energy Information Administration, 2019). Among the olefins, there are several carbon chains including ethylene, propylene, butane, and butadiene ("Petrochemicals, from naphtha to plastic," n.d.). Aromatics include benzene, toluene, and xylene. These molecules can then be treated in a petrochemical plant where they will react with a polymerization catalyst to form the polymer chain that will be used as the base material in new plastics, primarily polyethylene and polypropylene. For this reason, naphtha is considered "the predominant feedstock on a global basis" for plastic products (Dean, 2013). This process of polymerization is essential for creating a circular value chain within the plastics industry and is one of the most effective methods of turning waste plastic into new plastic. Therefore, pyrolysis received a score of 3 in plastic feedstock. This scenario and others can be seen in **Appendix 12**.

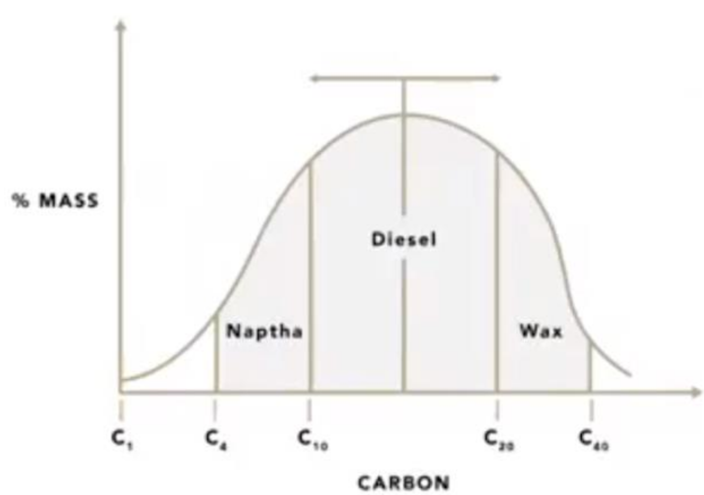

Figure 11: BME Pyrolysis Breakdown of Hydrocarbon Outputs

Gasification received a score of 0 in plastic feedstock, as it does not produce any product output that is used directly for making new plastics. Energy is the primary product of gasification, which will be discussed in section 5.3 below.

Depolymerization of PS received a 7 in plastic feedstock due to its yield percentage of plastic feedstock for new PS products. This score was based on information collected from INEOS Styrolution, who shared that while their process was not fully industrialized at the time of the interview, it would not be sustainable if the yield percentage of input PS waste to output PS feedstock was below 60%. However, they also shared that an expectation of 90% was optimistic but might not be realistic in the near future. With a potential yield rate between 60% and 90%, the decided score was given to be 7.

Glycolysis of PET received a score of 10 in plastic feedstock due to its yield percentage of plastic feedstock for new PET. This score was derived from information collected from Ioniqa, who shared that their process would "get one PET out" for every "one PET in". Based on this, the process yield percentage was assumed to be 99%. The yielded output is currently used as material to make new PET packaging and polyester fibers. However, it should be noted again that depolymerization of PS and glycolysis of PET require a very specific input to produce the respective yields, which the sorting facility will not be able to provide.

Incineration received a score of 0, as it does not produce plastic feedstock.

5.2.2 Fuels

Fuels refers to any liquid or gas outputs from the analyzed chemical recycling processes that can be burned or used otherwise for energy. As with plastic feedstock the scores in this subdomain refer to the percentage of the process's output that can be used as fuel.

Pyrolysis received a score of 7 in fuels because much of the hydrocarbon oil output can be used to produce fuel. Diesel is composed of hydrocarbons C_{12}-C_{20}, and it is widely used as a source of fuel for vehicles ("Diesel and gasoline," n.d.). As evidenced by **Figure 11** (above), diesel hydrocarbons are a large portion of the pyrolysis output. The 2009 study on pyrolysis reported that 86.6% of the light oil output (C_{11}-C_{29} range) was composed of diesel hydrocarbons. In addition to naphtha's use as plastic feedstock, it can be used as a blending product for gasoline (Miskolczi et al., 2009).

Gasification received a score of 1 in fuels due to a byproduct of PowerHouse's gasification process. In addition to the syngas produced for electricity production, PowerHouse yields 0.05 tonnes of 99.999% pure hydrogen gas for every tonne of solid plastic waste processed. This gas can be used to generate energy for hydrogen fuel cell vehicles.

Depolymerization, glycolysis, and incineration received scores of 0 in fuels because they do not produce any fuels.

5.3 Net Energy

The net energy domain conveys the energy consumed and produced by each chemical recycling process. The net energy domain will make up 10% of each process's final score because energy production is of less importance to the goals of the project. While energy consumption levels have implications on the CO_2 emissions of a process, they will be analyzed independently in section 5.4. The subdomains of this domain include electricity and heat as they are the two ways in which to measure energy production and consumption. Electricity and heat were weighted equally in this domain, at 50% each. The net energy domain scores can be viewed in **Table 11** below.

Table 11: Net Energy Domain Scores

Net Energy			
Subdomain	Electricity	Heat	Grade out of: **10.0**
Subdomain Weight	**50%**	**50%**	
Pyrolysis	0	0	**0**
Gasification	10	0	**5**
Depolymerization (PS)	0	0	**0**
Glycolysis (PET)	0	0	**0**
Incineration	10	10	**10**

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5.3.1 Electricity

Electricity refers to the amount required to operate the chemical recycling process, as well as the electricity produced by the process. Electricity production and consumption were considered into one score, with a score of 0 representing a process that had a net electricity production range between -600 and -460 kWh per tonne of solid plastic waste (kWh/t). The negative number describes the process as electricity consumption needed to run the process. A 10 represents a process with a net electricity production between 660 and 800 kWh/t. The positive value represents a net production of electricity and an amount that can be used outside the process.

Pyrolysis received a score of 0 because it has a net electricity production of -530 kWh/t. Since the process consumes 530 kWh/t, and produces 0 kWh/t, the result is an overall net electricity production of -530 kWh/t. This number was taken as the maximum amount of electricity consumed per tonne of solid plastic waste according to the report by the American Chemical Council (ACC), and can be referenced in **Appendix 8** (RTI International, 2012).

Gasification received a score of 10 because it has a net electricity production of 810 kWh/t because it consumes about 540 kWh/t and produces about 1350 kWh/t. 540 kWh/t was used as the maximum amount of electricity consumed and can also be referenced in **Appendix 9** and in the ACC report. 1350 kWh/t was the average electricity production of the gasification companies analyzed. The average was chosen to be represented in this analysis to encompass all gasification processes and to not favor one specific plant.

Depolymerization of PS received a score of 0 because it has a net electricity production of -520 kWh/t. It consumes about 520 kWh/t, and produces 0 kWh/t. This data was gathered from the INEOS Styrolution 2018 Sustainability Report, in which INEOS Styrolution consumed about 2090 kWh/t across 4 plants, which equates to about 520 kWh/t per plant (Lavallée, 2018).

Glycolysis of PET received a 0 since the data on electricity consumption was not available. Incineration received a score of 10 because it has a net electricity production of 800 kWh/t, according to ARC (Amager Resource Center, 2019).

5.3.2 Heat

Heat refers to the heat generated from a chemical recycling process that is marketed as a primary output of the process. A score of 0 represents a production of no heat, and a score of 10 represents a production of 2700 kWh/t of heat or more. This range was chosen based on the heat production of each process, as with electricity.

Each chemical recycling process received a 0 in heat because they do not produce any exportable heat. However, incineration received a 10 because it produces 2700 kWh/t. Even though this subdomain does not contribute to the comparison of chemical recycling processes, it was included to provide the overall comparison between each chemical recycling process and incineration.

5.4 CO_2 Impact

The CO_2 impacts domain conveys each chemical recycling process's environmental impact on global warming. This domain will make up 35% of each process's final score, as it addresses the aspects that are most important in the environmental considerations for a chemical recycling process.

The two subdomains of the CO_2 impacts domain are process-specific CO_2 emissions and system-wide CO_2 emissions, each weighted equally at 50%. Process-specific emissions refer to the emissions from solely the chemical recycling process, and system-wide emissions refer to the total emissions from the integration of a chemical recycling process into the current waste processing system. The CO_2 impacts domain scores can be viewed in **Table 12** below.

Table 12: CO_2 Impacts Domain Scores

CO_2 Impacts			
Subdomain	Process-specific CO_2	System-wide CO_2	Grade out of: 35.0
Subdomain Weight	**50%**	**50%**	
Pyrolysis	10	6	28.0
Gasification	9	4	22.8
Depolymerization (PS)	9	0	15.8
Glycolysis (PET)	10	0	17.5
Incineration	1	2	5.3

5.4.1 Process-Specific CO_2 Emissions

The chemical recycling process-specific CO_2 emissions refer to the quantity of CO_2 emitted for every tonne of solid plastic waste (tCO_2/t) processed by a chemical recycling process. The scores given to each process in this subdomain represent the amount of process-specific CO_2, emissions on a linear scale, with a score of 10 representing 0.0 tCO_2/t or lower, and a score of 0 representing over 3.5 tCO_2/t produced.

Before discussing how each chemical recycling process was designed, it is important to note that there was no ideal way to model chemical process equipment such as heat exchangers, reaction chambers, and distillation columns within EASETECH. Instead, one process block was used to represent the entire chemical recycling process. As some of the process data reported thus far has been estimated and uncertain to a degree, the chemical recycling process blocks will inherit that uncertainty, along with the subsequent process-specific CO_2 emissions. EASETECH is a powerful tool, but it requires specific data in order to be accurate, as will any system model.

Pyrolysis received a score of 10 because it was found to account for a net total of -0.155 tCO_2/t. The net total accounts for the direct CO_2 emissions into the atmosphere, the direct CO_2-equivalent emissions from other compounds, the CO_2 emissions from electricity consumption, and the emissions removed from the atmosphere from recycling plastic waste. Pyrolysis was found to directly emit 0.48 tonnes of CO_2 into the air per tonne of solid plastic waste processed. This metric was the maximum of the range of emissions data from the pyrolysis processes of different companies documented in the ACC report (RTI International, 2012). Other air emissions, as described in the ACC report, account for CO_2-equivalent emissions of 0.812 tCO_2/t based on the LCIA standard applied in EASETECH.

As described in section 5.3.1, pyrolysis consumes an average of 530 kWh/t. This was modeled as an external process in EASETECH, with the electricity accounting for approximately 0.244 kg of CO_2 emissions for every kWh consumed (Amager Resource Center, 2019). Therefore, electricity consumed to run pyrolysis accounts for approximately 0.130 tCO_2/t emitted. To this point, emissions from the pyrolysis process total to about 1.422 tCO_2/t. With an estimate of 10,650 tonnes of plastic waste processed by chemical recycling, it can be estimated that the pyrolysis process, independent of the rest of the system, would account for almost 15,200 tonnes of CO_2 per year. However, recycling plastic accounts for the removal of about 1.577 tCO_2/t (Amager Resource Center, 2019). Therefore, if implemented, pyrolysis would have an overall net CO_2 emissions rate of 0.155 tCO_2/t, which would account for removing approximately 1,650 tonnes of CO_2 from the atmosphere. The estimation on process-specific CO_2 emissions for pyrolysis can be visualized in **Figure 12** below.

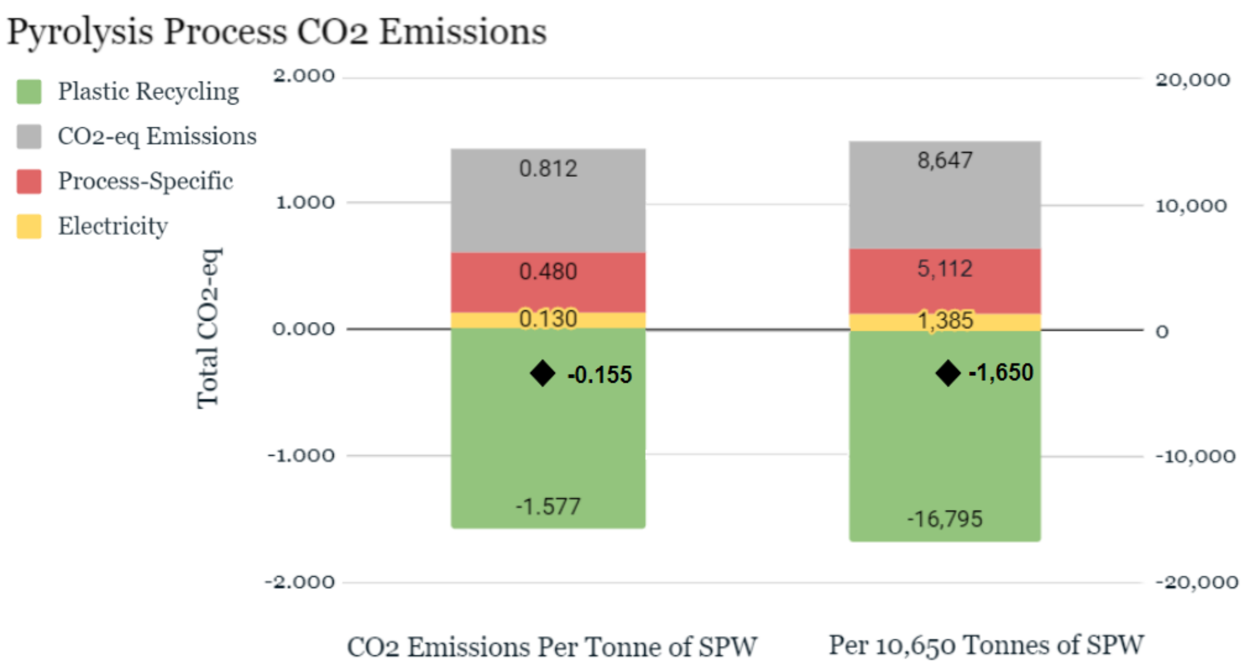

Figure 12: Pyrolysis Process-Specific CO_2 Emissions

Gasification received a score of 9 because it was found to account for a net total of 0.64 tCO_2/t. The net total accounts for the direct CO_2 emissions into the atmosphere, the direct CO_2-equivalent emissions from other compounds, and the CO_2 emissions from electricity production. Gasification was found to directly emit 0.52 tonnes of CO_2 into the air per tonne of solid plastic waste processed. This was the maximum of the range of gasification processes documented in the ACC report (RTI International, 2012). Other air emissions account for CO_2-equivalent emissions of 0.318 tCO_2/t, as calculated in EASETECH.

As described in section 5.3.1, gasification produces 810 kWh/t of electricity. With 0.244 kg of CO_2 emissions for every kWh of electricity consumed, 0.244 kg of CO_2 for every kWh of electricity produced are removed from the system. This equates to a removal of 0.198 tCO_2/t from the system due to the production of electricity. In total, the CO_2 emissions of the gasification process are 0.64 tCO_2/t. With an estimate of 10,650 tonnes of plastic waste processed in chemical recycling, it can be estimated that gasification would account for about 6,816 tonnes of CO_2. The estimation can be viewed in **Figure 13** below.

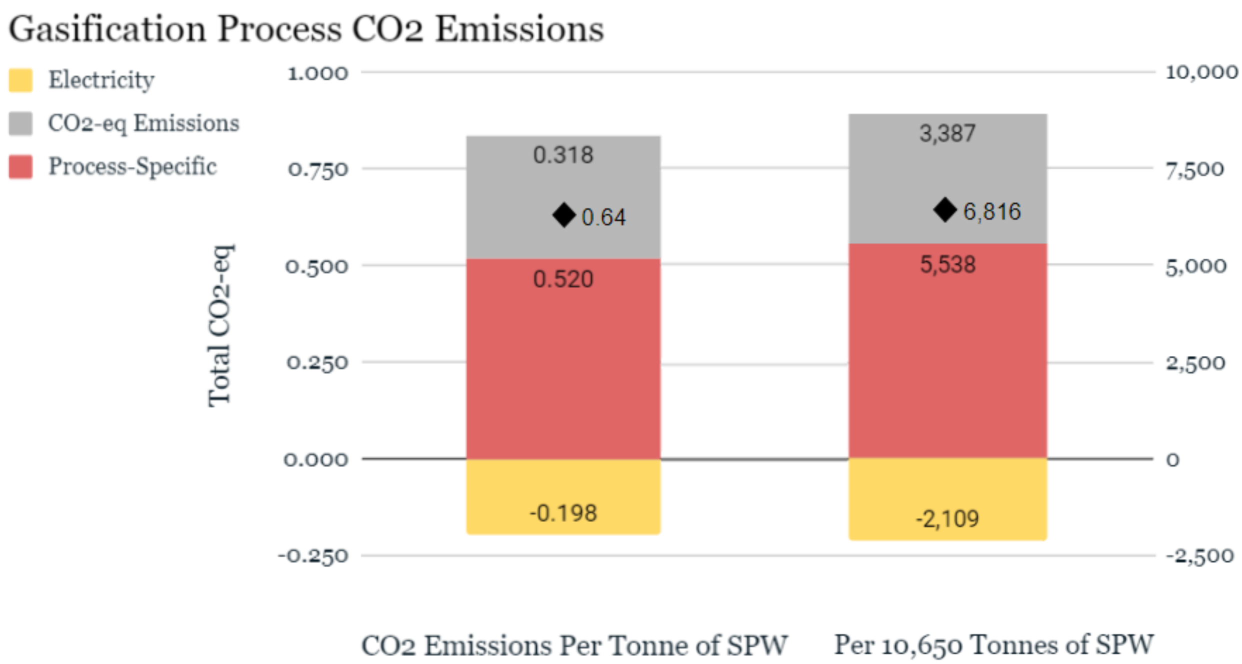

Figure 13: Gasification Process-Specific CO_2 Emissions

Depolymerization of PS received a score of 9 because it was found to emit 0.455 tCO_2/t. This metric was reported in INEOS Styrolution's 2018 Sustainability Report as 455 kilograms of CO_2 per tonne of solid plastic waste, and it incorporated process-specific emissions from fossil fuels (43.3%), steam (33.4%), electricity (22.5%), and other aspects (0.8%) (Lavallée, 2018). This emission rate does not account for the CO_2 removed from the atmosphere from the conventional production of PS.

Glycolysis of PET received a score of 10 because it was found to emit -1.132 tCO_2/t. This was reported in a Life Cycle Assessment on Ioniqa's process from CE Delft, which accounted for auxiliary and energy inputs, about 1.36 tCO_2/t, and avoided PET production, about -2.49 tCO_2/t (Bergsma & Lindgreen, 2018).

Incineration received a score of 1 because it was estimated to emit 3.28 tCO_2/t from the incineration of plastic waste, as described in section 4.1.1.The scores given to each process in this subdomain represent total system CO_2 emissions, with a score of 0 representing the upper boundary of 80,000 tonnes of CO_2 and a 10 represents a system total of 20,000 tonnes of CO_2 or less. The upper bound was based on the total CO_2 emissions for the current waste processing system, 73,550 tCO_2. The lower bound was based on Copenhagen's goal of reducing 59,000 tonnes of CO_2 from the waste processing system, according to Copenhagen Solutions Lab. With 80,000 tCO_2 as the upper bound, a reduction of 59,000 tCO_2 equates to 21,000 tCO_2, which was rounded down to 20,000 tCO_2 for simple scoring intervals. A score of 10 would indicate the near accomplishment of Copenhagen's goal.

5.4.2 System-Wide CO_2 Emissions

System-wide CO_2 emissions refer to the total estimate of CO_2 emissions in the waste processing system with a chemical recycling process implemented. Only systems with pyrolysis and gasification were assessed, as they are the only chemical recycling processes that take in a mixed plastic waste input.

The EASETECH application was used to capture the two possible waste processing systems with chemical recycling that could be implemented in Copenhagen, as was done for the current incineration process at Amager Bakke in section 4.1.2. The incineration model served as the baseline to which each chemical recycling process was added. With the municipality's incineration process benchmarked at 73,550 tonnes of CO_2 per 134,796 tonnes of residual waste, the goal was to model a chemical recycling alternative that could yield emissions lower than this threshold (Amager Resource Center, 2019).

The scores given to each process in this subdomain represent total system CO_2 emissions, with a score of 0 representing the upper boundary of 80,000 tonnes of CO_2 and a 10 represents a system total of 20,000 tonnes of CO_2 or less. The upper bound was based on the total CO_2 emissions for the current waste processing system, 73,550 tCO_2. The lower bound was based on Copenhagen's goal of reducing 59,000 tonnes of CO_2 from the waste processing system, according to Copenhagen Solutions Lab. With 80,000 tCO_2 as the upper bound, a reduction of 59,000 tCO_2 equates to 21,000 tCO_2, which was rounded down to 20,000 tCO_2 for simple scoring intervals. A score of 10 would indicate the near accomplishment of Copenhagen's goal.

The waste processing systems with pyrolysis and gasification include CO_2 emissions from the chemical recycling process, incineration plant, the sorting facility, and smaller aspects such as transport vehicles. The general structure of the waste processing system can be viewed in **Figure 14** below, which is a simplified version of the EASETECH models that can be found in **Appendix 13 and 14**.

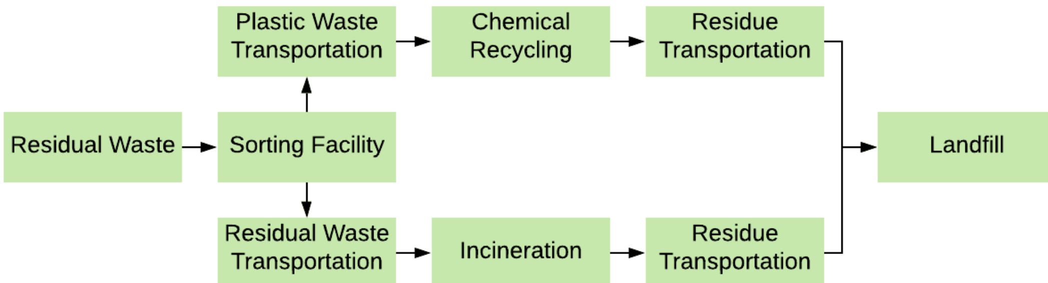

Figure 14: CPH Waste Processing with Chemical Recycling

The waste processing system with pyrolysis received a score of 6 in system - wide CO_2 emissions, as it accounted for 47,603 tonnes of CO_2 through the processing of 134,796 tonnes of residual waste. The pyrolysis process-specific emissions accounted for -1,650 tonnes of CO_2 from 10,650 tonnes of plastic waste, as described in section 5.4.1. The remaining 124,146 tonnes of residual waste at the sorting facility would be transported to the Amager Bakke waste-to-energy plant, at which incineration accounted for 47,090 tonnes of CO_2 emissions. The sorting facility accounted for 698 tonnes of CO_2 as described in section 4.1.2. The other aspects of the waste processing system, including transport vehicles, landfilling, and post-incineration waste processing, accounted for 1,465 tonnes of CO_2 emissions. In total, the summation of CO_2 emissions as calculated in EASETECH for the waste processing system with pyrolysis came to be 47,603 tonnes of CO_2.

The waste processing system with gasification received a score of 4 in system - wide CO_2 emissions, as it accounted for 56,064 tonnes of CO_2 through the processing of 134,796 tonnes of residual waste. The gasification process-specific emissions accounted for 6,816 tonnes of CO_2 from 10,650 tonnes of plastic waste, as described in section 5.4.1. As before, incineration accounted for 47,090 tonnes of CO_2, the sorting facility accounted for 698 tonnes, and other aspects accounted for 1,465 tonnes. In total, the summation of CO_2 emissions as calculated in EASETECH for the waste processing system with gasification came to be 56,064 tonnes of CO_2.

Depolymerization and glycolysis each received scores of 0 in system-wide CO_2 emissions, as they were not modeled due to the fact they do not take in a mixed plastic waste input. Incineration received a score of 2 for system-wide CO_2 emissions for 73,550 tonnes of CO_2 emitted from residual waste. This was just under the threshold of 74,000 tonnes for a score of 1. The emissions of the three systems considered in the analysis of system-wide CO_2 emissions can be viewed in comparison with one another in **Figure 15** below.

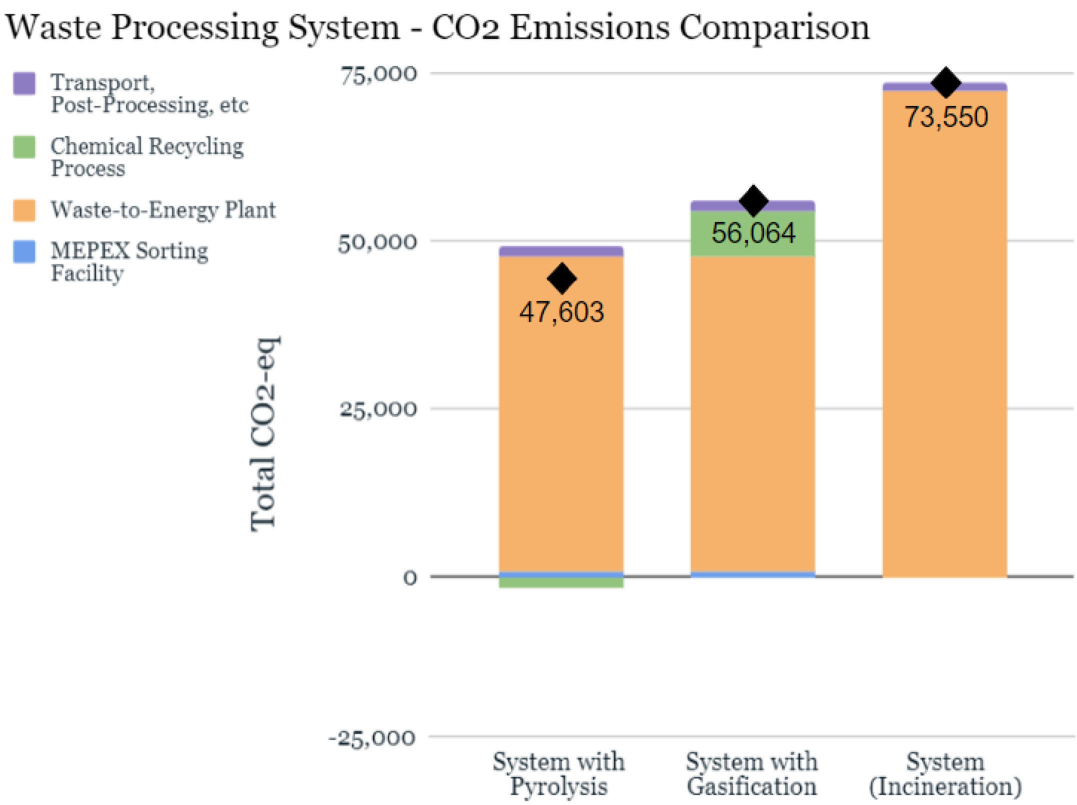

Figure 15: Waste Processing System CO_2 Emissions Comparison (based on 134,796 tonnes of residual waste)

5.5 Overall Scoring

After thorough collection and analysis of research, scenario modelling, and statistical mapping and comparing, data on each chemical recycling process was compiled into a decision matrix to serve as the tool of comparison. The decision matrix allowed for testing of multiple scenarios of importance based on a developed rubric of criteria and constraints. This produced numerical scores that would indicate the most feasible process to be implemented. The scores of each chemical recycling process and incineration in the four domains of plastic inputs, product outputs, net energy, and impacts can be seen in **Table 13** below.

Table 13: Waste Processing System Total Weighted Scores

Domain	Plastic Inputs	Product Outputs	Net Energy	CO_2 Impacts	Weighted Score
Domain Weight	**20.0**	**35.0**	**10.0**	**35.0**	**100.0**
Pyrolysis	**15.2**	**13.3**	**0.0**	**28.0**	**56.5**
Gasification	**20.0**	**0.7**	**5.0**	**22.8**	**48.5**
Depolymerization (PS)	**0.4**	**19.6**	**0.0**	**15.8**	**35.8**
Glycolysis (PET)	**1.5**	**28.0**	**0.0**	**17.5**	**47.0**
Incineration	**20.0**	**0.0**	**10.0**	**5.3**	**35.3**

Each process's total weighted score can be seen in the far-right column, and can be further visualized by the graphed scores in **Figure 16** below. Pyrolysis received the highest score with 56.5, followed by gasification with 48.5, glycolysis with 47.0, depolymerization with 35.8, and incineration with 35.3.

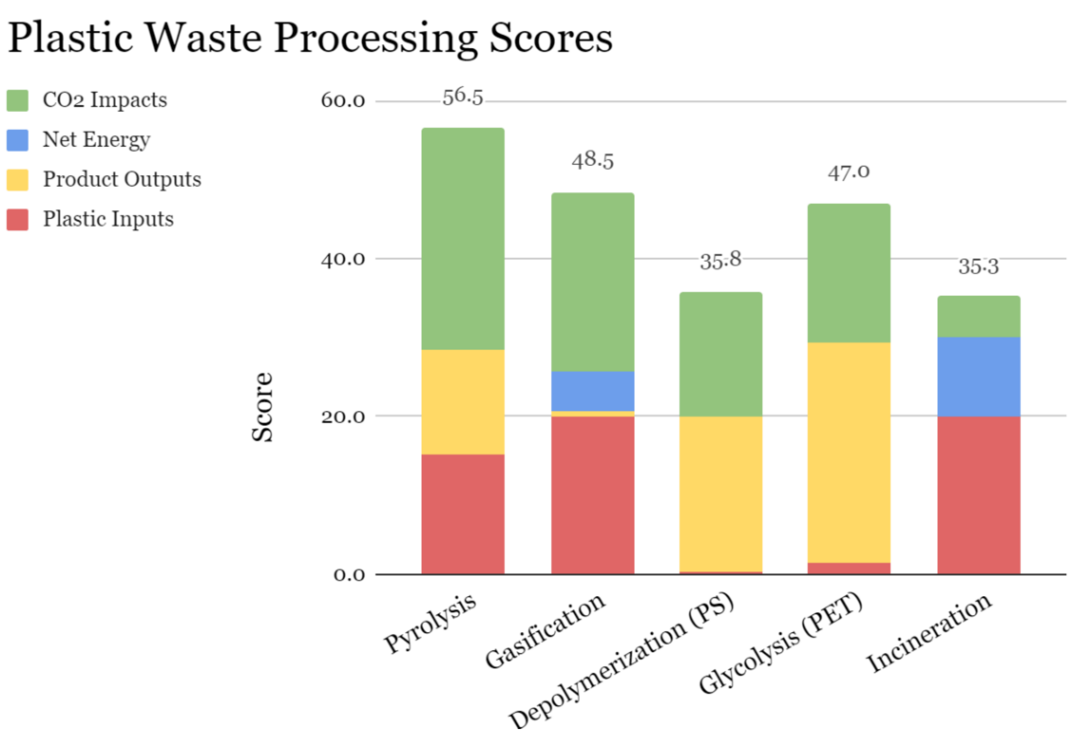

Figure 16: Plastic Waste Processing Scores Stacked Graph

CHAPTER 6

Societal Impacts

This chapter explores societal implications posed by perspectives from stakeholders and the role of consumers in recycling. By considering stakeholders, the team was able to identify change resistance towards chemical recycling as well as attitudes towards Copenhagen's current initiatives. By considering the large emphasis of consumer source separation, the team contemplates how a proposed process could impact the existing recycling habits and duties.

6.1 Stakeholder Perceptions

This section describes findings from the team's interviews with different stakeholders. The interview questions given, which can be found in **Appendix 15**, focused on the following categories: plastics, recycling, incineration, and environmental.

In order to maintain the integrity of the stakeholder's perspective without any bias or interference, the interviewee was not presented with any additional information outside of the interview questions. For the interviewee's privacy, names are omitted. The team would also like to acknowledge that the information provided by the interviewee may not entirely represent the views of the overall affiliation.

6.1.1 Danish Society for Nature Conservation

The Danish Society for Nature Conservation (DSNC) is Denmark's largest green organization with 130,000 members and over 1,500 volunteers (Danmark Naturfredningsforening, n.d.). The organization aims to create a greener and more sustainable Denmark through better waste sorting, recycling, and usage of renewable energy. A Miljøpolitisk Rådgiver (Environmental Policy Advisor, to be referred to as MR) from DSNC was not available for a teleconferencing interview but did respond to the team's initial questions via email.

The MR expressed concern with the utilization of EASETECH, stating that DSNC is in opposition to the application and the Technical University of Denmark due to EASETECH's LCA modeling which "only focuses on Cradle to Grave….not using a Cradle to Cradle LCA approach which would reflect a circular economy." Because of this approach, the MR noted that multiple ‘problematic reports’ were produced including those that favored incineration as the better “grave”. The MR suggested that EASETECH was developed with different municipal incinerator organizations as sponsors and strongly advised the team to shift to an alternative research tool.

Moreover, the MR expressed a strong frustration with plastics being shipped abroad for processing, to countries such as Sweden and Germany, as the plastic recycling in those countries still needs greater improvement. Overall, the MR would like plastic waste to be processed where it can be best recycled but believes that the argument for managing plastic waste internally would only benefit municipal waste companies such as incinerators or pyrolysis companies.

The MR identified that at the core of the plastics issue, circularity would be achieved by reducing, reusing, and recycling the materials, with the reduction of material consumption and production, especially single-use plastics, as a top priority. The MR claimed that currently, “There is no recycling except for recycling of paper, metal and electronics...Rule no. 1 for recycling of plastic is a separate collection of plastic waste from drink and food packaging”. Due to this lack of recycling outlets, the MR asserted that Copenhagen burns all burnable waste even with source separation. The MR discourages incineration as it is the “most harmful method” to handle plastics because “incineration is the destruction of resources, the end of life”.

When discussing potential alternatives to the incineration of plastics, there was a substantial opposition to chemical recycling. The MR noted that chemical recycling was too dangerous due to the release of hazardous materials, such as dioxins, without reactions from authorities where, “they often say, ‘don’t worry the wind is in the right direction!’” Mechanical and biological treatment should be sufficient enough in treating plastics; if the plastic is too toxic for those processes, it should be destroyed at hazardous waste incinerators until it is phased out. In order to solve the sustainability issue and achieve a circular economy, the MR favored plans such as Bornholm’s proposal. Bornholm is a Danish island that aims to be the first region in Europe without waste incineration through extensive recirculation of discarded materials (BOFA, n.d.). The MR believed that the initiatives expressed by Bornholm should be adapted for Copenhagen, as Copenhagen’s progress has been stagnant with less unified efforts and larger niche investments.

6.1.2 Amager Resource Center

The Amager Resource Center (ARC) manages the waste in Copenhagen and actively pursues greener methods in order to contribute to a better environment and climate. ARC built Amager Bakke, a new incineration plant in 2019, but is also involved in ongoing development projects such as organic waste separation and collaborating in test labs to optimize recycling practices (Amager Resource Center, n.d.). An Environmental Manager (to be referred to as ER) from ARC was interviewed via a teleconferencing platform.

The ER noted that the source separated plastic fraction would continue to be shipped abroad for processing, as Denmark does not currently have mechanical recycling facilities. However, the ER communicated concern with the municipality exporting waste due to 'scandals' where Danish waste was found in other countries. As Denmark continues to set ambitious climate and waste goals, the ER strongly believes in Copenhagen's responsibility for ensuring their recycled fractions are truly recycled.

With that being said, the ER believes that incineration is an adequate way to handle residual waste as it reduces litter and at least converts waste into energy. In terms of waste plastic within residual waste, the ER sees chemical recycling as a possible alternative to reduce CO_2 emissions and to improve circularity. This perspective is derived from the fact that the current waste processing system makes it, "too easy to leave plastic waste in the residual waste," which is a problem that directly correlates to consumer participation. Since the ER is skeptical of recycling habits changing, they suggested that more sustainable packaging and designing of products would be ideal. Overall, the ER believes that the municipality is attempting to holistically reach their goals by investing and considering a diverse range of solutions.

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6.2 Consumer Participation

Consumer participation describes the role played by the everyday consumer in the industry of plastic recycling. This represents another factor that must be examined when considering potential alternatives to current recycling plans in Denmark, as any diversion from the current system may require an adaptation at the consumer level.

When it comes to waste management, different countries require different levels of cooperation and commitment from their consumers. Common examples of these commitments include consumer sorting of waste into bins/boxes and washing of certain waste. In the plastic recycling industry, municipalities with less capable sorting facilities or processes that require well-sorted polymers may require consumers to divide their plastic waste into any number of fractions, while other less sensitive municipalities may just have one mixed-plastic waste stream (Helena et al., 2018). Furthermore, each recycling process has different levels of tolerance toward plastic contamination. Based on the effectiveness of the facility's decontamination stations, they may also request the consumers wash their plastics before disposing of them. These considerations were all accounted for when assessing the feasibility of chemical recycling implementation in Denmark.

Incineration is the current method of handling plastic waste in the residual waste stream, and therefore doesn’t require any change in consumer behavior. By handling plastic within the residual waste stream, incineration allows for no further sorting of plastics to be required at the consumer level. However, the Copenhagen municipality is already underway in planning to construct a sorting facility that removes plastics from the residual waste stream, without the need for sorting at the consumer level. This facility is projected to be fully operational by 2021 or 2022. With this future scenario in mind, pyrolysis would be an appealing way to process the mixed plastic stream, leaving consumers with no new responsibilities (Tullo, 2019).

Regardless, washing and decontaminating plastic waste may remain an ideal duty of the consumer. Although pyrolysis can take all types of plastic waste and tolerate certain levels of contamination, at a certain point the argument becomes economical instead of plausible. If contamination of plastic waste crests a certain threshold, it becomes no longer reasonable to send the plastic through the pyrolysis process, as the energy intake to heat the process to remove all the impurities is too great to justify the output. As such, the consumers have no specific degree of purity to adhere their plastics to. However, the more cleaning the consumers do, the more economical the recycling process (Wecker, 2018).

Denmark as a country — and at the consumer level — holds environmental issues in much higher regard than other parts of the world. As such, their consumers are more likely to cooperate and show greater willingness to act in order to implement a new recycling process. This cooperation can and should be utilized in the pursuit of clean plastic waste. However, if pyrolysis were to be implemented into the waste system, there should be little to no change resistance from consumers, as no additional adaptation would be required at the consumer level.

CHAPTER 7
Conclusion

After carefully deliberating all technical and operational considerations, it was determined that pyrolysis is the most feasible chemical recycling method for Copenhagen to implement. This is because of this process is able to accept mixed plastic intake, contribute to circularity, have minimal societal concerns, and reduce the carbon footprint of plastic waste management.

The technical data obtained from research and company interviews led to the creation of the decision matrix. This tool allowed the team to directly compare each investigated chemical recycling process by the domains of accepted plastic inputs, yielded product outputs, net energy consumption or generation, and environmental impact from CO_2 emissions. A ranking system was created to reflect and support the scores the team gave to fairly represent each process. Pyrolysis received a greater score than incineration, and the highest score out of the four chemical recycling processes in the technical decision matrix.

In addition, pyrolysis performed equally well considering the consumer impacts and change resistance, which are important facets to the implementation of any process. While chemical recycling seems appealing from most angles, the team expects obstacles and resistance when it comes to change. The restructuring of a waste processing system is no exception; fortunately, consumers would not experience a major change to their recycling habits. The material recovery facility will be vital for the implementation for any chemical recycling process and is already on the roadmap to be completed in 2021. The material recovery facility will ensure that plastic within the residual waste stream will be directed to the chemical recycling process to be properly recycled.

However, chemical recycling is still a fairly new concept, and, to some, it can be perceived as intimidating and unnatural. People commonly associate thermolysis especially with the destruction of resources, as we have seen from our stakeholder interviews. Despite these concerns, pyrolysis will not only save resources from the dead end of incineration, but will substitute the demand for producing new resources, with the recycling of existing materials; while additionally decreasing carbon dioxide emissions. And despite the profound restructuring at the industrial level, the implementation of pyrolysis will have little to no effect at the consumer level, due to the process's diverse acceptance of plastic waste types.

Ultimately, pyrolysis is the process best suited to address Copenhagen's environmental goals outlined in the CPH 2025 Climate Plan. Introducing pyrolysis to the waste processing system has the potential of reducing CO_2 emissions from the waste processing system about 35% percent. By recycling old plastic waste into new plastic polymers, pyrolysis decreases the need to produce plastic the traditional way from crude oil. It fosters both the decrease in net carbon dioxide emissions and embodies a more ethical usage of the world's existing resources through circularity. As we address the evolving issue of climate change, we must always consider that it is our responsibility to protect and manage the world's natural resources more ethically.

CHAPTER 8
Recommendations

The team recognizes that this project serves as a technically-focused preliminary feasibility study of implementing chemical recycling in Copenhagen. Due to the project timeline and inability to be present in Copenhagen, the team was not able to fully capture the economic and organizational feasibility of pyrolysis, discuss alternative routes for plastic in residual waste, evaluate the social impact of chemical recycling, or incorporate future technologies.

For the implementation of pyrolysis, the team recommends assessing the economic and organizational feasibility of pyrolysis. These two factors would ultimately determine the return on investment for the municipality as well as the physical infrastructure or partnerships required, to build the subsystems and technical equipment necessary, in order to fully execute pyrolysis.

For the discussion of alternative routes of plastic in residual waste, the team recommends exploring and comparing paths excluding chemical recycling entirely. These paths include the possibility of shipping waste plastic sorted from residual waste alongside the remaining plastic fraction, building infrastructure to mechanically recycle it, or analyzing the abroad facilities the plastic fraction is currently shipped to.

For the social impact of chemical recycling, the team recommends conducting field studies to better evaluate the role of consumer participation in how and why plastic ends up in residual waste. If plastics were eliminated from residual waste, the municipality would not be interested nor would it need to conduct chemical recycling.

For the future consideration of near-future technologies, such as carbon capture, the team recommends further exploration into its capability and emission reduction for the municipality. In the figure below, different scenarios of carbon capture efficiency are displayed for the waste processing system. Each scenario is compared to the current system with no carbon capture technology, as evidenced by the cluster of three bar graphs on the far left underneath “0% CC” in **Figure 17** below. Carbon capture would only effect the emissions from the Amager Bakke waste-to-energy plant, shown by the reduction in size of the orange bar in each scenario.

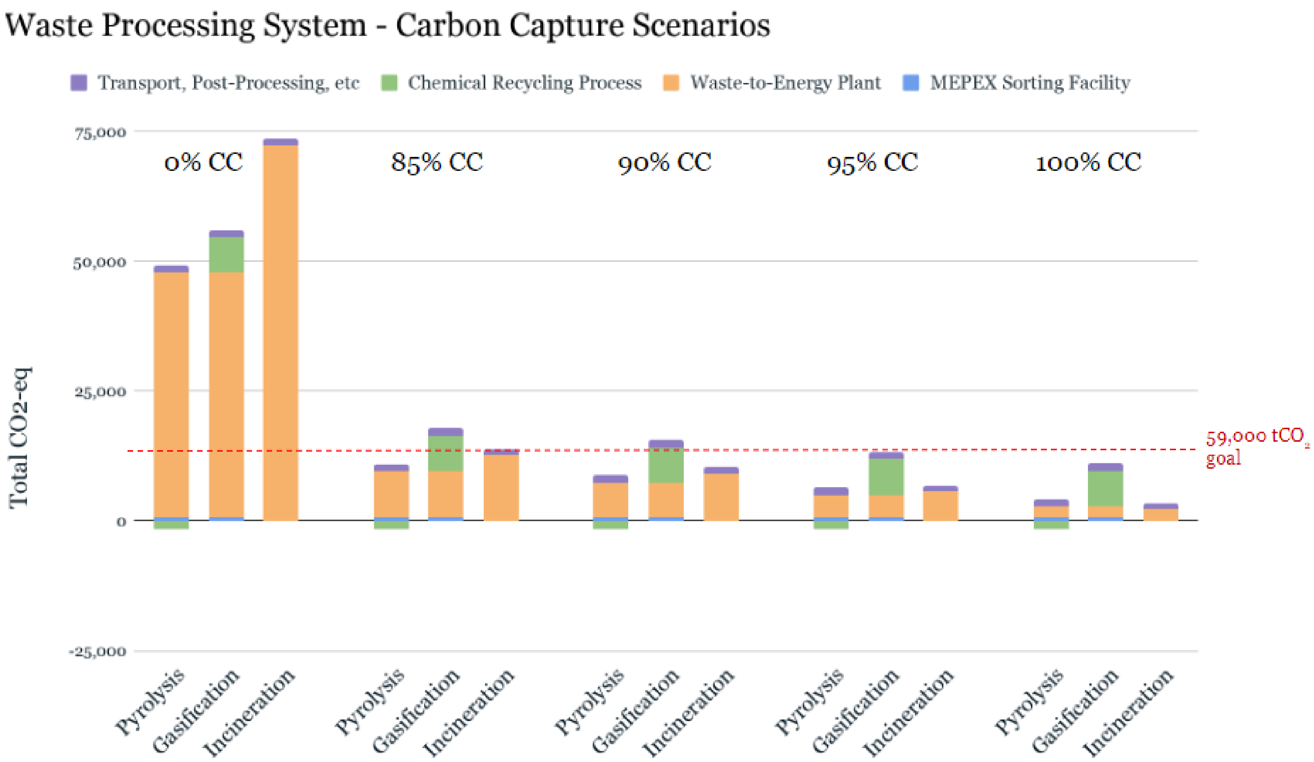


Figure 17: Waste Processing System with Carbon Capture Scenarios

As communicated by Copenhagen Solutions Lab, one of Copenhagen's goals is to reduce the CO_2 emissions in the waste processing system by 59,000 tonnes. Reducing the current system's emissions of 73,550 tonnes by that amount yields a threshold of 14,550 tonnes, as seen by the red dotted line in the figure. Carbon capture technology would bring the current system's emissions below this threshold, assuming the efficiency of carbon capture is above 85%.

Bibliography

(2019). CO_2 report [Data set]. Amager Resource Center.

(2019). Weighing - Overview - Power BI Report. Amager Resource Center.

Abildgaard, J. (2017, June). Copenhagen 2025: Climate and green growth. Presentation presented at BASE London.

Achilias, D. S., Andriotis, L., Koutsidis, I. A., Louka, D. A., Nianias, N. P., Siafaka, P., … Tsintzou, G. (2012). Material Recycling - Trends and Perspectives. InTech. Retrieved from https://cdn.intechopen.com/pdfs/32560/InTech-Recent_advances_in_the_chemical_recycling_of_polymers_pp_ps_ldpe_hdpe_pvc_pc_nylon_pmma_.pdf

Al-Salem, S. M., Lettieri, P., Baeyens, J. (2009). Recycling and recovery routes of plastic solid waste (PSW): A review. Waste Management, 29(10), 2625-2643. http://doi.org/10.1016/j.wasman.2009.06.004

Amager Bakke waste-to-energy plant. (n.d.). Retrieved from https://www.power-technology.com/projects/amager-bakke-waste-energy-plant/

Amager Resource Center. (n.d.). Better sorting of plastic. Retrieved from https://www.a-r-c.dk/affald-til-ressourcer#/holdspiller/bedresorteringafplast

Amager Resource Center. (n.d.). Find recycling space. Retrieved from https://www.a-r-c.dk/privat/genbrugsplads/find-genbrugsplads

Amager Resource Center. (n.d.). National strategi for CO_2-fangst. Retrieved February 26, 2020, from https://www.a-r-c.dk/

Amager Resource Center. (n.d.). Rethink Plastic. Retrieved from https://www.a-r-c.dk/affald-til-ressourcer#/holdspiller/rethinkplastic

Baytekin, B., Baytekin, H. T., & Grzybowski, B. A. (2013, August 20). Retrieving and converting energy from polymers: deployable technologies and emerging concepts. Retrieved February 17, 2020, from https://pubs.rsc.org/-/content/articlepdf/2013/ee/c3ee41360h

Bergsma, G., & Lindgreen, E. R. (2018). Summary of Ioniqa LCA: screening carbon footprint analysis (pp. 1–9). CE Delft . Retrieved from https://www.cedelft.eu/en/publications/download/2591

BOFA. (n.d.). Bornholm showing the way – without waste 2032 (pp. 1–14). Retrieved from https://bofa.dk/wp-content/uploads/2019/01/BOFA_mini-publikation_UK_A4_160119.pdf

Case: Amager Bakke. (n.d.). Retrieved from https://stateofgreen.com/en/partners/amager-resource-centre/solutions/copenhill/

Circular economy - definition, principles, benefits and barriers. (n.d.). Retrieved from https://youmatter.world/en/definition/definitions-circular-economy-meaning-definition-benefits-barriers/

Copenhagen Municipality. (n.d.). Sydhavn Genbrugscenter. Retrieved February 26, 2020, from https://sydhavngenbrugscenter.kk.dk/

Danmark Naturfredningsforening. (n.d.). Retrieved May 6, 2020, from https://www.dn.dk/home/english-page/

De Andrade, M. F. C., Souza, P. M. S., Cavalett, O., & Morales, A. R. (2016). Life cycle assessment of Polylactic Acid (PLA): Comparison between chemical recycling, mechanical recycling, and composting. *Journal of Polymers and the Environment*, *24*(4), 372-384. http://doi.org/10.1007/s10924-016-0787-2

Dean, C. (2013, March). Naphtha catalytic cracking for propylene production. Retrieved May 6, 2020, from https://www.digitalrefining.com/article/1000787,Naphtha_catalytic_cracking_for_propylene_production.html#.XrMak6hKiUk

Diesel and gasoline. (n.d.). Retrieved May 4, 2020, from https://www.iea-amf.org/content/fuel_information/diesel_gasoline

Ellen Macarthur Foundation. (2013). Towards the circular economy: economic and business rationale for an accelerated transition (Vol. 1, pp. 1–96). Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Eriksen, M.K., Christiansen, J.D.m Daugaard, A.E., & Astrup, T.F. (2019). Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling. *Waste Management, 96*. 75-85. https://doi.org/10.1016/j.wasman.2019.07.005

Eurostat. (2019, May 11). How much plastic packaging waste do we recycle? Retrieved from https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20191105-2

Fredriksen, K. Ø. (2017). Waste sorting plant from households- estimates of dividends and investment needs [PDF file] (pp. 1–37). Mepex Consult.

Gaia. (2019) Plastic Pollution and Waste Incineration. Retrieved from https://www.no-burn.org/wp-content/uploads/Plastic-x-Incineration_final-Nov-14-2019-1.pdf

Gray, A. T., Ferrarotti, B. M., Procaccini, J. T., & Bigham, K. (2019). Circular Economy in Small Companies Within Amager. Retrieved from https://digitalcommons.wpi.edu/iqp-all/5378

Grigore, M. E. (2017). Methods of Recycling, Properties, and Applications of Recycled Thermoplastic Polymers. Recycling, 2(4), 24-33. https://doi.org/10.3390/recycling2040024

Helena, D., Valeria, P., Ville, M., Olli, S., Reetta, A. (2018). Recycling potential of post-consumer plastic packaging waste in Finland. Waste Management, 71, 52-61. http://doi.org/10.1016/j.wasman.2017.10.033

Here's how to sort. (n.d.). Retrieved from https://www.a-r-c.dk/privat/farvezoner

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1526), 2115-2126. https://doi.org/10.1098/rstb.2008.0311

INEOS Styrolution. (2019). Sustainability Report 2018. Retrieved from http://www.ineos-styrolution.com/INTERSHOP/static/WFS/Styrolution-Portal-Site/-/Styrolution-Portal/en_US/INEOS-Styrolution-sustainability-report-2018.pdf

Lavallée, M. (2018). *Polystyvert unveils the world's first polystyrene dissolution recycling plant* [Press release]. Retrieved from https://resource-recycling.com/plastics/wp-content/uploads/sites/4/2018/08/2018-08-20-EN-Press-Release-plant-inauguration-FINAL.pdf

LeBlanc, R. (2020, February 3). Single-stream recycling and the future of waste. Retrieved February 16, 2020, from https://www.thebalancesmb.com/an-overview-of-single-stream-recycling-2877728

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., de Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy - weeding out the toxics first. *Environment International, 94*, 230-234. https://doi.org/10.1016/j.envint.2016.05.012

Lichtarowicz, M. (2014, September 7). Cracking and related refinery. Retrieved May 4, 2020, from https://www.essentialchemicalindustry.org/processes/cracking-isomerisation-and-reforming.html

Mastellone, M. L. (2019). A feasibility assessment of an integrated plastic waste system adopting mechanical and thermochemical conversion processes. Resources, *Conservation & Recycling*: X, 4, 100017. http://doi.org/10.1016/j.rcrx.2019.100017

Ministry of Environment and Food. (2018). Strategy for circular economy: more value and better environment through design, consumption, and recycling (pp. 1–38).

Retrieved from https://mfvm.dk/publikationer/publikation/pub/hent-fil/publication/strategy-for-circular-economy/

Miskolczi, N., Bartha, L., & Angyal, A. (2009). Pyrolysis of Polyvinyl Chloride (PVC)-Containing Mixed Plastic Wastes for Recovery of Hydrocarbons. Energy & Fuels, 23(5), 2743–2749. https://doi.org/10.1021/ef8011245

Muthu, S. S. (2015). Environmental implications of recycled and recycled products.

New discovery: Danish plastic waste from households ends up in Malaysia. (2019, September 29). Retrieved from https://plasticchange.org/knowledge-center/new-discovery-danish-plastic-waste-in-malaysia/

Paris Agreement, Nov. 24, 2016, 2-3.

Petrochemicals, from naphtha to plastic. (2015, January 15). Retrieved May 4, 2020, from https://www.planete-energies.com/en/medias/infographics/petrochemicals-naphtha-plastic

Petroleum hydrocarbon chains. (n.d.). Retrieved May 11, 2020, from http://www.caslab.com/Petroleum-Hydrocarbon-Ranges/

Plastics, WARM 13Plastics1–14 (2015). Retrieved from https://archive.epa.gov/epawaste/conserve/tools/warm/pdfs/Plastics.pdf

PowerHouse Energy Group. (2019). *Enabling low cost processing of waste plastics for power, heat and hydrogen production streams* [Brochure]. [United Kingdom].

Ragaert, K., Delva, K., & Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste. *Waste Management, 69*, 24-58. https://doi.org/10.1016/j.wasman.2017.07.044

Reuse and recycling in Denmark. (n.d.). Retrieved February 12, 2020, from https://dakofa.com/element/test-article-next-week/

Rosendal, R. M. (2014, November). Danish policy on waste management - Denmark without waste. Retrieved February 27, 2020, from https://www.researchgate.net/publication/287210935_DANISH_POLICY_ON_WASTE_MANAGEMENT_-_DENMARK_WITHOUT_WASTE

RTI International. (2012). Environmental and economic analysis of emerging plastics conversion technologies (pp. 1–70). Research Triangle Park , NC. Retrieved from http://plastics.americanchemistry.com/Sustainability-Recycling/Energy-Recovery/Environmental-and-Economic-Analysis-of-Emerging-Plastics-Conversion-Technologies.pdf

Seamen, G. (2012, May 2). Plastics by the Numbers. Retrieved from https://learn.eartheasy.com/articles/plastics-by-the-numbers/

Sharobem, T. T. (2010). Tertiary Recycling of Waste Plastics: An Assessment of Pyrolysis by Microwave Radiation. Retrieved from http://www.seas.columbia.edu/earth/wtert/sofos/Sharobem_thesis.pdf

Shivkumar, S. (2019, October-December). Plastics (ME 2821). Course presented weekly in Higgins Laboratories, Worcester, MA.

Stefany. (2018, November 13). Recycling In Denmark - How To Dispose Of Your Trash Correctly. Retrieved February 17, 2020, from https://www.denmarknu.dk/recycling-in-denmark/

Technical and Environmental Administration. (2012). CPH 2025 climate plan (Sept 2012, pp. 1–61). Copenhagen: Technical and Environmental Administration. Retrieved from https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=983

Technical and Environmental Administration. (2016). CPH 2025 climate plan*: Roadmap 2017 -2020.* Retrieved from https://urbandevelopmentcph.kk.dk/artikel/cph-2025-climate-plan

The Danish Government, (2013, November). Denmark without waste. Retrieved from https://eng.mst.dk/media/mst/Attachments/Ressourcestrategi_UK_web.pdf

The Danish Government, (2015, April). Denmark without waste II. Retrieved from https://eng.mst.dk/media/164923/denmark-without-waste-ii_wasteprevention.pdf

The Editors of Encyclopedia Britannica (2019, November). Recycling. Retrieved from https://www.britannica.com/science/recycling/Plastics

The feasibility study – key factors. (2017, January 18). Retrieved February 10, 2020, from https://programsuccess.wordpress.com/2018/05/01/the-feasibility-study-key-factors/

Thermochemical conversion processes. (n.d.). Retrieved February, 29, 2020 from https://www.energy.gov/eere/bioenergy/thermochemical-conversion-processes

Tullo, A. H. (2019). Plastic has a problem; Is chemistry the solution? *C&EN, 97*(39)*, 29-34.* https://doi.org/10.1021/cen-09739-cover

U.S. Energy Information Administration - EIA - independent statistics and analysis. (2019, June 4). Retrieved April 30, 2020, from https://www.eia.gov/tools/faqs/faq.php?id=34&t=6

US EPA. (n.d.) Dioxins and Furans. Retrieved from https://archive.epa.gov/epawaste/hazard/wastemin/web/pdf/dioxfura.pdf

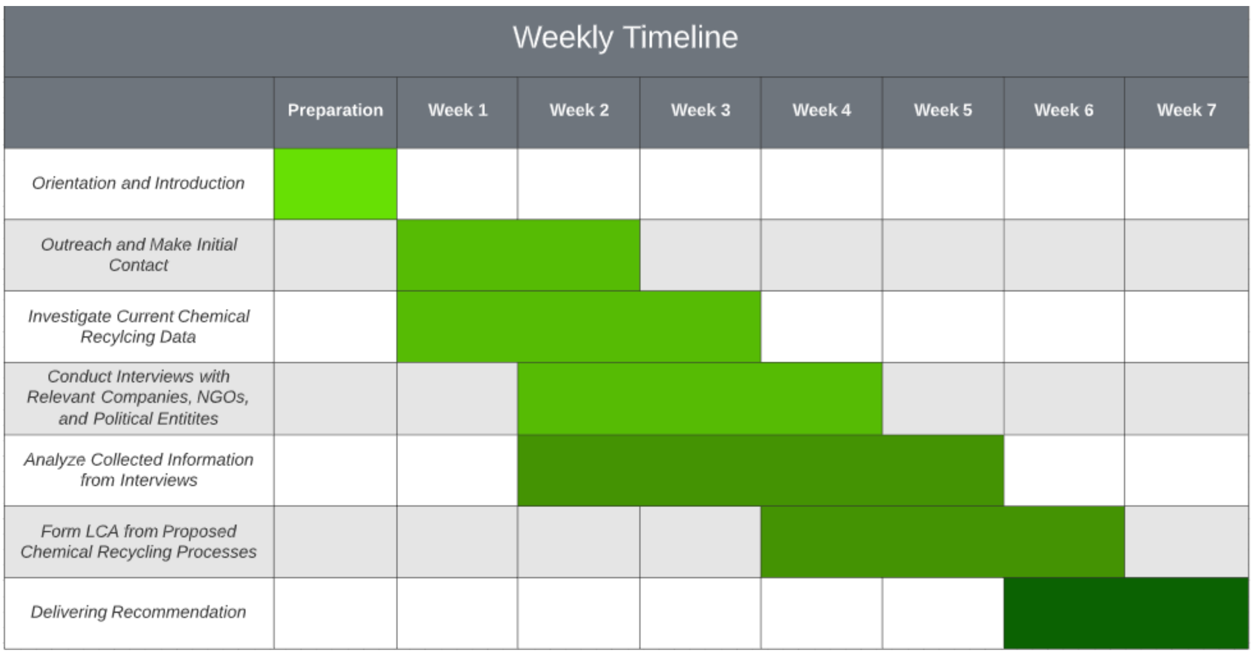
Valence, S. D. (2019, October 23). The slopes are green at Copenhagen's first ski hill. Really. Retrieved February 27, 2020, from https://www.nytimes.com/2019/10/23/travel/copenhagen-ski-hill-powerplant.html

Wecker, K. (2018, October 12). Plastic waste and the recycling myth. Retrieved February 17, 2020, from https://www.dw.com/en/plastic-waste-and-the-recycling-myth/a-45746469

What is feasibility study and its importance in project management. (2020, January 21). Retrieved February 10, 2020, from https://www.simplilearn.com/feasibility-study-article

Appendices

Appendix 1: Project Gantt Chart



Appendix 2: Chemical Recycling Firms

The investigation of chemical recycling was completed through both preliminary research and semi-structured interviews of private firms that actively implement a chemical recycling process. The list of firms contacted, and other relevant information is shown.

Company	Process	Headquarters	Company Email	Company Website
Agilyx	Pyrolysis	Tigard, OR, USA	info@agilyx.com	https://www.agilyx.com/
BASF	Pyrolysis	Ludwigshafen, Germany	https://www.basf.com/us/en/legal/contact.html	https://www.basf.com/us/en.html
Braven	Pyrolysis	N/A	info@bravenenvironmental.com	https://bravenenvironmental.com/#about
Brightmark Energy	Pyrolysis (preceded by mechanical recycling)	San Francisco, CA, USA	plasticsreninq@brightmarkenergy.com	https://www.brightmarkenergy.com/
Carbios	Enzyme-aided Depolymerization	St-Beauzire, FR	contact@carbios.fr	https://carbios.fr/en/
Eastman Chemicals	Carbon Renewal (Pyrolysis)	Kingsport, TN	https://www.eastman.com/Pages/Contact_Us.aspx	https://www.eastman.com/Pages/Home.aspx
INEOS Styrolution	Depolymerization	Channahon, Illinois	INSTY.info@ineos.com	http://www.ineos-styrolution.com/index.html
Ioniqa	Hydrolysis / Glycolysis	The Netherlands	info@ioniqa.com	https://ioniqa.com/
Loop Industries	Depolymerization	Terrebonne, QC, CAN	info@loopindustries.com	https://www.loopindustries.com/en/

LyondellBasell	Catalysis in Pyrolysis	Rotterdam, Netherlands	https://www.lyondellbasell.com/en/utilities/contact-us/media-relations/media-relations/?id=18184	https://www.aschulman.com/
New Hope Energy	Mech + Pyrolysis	Tyler, TX, USA	https://newhopeenergy.com/contact-us-1	https://newhopeenergy.com/
Pyrowave	Catalytic Microwave Depolymerization	Oakville, Canada	https://www.pyrowave.com/en/contact-us	https://www.pyrowave.com/en/
Polystyvert	Sounds like Catalytic dissolving?	Montreal, Canada	http://www.polystyvert.com/en/contact/	http://www.polystyvert.com/en/
PowerHouse Energy Group	Gasification	Thornton, UK	inquire@powerhousegroup.co.uk	https://www.powerhouseenergy.net/dmg/
Plastic Energy	Thermal Anaerobic Conversion (Pyrolysis)	London, UK	info@plasticenergy.com	https://plasticenergy.com/
Quantafuel	Catalysis	Skive, DK	contact@quantafuel.com	https://quantafuel.com/
Recycling Technologies	Depolymerization	Swindon, UK	https://recyclingtechnologies.co.uk/contact/	https://recyclingtechnologies.co.uk/
Renewology	N/A	Salt Lake City, Utah, USA	info@renewlogy.com	http://renewlogy.com/renew-energy/
Makeen Energy	Pyrolysis	Randers, Denmark	info@makeenenergy.com	http://www.makeenenergy.com/home/

Appendix 3: Citizen Interview Questions

The intention of the citizen interviews was twofold: to assesses why the consumers recycle as well as their perception of current or proposed recycling, and to encompass the implication of how the consumers recycle materials, particularly how types of plastics are recycled around the city.

The infrastructure surrounding recycling reflects Denmark's political commitment to sustainability and improving the recycling habits of consumers. However, since the participation of consumers is vital to the effectiveness of a new chemical process, it was important for the team to understand the consumer's current stance regarding recycling. This would be best accomplished through surveying consumers. The proposed questions are as shown below.

1) **Why do you currently recycle?** *This question would provide information about the current stance the Danish have toward recycling. It would allow the team to gauge whether recycling is done out of personal interest or requirement.*

2) **What recycling checkpoints/centers have you been to?** *If the consumer is aware of the different resources available, this question would help the team understand the awareness of the consumer.*

3) **What was your experience like at those checkpoints/centers? What can be improved at these checkpoints/centers?** *These questions both target the consumer's interaction at these checkpoints as a way for the team to determine points of improvement. If the Danes are not using the recycling checkpoints or centers, it is important to understand what factors have deterred them.*

4) **How educated do you feel about how to recycle?** *If a lack of recycling stems from misconceptions, then we could draw conclusions on how to better distribute information.*

5) **How would you rank the following waste management methods: incineration, mechanical recycling, chemical recycling?** *This directly confronts the consumer by allowing them to reflect on Denmark's current system and shed light on their perception of it.*

We also wanted to know how the Danes' distinguish plastic from residual waste, with the aim of finding a route cause as to why such a high volume of recyclable plastic is not properly source separated. This would be best accomplished through surveying consumers, interviewing shop owners, conducting field observations, and researching previous strategies. Surveying consumers and interviewing shop owners would diversify our pool for recycling entities since shop owners, particularly restaurants, would be managing a larger volume of waste than individual households. The proposed questions and intention of each question are shown below.

1) **What steps do you take to recycle?** *This question would provide insight on source separation as well as familiarity with different collection stations and drop off stations.*
2) **What are the maximum number of steps you would be willing to take to recycle?** *This question explores a partial opinion on the current recycling processes, but ultimately helps the team gauge the effort the consumer is willing to put forth.*

3) **After using a product made of or with plastic, what is your first inclination on how to dispose of it?** *This question specifically asks about plastic recycling to better understand both perception and action taken.*

4) **Do you regularly wash dirty plastics before recycling them?** *This question will partially reveal how well-informed the citizen is of how they can treat plastics. This will also help identify a potential reason why plastics are placed into the residual waste bin.*

5) **What plastic objects would you place into a residual waste bin?** *This better describes the perception of residual waste from plastic waste.*

6) **Are there any obstacles that prevent you from recycling plastic?** *This question probes into the boundaries that the consumer may face when recycling plastic whether that be socially, economically, or convenience based.*

Appendix 4: List of Stakeholders

Stakeholders were interviewed in a semi-structured format to elicit their perceptions on Copenhagen's system as well as the acceptance of a new recycling method. The list of contacted stakeholders are shown below.

Company	Status (Public, Private, NGO)	Headquarters	Company Email	Website
Danish Society for Nature Conservation	NGO	Copenhagen	dn@dn.dk	https://www.dn.dk/home/english-page/
Green Transition Denmark	NGO	Copenhagen	info@rgo.dk	https://rgo.dk/frontpage-english/
Eco-net	NGO	Copenhagen	eco-net@eco-net.dk	http://www.eco-net.dk
Friends of the Earth Europe --> NOAH Friends of the Earth Denmark	NGO	Brussels, Belgium	noah@noah.dk	http://noah.dk/om-noah
Plastindustrien (Plastic Industry)	Advocacy/Regulatory Organization	Denmark	kontakt@plast.dk	https://plast.dk/om-os/
Zero Waste Europe	NGO			https://zerowasteeurope.eu/portfolio/zero-waste-denmark/

Appendix 5: Chemical Recycling Interview Questions

The goal of this discussion was to fully explore the feasibility and challenges of the chemical recycling processes implemented by the company. It was in our interest to explore the technology available for chemical recycling as well as the systems required to make these processes feasible. The questions asked are as shown below, with the intention of each question italicized.

Process

1) **Among the classifications of chemical recycling, including pyrolysis, gasification, hydrogenation, glycolysis, methanolysis, depolymerization, and others, which does your corporation's process resemble, include, or compare with the most? (How would you describe your company's approach to chemical recycling?)** *This question provides clarification about the corporation's current process. It could also reveal clarity in the implementation of a singular process along with its process variations.*

2) **Please describe your process to the fullest extent that you can provide.** *We want to learn more about the systems and technology that support the process*

3) **What input(s) does your process require in terms of chemical materials, input feed, and energy?** *We do not expect to be provided direct figures due to privacy concerns but would appreciate intervals or averages.*

   a) **We would also like to understand, to the extent of which you are able: plant operating costs, value of output (per polymer), and recovered plastic yield (in percent)**
   b) **Why did the company decide to implement chemical recycling methods?**

Inputs/Sourcing

4) **What polymer type(s) serve as input(s) to the chemical recycling process?** *Due to the various types of plastics, we would like further insight into how different chemical processes can handle or be ideal for a respective plastic.*

5) **What is the form, cleanliness, and quality required for the input plastic waste to be used in the chemical recycling process?** *This will help determine the threshold of contamination the chemical recycling process can handle.*

6) **What processes, if any, must the input plastic waste first go through before serving as input to the chemical recycling process?** *This question would provide the team with additional plastic treatments required for the recycling process. Depending on the amount of infrastructure desired to increase the efficiency of the process, the team can determine if said chemical process is feasible.*

Outputs

7) **What desired and undesired outputs do the corporation's chemical recycling process yield?** *This will help determine the efficacy of the plastic produced which will give the team a better grasp of the process' success. If there is an undesired byproduct, whether that be gaseous or tangible, it would be important for the team to account for these.*

8) **In what industries can your recovered plastic output be used?** *We would like to identify the lifecycle of the plastic and the efficacy of its products after undergoing a chemical recycling process.*

9) **What percentage of the input material is yielded on the output?**

Impacts

10) **What are the benefits of your chemical recycling process compared to other plastics recycling processes?** *It will be important for the team to understand the explicit benefits the chemical recycling yields over other alternatives.*

11) **What is the return on investment (ROI) for your company with this process?** *Allows us to understand how financially beneficial the process is.*

12) **Are there environmental impacts, such as CO_2 or other emissions (dioxins, furans, nitrous oxide, sulfur oxide, ozone etc.), associated with this chemical recycling process? If so, in what quantities?** *Because we are especially concerned with CO_2 emissions, it will be crucial that we understand the impact of the process. This question may also shed light on other factors we have not yet considered.*

13) **Are there any other factors that we should be aware of with this process?** *For our feasibility study, we would like to have a monetary baseline as we do not expect the operation costs of these corporations to be available to the team. We also want to pinpoint important areas of concern that should be considered.*

Appendix 6: Summary of Chemical Recycling Interviews

The following tables is information gathered from the team's chemical recycling interviews and is organized by company. Each company was noted that the intent of this interview was to gather information for our undergraduate research project only and that the team was not attempting to gather any proprietary data.

Brightmark Energy	
Location	San Francisco, California, USA
Process Type	Thermal Pyrolysis
Process Notes	• BME can slightly adjust the output hydrocarbon mix, has lower temperatures, and reuses released gas internally to heat the vessels • Considered gasification, but it requires a higher oxygenated environment, significantly more energy to break the polymers, more capital, and is an 'over-engineered' solution • BME is 14% better than typical plastic production from greenhouse gas emission perspective
Capacity	• 751 L of fuel produced / tonne of solid plastic waste • Ashley plant processes 100,000 tons of plastic per year using 4 vessels produces 18M gal of fuel, 6M gallons of wax • Operates 24/7, 93% efficient
Preparation of Plastic	• Mixed waste streams require more processing post MRF's to make it the ideal input due to contamination • Shred, dry, and pelletize plastics • BME can handle up to 8% moisture and contamination content
Inputs	• Primarily handles mixed plastics types LDPE, PP, PS, OTHER (4-7) • Can handle PET (1) and LDPE (2), but does not typically see large quantities of these in their intake waste stream • Will separate out PVC (3), but can process up to 8-9% in their streams
Outputs	• Ultra-low Sulfur Diesel (middle of carbon-chain spectrum) • Naphtha (blending for gasoline or feedstock for plastic) • Food-grade/paraffin waxes • Char (can be used for construction)
INEOS Styrolution	
Location	Channahon, Illinois, USA
Process Type	Depolymerization of Polystyrene
Process Notes	• Requires less heat than pyrolysis and always breaks down to styrene • Easier plastic-to-plastic conversion process with less CO_2 output • Sourcing of PS is readily available

	• EU is strongly encouraging the use of recycled materials and creating a more circular economy
Capacity	• Indaver plans to operate a 15,000 ton plant next year • 30,000 ton / year plant in the works
Preparation of Plastic	• Sourced from MRF where FT-NIR can detect PS at nearly 100% regardless of color
Inputs	• Requires clean and sorted PS (6) with 95% purity • Purity ideally will allow monomers to be formed into food-grade plastic
Outputs	• Styrene monomer (once purified, feedstock for more plastic like ASN, ABS, and ASMA) • Palm oils (for food or fuel) • Undesired: lost PS due to efficiency, Benzene, Alphumethastryene, charcoal residue
Ioniqa	
Location	The Netherlands
Process Type	Catalytic Glycolysis of PET

Process Notes	• The innovation was in the catalyst; could speed up depolymerization and was able to take out waste stream impurities
	• Focus on PET and PET packaging but can be applied elsewhere
	• Heat the PET to a few hundred degrees in a closed system with ethylene glycol and the catalyst, also use nitrogen to make sure end product does not explode in the reactor
	• 75% lower CO_2 footprint than oil-based plastics,
	• Produces 1-1.3 tonnes CO_2 /dry tonne of SPW from CE Delft LCA
	• Other processes not favorable
	  ○ Hydrolysis breaks down PET into PTA and ethylene glycol; requires more energy to make these outputs into a PET resin
	  ○ Methanolysis uses sulfans and forms of DMT which are not permitted for use in the Europe

Capacity	• Rotterdam plant 1 kilotonne plant • Holland plant 10 kilotonne plant
Preparation of Plastic	• Sourced from an MRF • Prefer a 90-95% PET content for efficiency and economics
Inputs	• Shredded PET only
Outputs	• BHET (the astrofied form can be re-polymerized to make PET resin)

	○ Viscosity 0.6 = used to make polyester fibers ○ Viscosity 0.8 = used for packaging
Plastic Energy	
Location	London, UK
Process Type	Thermal Pyrolysis
Process Notes	• PE found it necessary to collaborate with waste management companies in order to have a continuous source of plastic • Working with the petrochemical industry to adapt the outputs for targeted usage
Capacity	• 860 L of fuel / dry tonne of SPW • Both Sevilla and Almeria (Spain) plants operate 24/7 • Plans for 20 chemical recycling plants by 2030, currently building 5
Preparation of Plastic	• Sourced from other WM companies and chemical recyclers with feedstock guidelines • Optically sort polymer types and limit moisture internally
Inputs	• Handles mixed plastics types L/HDPE, PP, PS, OTHER (2, 4-7) • Will separate out PET (1) and PVC (3) because of its oxygen content • Limit type 7 plastic to avoid contamination and impurities
Outputs	• 70-75% TAC oil or hydrocarbon oil (crackers can use for new plastic) • ~10% max char (construction, bricks, roads) • 15% syngas (used internally to keep ovens heated)
Powerhouse Energy Group	
Location	Thornton, UK
Process Type	Gasification
Process Notes	• Plastics fed into a thermal conversion chamber at 1100°C with an oxidizing agent to melt and vaporize plastic • Works within European emission levels, only combustion in process is from a gas engine for electricity generation • Converting at least 85% of the inherent energy into syngas energy, when you take away the parasitics of heating the chamber • About 40% efficient in converting that gas into electricity
Capacity	• Processes 40 tonnes of mixed plastics / day
Preparation of Plastic	• Sourced from customer feedstocks • Customer feedstocks are tested to determine output yields

Inputs	• Handles all colored mixed plastics, 1-7 and beyond • Prefers high calorific products • Can take 100% PVC, does a caustic wash to avoid chlorine gas
Outputs	• 3.8 MWe Electricity (marketable) • 2.2 MWe (th) Heat (used internally to heat thermal chamber) • 2 tonnes of 99.999% Hydrogen (used in fuel cell vehicles) • Syngas for industrial use

Appendix 7: Mechanical Recycling Interview Questions

The goal of this discussion was to fully explore the benefits of the mechanical recycling processes implemented by the company. It was in our interest to explore the technology that supports chemical recycling and the systems required to make that process feasible, one of which is mechanically sorting plastic waste by polymer. The questions asked are as shown below, with the intention of each question italicized.

__**Process**__

1) **How would you describe your company's process of mechanical recycling?** *Mechanical recycling is an imperative step for the implementation of chemical recycling. Chemical recycling requires plastics to first be separated from residual waste and then sorted by polymers type from mixed plastic waste. This allows the interviewee to explain their process first, to frame the interview and the rest of the questions around their specific process.*

__**Collection**__

2) **If applicable, does your company directly participate in waste collection?** *This provides insight in the potential partnership or collaborative efforts companies have with a town/city's waste management. Following questions expand on logistical inquiries.*
    a) **Where does it collect from?**
    b) **What kinds of waste does it collect?**

3) **If your company doesn't collect residual waste, where/who do you receive waste from?** *This gives more context on how the company sorts and what their inputs look like.*
    a) **How would you describe the residual waste once it moves to the next phase of recycling (is it dirty, clean, sorted, unsorted, etc)?**

__**Sorting/Separation**__

4) **If applicable, how does your company participate in separation of plastic waste from residual waste?** *Separating plastic out from a mixture of residual waste is one of the most important aspects of chemical recycling, as the input to chemical recycling needs to be of a certain standard.*
    a) **How is the waste processed to separate plastic waste from residual?**
    b) **What are some of the challenges of this process?**
    c) **How would you describe the plastic output of this phase of the process?**

5) **If applicable, how does your company participate in the sorting of plastic polymers?** *Because plastics are not source-segregated into their respective*

polymer types and mixed polymers cannot be treated together, it is important to understand what technologies and processes are used to sort the mixed plastic waste.

a) **What processing techniques or equipment are used to achieve this?**
b) **What are some of the challenges of this process?**
c) **How effective is this process at sorting plastic polymers?**
d) **Once polymers are sorted, do they require additional decontamination treatment?**

6) **What makes a plastic unfit for mechanical recycling?** *The plastic waste entering the facility may need to fulfill specific requirements.*
a) **What contaminants does your company address?**
b) **How do you determine the point at which a plastic is too contaminated?**
c) **What do you do with this contaminated plastic?**

Output

7) **Does your company participate in the transformation of sorted plastic waste into new plastic feedstock?** *The plastic waste that is separated from residual waste and sorted by polymer needs to go through more processing to allow it to be reused.*
a) **What are the kinds of recovered polymers used and how are they processed to achieve this?**
b) **What is the output of this process?**
c) **How is this recycled feedstock used in industry?**

Appendix 8: Pyrolysis Process Data

Pyrolysis Process Data							
Company	**Status**	**SPW (Ton or Tonne)**	**Overall Fuel Produced (gal or L)**	**Overall Fuel per SPW (L/tonne)**	**Power Consumption (kWh/ dry tonne)**	**CO_2 Emissions (tonnes of CO_2 / dry tonne of SPW)**	**Est. Annual CO_2 for CPH***
Agilyx[b]	Active	10 tons	2520 gallons	1051.52	551	0.4799	3915.984
Biofabrik[b]	Active	250-1000 tonnes	250-1000 L	1000	1000	--	--
BME[a]	Active	100,000 tons	18,000,000 gallons	751	--	--	--
Climax Global Energy[b]	Active	1 ton	210 gallons	876.26	--	0.2494	2035.104
Envion[b]	Inactive	1 ton	177.24 gallons	739.56	550	.0369 - .00923	301.1 - 75.3168
JBI[b]	Inactive	1 ton	247.7 gallons	1033.57	0.33	0.000149	1.21584
Quantafuel[b]	Active	16,000 - 18,000 tonnes	15,000,000 L	800	--	--	--
Plastic Energy[a]	Active	--	--	860	--	--	--
Veba[b]	--	700 tonnes	--	--	220	--	--
Generalized from ACC[b]	--	--	--	--	0.36 - 529.1	0.2494 - 0.4799	2035.104 - 3915.984
Average	**Actives Only**			**889.79**	**529**	**0.48**	

Note: the following superscripted letters in the company name column indicates where the data was collected

a. Data collected from interviews (can be viewed in appendix)

b. RTI International, 2012

Appendix 9: Gasification Process Data

Gasification Process Data							
Company	**Status**	**SPW (Ton or Tonnes)**	**Electricity Produced (MW)**	**Electricity per SPW (KWh / tonne of plastic)**	**Power Consumption (kWh/dry tonne)**	**CO_2 Emissions (tonnes of CO_2 / dry tonne of SPW)**	**Est. Annual CO_2 for CPH (tons or tonnes)**
Enerkem[b]	Active	--	--	--	540	0.183	1853.6985
GeoPlasma[b]	Active	600 tons	22	970.0	--	--	--
Plasco Conversion Technologies[b]	Active	93 tons	4	1050	--	0.3528	3573.6876
Powerhouse[a]	Active	40 tonnes	3.8	2040	250	--	--
Ze-gen[b]	Inactive	--	--	--	220	0.1719	1741.26105
Generalized from ACC[b]	--	--	--	1020 - 1435	220-540	0.1719 - 0.5225	1741.26 - 5292.66
Average	**Actives Only**			**1350**	**540**	**0.52**	

Note: the following superscripted letters in the company name column indicates where the data was collected

a. PowerHouse Energy Group, 2019

b. RTI International, 2012

Appendix 10: Chemolysis Process Data

Chemolysis Process Data					
Company	**Status**	**SPW (Ton or Tonnes)**	**Feedstock produced**	**Power Consumption (kWh/dry tonne)**	**CO_2 Emissions (tonnes of CO_2 / dry tonne of SPW)**
INEOS Styrolution[b]	Active	--	--	523	0.455
Ioniqa[a]	Active	--	--	--	1 - 1.3
Eastman Chemicals[c]	Active	--	--	--	1.226
Polystyvert[d]	Active	600 tonnes / year	125kg/h	--	--

Note: the following superscripted letters in the company name column indicates where the data was collected

a. Data collected from interviews (can be viewed in appendix)

b. INEOS Styrolution, 2019

c. RTI International, 2012

d. Lavallée, 2018

Appendix 11: 2011 Study on Pyrolysis and Hydrocarbon Yields

Hydrocarbon Data for GASOLINE							
Hydrocarbon	**S1**	**S2**	**S3**	**S4**	**S5**	**Average**	**Naphtha/Diesel**
C5	3.76%	3.18%	3.83%	4.03%	3.79%	3.72%	**64.84%**
C6	7.76%	7.68%	7.68%	7.07%	6.30%	7.30%	
C7	3.59%	3.76%	3.42%	3.81%	3.31%	3.58%	
C8	6.24%	6.93%	5.70%	6.48%	6.69%	6.41%	
C9	18.32%	15.90%	17.21%	17.17%	16.80%	17.08%	
C10	11.45%	10.20%	11.40%	10.10%	10.34%	10.70%	
C11	6.44%	7.45%	5.48%	6.98%	6.32%	6.53%	
C12	9.26%	10.28%	10.19%	9.09%	8.82%	9.53%	
C13	0.85%	1.04%	1.00%	1.44%	1.86%	1.24%	**2.22%**
C14	0.79%	0.29%	0.33%	0.05%	0.04%	0.30%	
C15	0.26%	0.56%	0.42%	0.05%	0.16%	0.29%	
C16	0.42%	0.29%	0.16%	0.05%	0.08%	0.20%	
C17	0.32%	0.43%	0.09%	0.05%	0.08%	0.19%	
Aliphatic Total	**69.46%**	**67.99%**	**66.91%**	**66.37%**	**64.59%**	**67.06%**	
Aromatic Total	**30.54%**	**32.01%**	**33.09%**	**33.63%**	**35.41%**	**32.94%**	

Hydrocarbon Data for LIGHT OIL							
Hydrocarbon	**S1**	**S2**	**S3**	**S4**	**S5**	**Average**	**Diesel/Heavy**
C11	0.11%	0.12%	0.00%	0.20%	0.16%	0.12%	**86.55%**
C12	6.82%	7.02%	7.71%	8.80%	9.61%	7.99%	
C13	6.09%	6.76%	6.25%	6.99%	7.47%	6.71%	
C14	6.82%	7.67%	7.20%	6.46%	8.24%	7.28%	
C15	16.73%	16.82%	17.05%	18.79%	17.69%	17.42%	
C16	14.75%	16.16%	15.60%	16.50%	16.21%	15.84%	
C17	9.40%	8.39%	8.30%	9.03%	8.42%	8.71%	
C18	14.84%	14.29%	14.25%	15.72%	14.73%	14.77%	
C19	5.76%	6.37%	5.03%	5.51%	5.09%	5.55%	
C20	2.77%	2.54%	2.12%	1.75%	2.22%	2.28%	

C21	2.46%	2.72%	3.09%	2.30%	2.49%	2.61%	
C22	2.24%	3.52%	2.73%	1.80%	2.01%	2.46%	
C23	1.71%	1.33%	1.94%	1.42%	1.27%	1.53%	
C24	2.83%	1.93%	2.88%	1.82%	1.46%	2.18%	
C25	0.98%	0.64%	0.50%	0.06%	0.05%	0.45%	**12.80%**
C26	2.83%	1.81%	1.69%	1.10%	0.76%	1.64%	
C27	0.65%	0.53%	0.88%	0.44%	0.38%	0.58%	
C28	0.76%	0.70%	1.44%	0.77%	0.49%	0.83%	
C29	0.53%	0.52%	0.52%	0.51%	0.53%	0.52%	
Aliphatic Total	**99.08%**	**99.84%**	**99.18%**	**99.97%**	**99.28%**	**99.47%**	
Aromatic Total	**0.92%**	**0.16%**	**0.82%**	**0.03%**	**0.72%**	**0.53%**	

Hydrocarbon Data for HEAVY OIL			
Hydrocarbon	**Aliphatic Paraffin**	**Aliphatic Olefin**	**Aromatic**
S1	52.10%	33.80%	14.10%
S2	53.30%	32.40%	14.30%
S3	51.00%	32.50%	16.50%
S4	54.30%	33.80%	11.90%

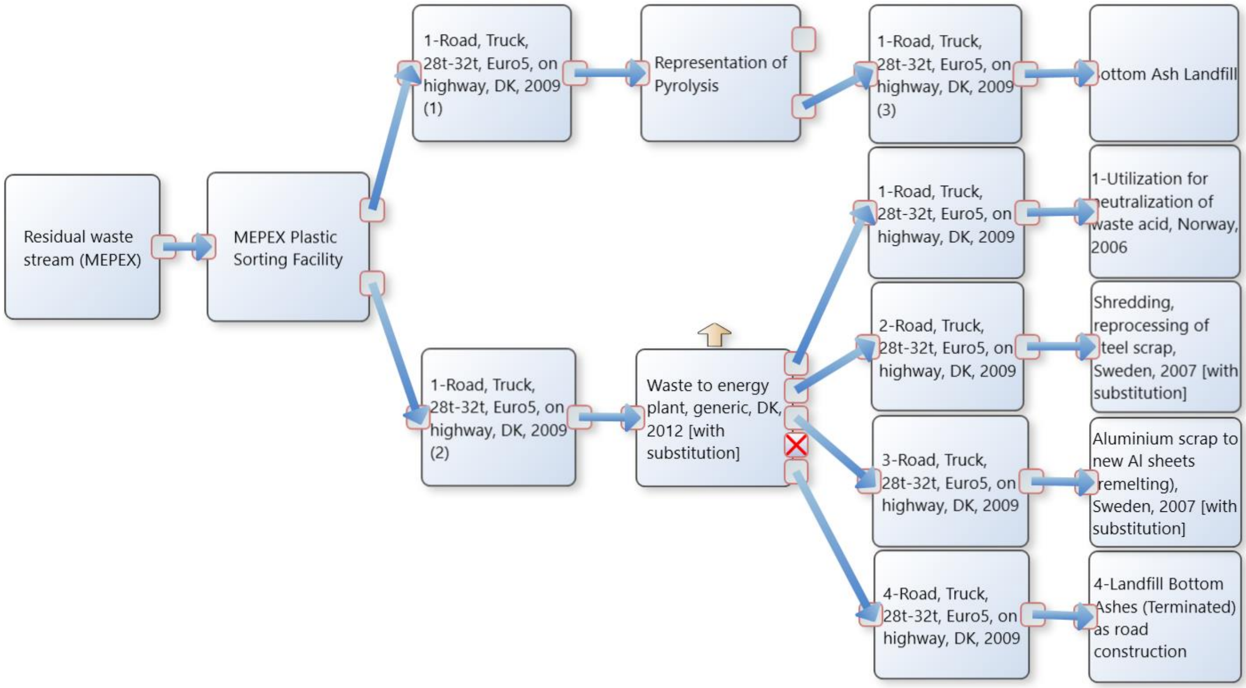
Note: The data tables are from Miskolczi, Bartha, & Angyal (2009)

Appendix 12: Pyrolysis Hydrocarbon Yield Percentage Scenarios

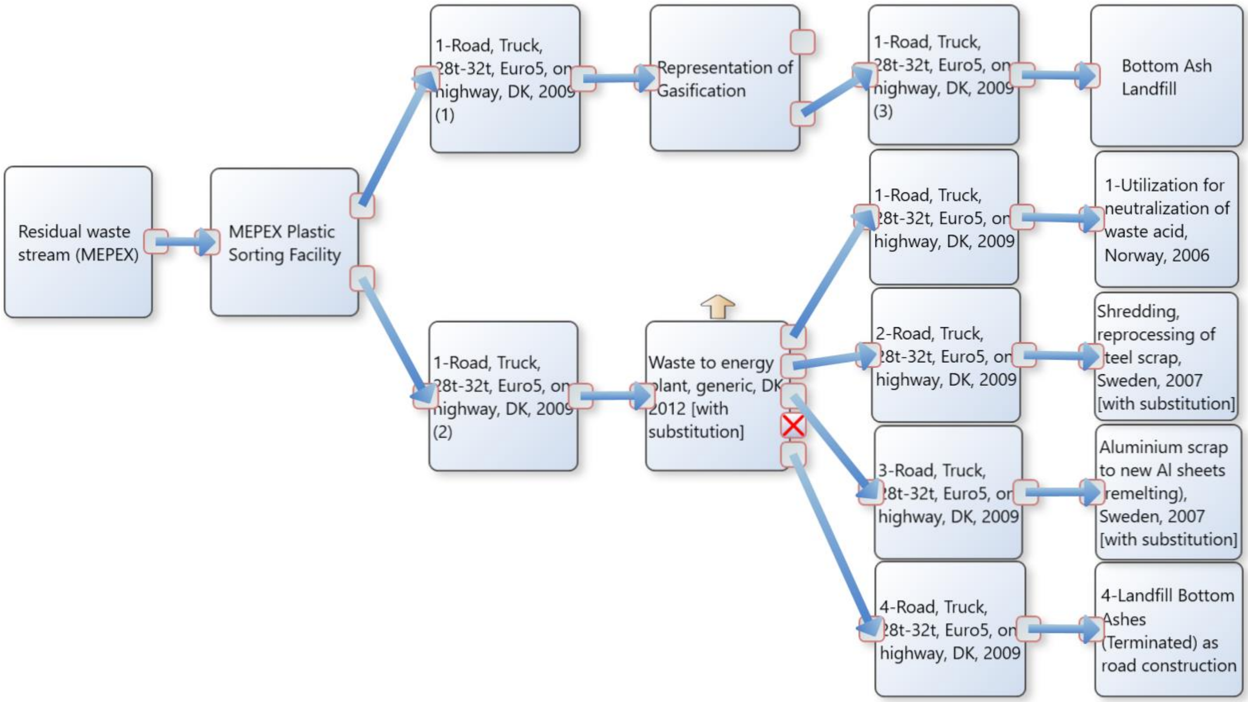
Based on a total output yield of 890 liters

Type of Fraction	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
	Percentage	Quantity (L)	Percentage	Quantity (L)	Percentage	Quantity (L)	Percentage	Quantity (L)
Naphtha	0.10	89.0	0.15	133.5	0.20	177.9	0.25	222.4
Diesel	0.80	711.7	0.70	622.8	0.60	533.8	0.50	444.8
Heavy	0.10	89.0	0.15	133.5	0.20	177.9	0.25	222.4

Appendix 13: Waste Processing System with Pyrolysis EASETECH Diagram



Appendix 14: Waste Processing System with Gasification EASETECH Diagram



Appendix 15: Stakeholder Interview Questions

The goal of this discussion was to gather opinions on different types of plastic waste management alternatives, including incineration and chemical recycling. It was in our interest to explore and capture the environmental implications of incineration and chemical recycling in our feasibility study. The questions asked are as shown below, with the intention of each question italicized.

Plastics

1) **Where do you think plastic goes once it is recycled?** *Opens thoughts on what happens to the recyclables once the truck takes it away.*

2) **In what ways can plastics be used more sustainably?** *Insight into the different applications of plastics and could comment on their lifespan. Could also comment on the consumer behaviors of the Danes or design of the plastic products themselves.*

3) **What are some strengths and weaknesses to the current system of collecting and recycling waste in Copenhagen?** *Ties into the social aspect of how the Danes recycle as well as how the population is supported to effectively recycle. Helps identify gaps in the system.*

Recycling

4) **How can recycling be improved to reduce environmental impact?** *Adds environmental outlook on the preference of future recycling strategies, which can be considered when evaluating potential alternatives.*

5) **Do you have an opinion on chemical recycling?**
    a. **Does chemical recycling appear to be an attractive method to reusing plastics? Why?**

Incineration

6) **What is your opinion on incineration?** *Gives a different viewpoint (more social/environmental rather than industrial) on the effect incineration has on the environment and if they have any other ways they think is cleaner.*

7) **Do you think that there is an alternative method of waste management, that Denmark could currently implement, to incineration?**

Environmental

8) **What environmental initiatives are the most pressing for Denmark?** *Provides the opportunity for the interviewee to express what's most important to them.*

9) **What are your thoughts on Copenhagen's progress to address these initiatives?** *Provides a place for the organization to discuss current system and plans.*