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# Challenges to Sustainable Plastic Recycling

## Exploring chemical recycling as a complement to mechanical recycling to handle plastic waste

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Gothenburg, Sweden 2019



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Cover: [Collection of plastic waste placed on a recycling logo to represent circularity of plastic material. Photographer: Ashwin Sidharthan.]

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### **ABSTRACT**

The use and production of plastics has increased substantially over the years leading to an increase in the generation of plastic waste. Today, plastic waste is either used for energy recovery by incineration or recycled mechanically. However, there has been developments in chemical recycling being a possible alternative to handle plastic waste. The interest for chemical recycling is mainly to do with the improved purity of the secondary raw material, which could be used as an alternative to crude oil, which is what plastic manufacturing is currently dependent on today. Since chemical recycling has not been implemented yet, this thesis sets out to understand what challenges would have to be addressed in order to have sustainable plastic recycling. This leads to the research questions that this project has set out to answer:

1. What are the remaining challenges to sustainable material recycling of plastic waste if chemical recycling is implemented as a complement to mechanical recycling in Västra Götaland?
2. What are the barriers to and drivers for transition from the current system to this new system?

To begin addressing the research questions it was necessary to define sustainable plastic recycling. In order to understand the challenges that chemical recycling might face, mapping and finding the current challenges in the plastic recycling system was necessary. A brief system mapping of the plastic waste value chain was done followed by interviews with stakeholders from different part of the value chain. The data from the interviews were collected and categorized in order to address the research questions.

The identified challenges to meeting the sustainability criteria in the current system were the lack of market for recycled plastic, lack of either quality or quality assurance and lack of policies that encourage the use of recycled materials. It was also seen that the sorted plastic is exported outside Sweden and there are no regulations meant to track this exported waste.

While chemical recycling can be used to produce better quality secondary raw material, the process is today both energy intensive and expensive. There are no regulations specifically addressing recycled plastics from chemical recycling. There is also uncertainty about the market demand for the secondary raw material. This process would require high volume of plastic feed for recycling to be economically feasible.

The barriers identified for transitioning into the new system are uncertainties with respect to investment and ownership, leading to a lack of a business model to set up the recycling plant. There are also certain technological challenges when it comes to addressing different streams of the plastic waste.

The drivers identified for transitioning into the new system is the willingness to collaborate for change between actors in the value chain. National and regional goals also restrict the possibility to incinerate plastics. The secondary raw material from chemical recycling can be accepted in chemical industries without having to make drastic changes in their existing technology.

**Keywords:** Plastic waste, Plastic recycling, Chemical recycling, Mechanical recycling, Backcasting, System Mapping, Västra Götaland

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Lastly, we would also like to extend a large thank you to all the stakeholders that have been involved.

## **List of abbreviations**

CE: Circular economy

EPR: Extended Producer Responsibility

EU: European Union

GHG: Greenhouse gases

CO<sub>2</sub>: carbon dioxide

CO: carbon monoxide

H<sub>2</sub>: Hydrogen

CH<sub>4</sub>: Methane

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# 1 Introduction

Plastic is a material that is widely used in society today and the production has increased over the years (Geyer et. al, 2017). Currently all the plastic waste in Sweden is either mechanically recycled or used for energy recovery by incineration (The Swedish Ministry of the Environment, SOU 2018:84). However, in this thesis, the challenges to sustainable recycling of plastic waste if chemical recycling were to be implemented as a complement to mechanical recycling is investigated. This is further motivated by highlighting some of the drivers to transition towards this newly predicted system.

## 1.1 Regional Goals Addressing Plastics

The Swedish Ministry of the Environment, in SOU 2018:84, suggests that circular economy is the goal when it comes to plastics in Sweden. Today the flow of plastics in society is a linear, buy-throw away system. In order to have a more circular flow, aspects such as material recycling should be improved. Barra (2018) describe circular economy as the much needed and sustainable alternative to the linear economic model prevalent today. Circular economy aims to keep resources in use for as long as possible in order to recover material at its end-of life.

Sweden has set up various regional and national goals in order to guide sustainable development. One of the national goals is to have zero net emissions of greenhouse gases (GHG) by the year 2045 (Government Offices of Sweden Ministry of the Environment and Energy, 2017). On a regional level, goals in Västra Götaland, Klimat 2030, have been defined which say that by the year 2030 the region shall be fossil independent (Västra Götalandsregionen & Länsstyrelsen i Västra Götalands län, (n.d.)). The target is to reduce greenhouse gas emissions by 80% compared to the emissions of the year 1990. One of the focus areas is defined as *renewable & resource efficient products and services*. Under this there are goals addressing circularity. The chemical industry is also expected to use recycled materials in their production.

## 1.2 Plastics: production, use and problems

Plastics are polymers, which are long chain of monomers (European Commission, 2018). They are mostly composed of carbon and hydrogen. Other elements like oxygen, chlorine, fluorine and nitrogen are also found in different types of plastics.

Plastics are typically easy to shape and manufacture, robust, non-biodegradable, non-corrosive, lightweight and cheap to manufacture (Worrell & Reuter, 2014). Additional substances are used to give the product flame resistant properties, certain rheological properties, antifungal properties and different colours (Hestin et al., 2017). Manufacturing of plastic products use additional substances like plasticizers, other additives and fillers to the polymer to give the material unique properties based on its application (Hestin et al., 2017). It is estimated that there are 3377 chemicals associated with plastic production as of today (Groh et al., 2019). Because of an attractive range of properties, plastics and plastic-based material make up most of the products we see around us today. Plastics are a key material used in packaging, transportation, construction, healthcare and the electronics sector, see table 1 (Worrell & Reuter,

2014). Packaging (40%) and construction (19.7%) are the two sectors that are primarily dependent on plastics. The growth of the packaging industry was largely an effect of the trend to use single-use containers. This range of numerous types of plastics with different substances used for their manufacturing, has made sorting and recycling of plastics extremely challenging.

*Table 1 Different types of plastics, their application and share of all plastics being used based on type (Worrell & Reuter,2014)*

<b>Plastic type and abbreviation</b>	<b>Application</b>	<b>Market share</b>
Polypropylene (PP)	Buckets, Caps for bottles, Boxes, Dairy product cups, Industrial adhesive tapes	19.3%
Low Density Poly Ethylene (LDPE)	Foils, Films, Sack and covering wraps for fruits and vegetable bags, Carrier bags, Shrink wraps	17.5%
High Density Polyethylene (HDPE)	Thick-walled applications such as bottles and flasks, Barrels, Crates, Packaging for carpets and instruments	12.3%
Poly Vinyl Chloride (PVC)	Blister and press-through packs for medication, Films for perishables	10.2%
Polyethylene Terephthalate (PET)	Bottles and flasks for soft drinks, mineral water, detergents and pharmaceutical products, Blister packs, Packaging for ready meals	7.4%
Polystyrene (PS)	Food service disposables, Boxes and dishes for meat products and vegetables, Boxes for ice, Boxes for video tapes	6.6%

According to Ellen MacArthur Foundation (2016), the increased usage of plastic in everyday life has substantially increased their production over the years. It is estimated that as of 2015, approximately 8300 million tonnes of primary oil-based plastic had been produced, resulting in an accumulation of 6300 Million tons of waste around the world (Geyer, Jambeck, & Law, 2017). The production of plastics has increased 20-fold, from 50 million tonnes in 1964 to 311 million tonnes in 2014 (Ellen MacArthur Foundation, 2016). Plastic production currently depends on fossil raw material. Today, plastics production uses 6% of the global oil production. Going by this trend, the production of plastics is expected to increase by 4 times by 2050, and could account for up to 20% of the oil production (Ellen MacArthur Foundation, 2016).

This steep increase in dependence and production of plastics, along with its properties, has led to accumulation of plastic waste (Miliotis et al., 2018). Plastic pollution has become so severe that it has become a global concern in recent years.

### **1.3 Plastic waste handling system**

The focus of this thesis is on recycling of plastic waste in Sweden. Plastic waste in Sweden is addressed in a number of ways. There are regulations addressing who is responsible for the waste and how the waste is handled. This section also briefly explains the different processes used to recycle plastics

#### **1.3.1 The Extended Producer Responsibility**

Sweden has the Extended Producer Responsibility (EPR) act to address e.g. the plastic packaging (The Swedish Ministry of the Environment and Energy, SFS 2018:1462). This regulation holds the producers responsible for collection and recycling of waste. The act also includes some aspects when it comes to production of packages. Between the years 2019 and 2025 some changes to the EPR scheme will take place. One of the changes, for example, includes that producers need to have sorting stations closer to consumers.

#### **1.3.2 The Waste hierarchy**

The waste hierarchy in EU's Waste directive 2008/98/EC is a prioritization of different waste handling options, see Figure 1. The hierarchy explains the best and worst ways to deal with waste, with the best being prevention (reduction of waste) and worst being disposal (landfilling). While prevention and re-use is placed higher up on the waste hierarchy and is preferred over the other steps, this thesis primarily focuses on how to handle the waste generated. Hence the focus will be limited to recycling of plastic waste.

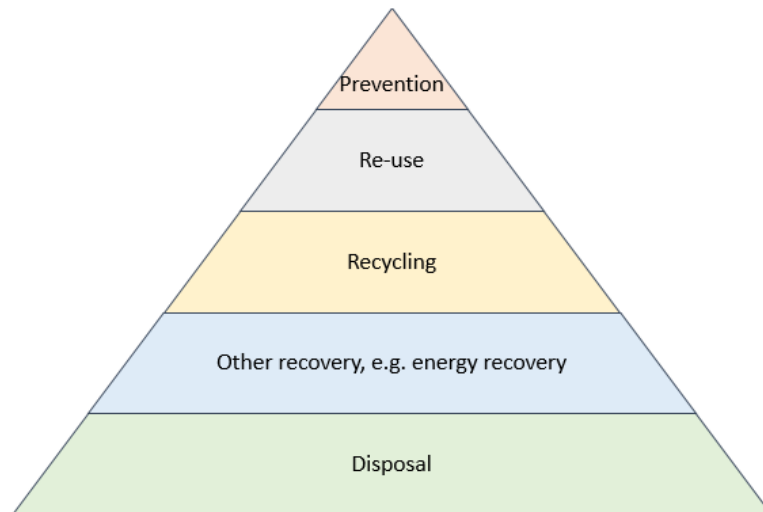


Figure 1 The waste hierarchy

This waste hierarchy is central in the Swedish waste regulation (2011:927). Today most of the plastic waste goes for energy recovery and the rest goes for material recycling (The Swedish Ministry of the Environment, SOU 2018:84). Material recycling of plastics currently involves only mechanical recycling. In the following sections, the different levels of the waste hierarchy for plastic waste in Sweden will be described.

### 1.3.3 Disposal: Landfilling

Landfilling has been the most common way to dispose of plastic waste globally (Geyer et al., 2017). However, in Sweden, landfilling is only allowed to handle waste that cannot be treated in any other way, e.g. highly contaminated materials (AvfallSverige, 2018). Because of this restriction, plastic waste is not allowed to be landfilled in Sweden. It has been seen that the recycling rate of plastics, either as energy recovered, or as material recycled, is high in countries that have a ban on landfills (PlasticsEurope EPRO, 2018). This indicates legislative intervention also plays a big role in influencing circularity of material and in transitions towards sustainable solutions.

### 1.3.4 Other recovery: Energy recovery

Energy recovery is the process where large volumes of the waste is sent for incineration to produce either heat or heat and electricity (AvfallSverige, 2018). In Sweden, About 70% of the plastic waste is used for energy recovery (Milios, Holm Christensen, et al., 2018). This has been an important step to handling plastics instead of landfilling (Milios, Esmailzadeh Davani, & Yu, 2018). However, energy recovery does not address the challenge of moving away from dependence of fossil raw material and the transition towards a circular economy. Also, inefficient recycling of plastic waste leads to an annual loss of about 8 billion SEK, which leads to about 80% loss in the value of the material (Material Economics, 2018).

### **1.3.5 Recycling: Material recycling**

Material recycling is the process where some material is recovered from the plastic waste in order to be used to produce new products (Worrell & Reuter, 2014). There are two broadly distinguishable approaches to material recycling from plastic waste:

- Mechanical recycling
- Chemical recycling

#### **1.3.5.1 Mechanical recycling**

Mechanical recycling is the most common process used for material recycling. The process involves four steps (Kaplinsky Morris, 2002):

1. The collected plastic waste is first washed and then sorted into different grades and colours.
2. The sorted waste is shredded into tiny fragments.
3. The shredded plastic is washed and dried.
4. The material is finally melted and reprocessed to make pellets or products directly.

The process is dependent on sorting of the waste. A homogeneous waste stream will lead to high quality recycled material (Worrell & Reuter, 2014). The sorting itself is detailed and labor intensive and it cannot treat contaminants like sulphates, halogens and other elements. As seen in Table 1, there are multiple types of plastics used in society today. This makes the sorting stage extremely challenging. The process is also not well suited to handle mixed plastic waste.

The mechanically recycled plastics loses 10% of its material quality, leading to a degradation of the material over time (Ragaert et al., 2017). This is because the process leads to breaking of some long polymer chains each time the material is recycled. It is estimated that with the current recycling system, plastic can be mechanically recycled about seven times before they lose their properties and becomes impossible to use (FTI, 2018a). However, this condition is applicable only if the plastic being recycled is not contaminated and treated correctly. The number of times that the plastic can be recycled, in reality, might be lower.

The secondary raw material cannot be used for products that come in contact with food. This is because of the possibility of contaminants that might not be cleaned or sorted properly before recycling. Some plastic materials are also difficult or unprofitable to sort, or just cannot be recycled mechanically because of contaminants or inefficient sorting. This results in a low material recycling rate for plastics in Sweden and hence most of this material is sent for energy recovery (Avfall Sverige, 2018).

#### **1.3.5.2 Chemical recycling**

According to Al-Salem, Lettieri, & Baeyens (2009), chemical recycling is a process where plastic material is broken down into smaller molecules resulting in production of a liquid or gaseous end product. These can be used as feedstock for the production

of petrochemicals and plastics. Chemical recycling has the potential to recycle plastic waste while meeting the quality and sorting drawbacks mentioned for mechanical recycling. The process can accept a wider range of plastic waste products without extensive sorting and the output can meet the quality standards set by fossil fuel dependent raw material. While there are different routes for chemical recycling of plastic waste, two commonly explored options are gasification and pyrolysis.

Pyrolysis is an endothermic process where the carbon-based material undergoes material decomposition to produce pyrolytic oil, gas and char residues (Ragaert et al., 2017). Pyrolysis is dependent on how the plastic waste is sorted. The type of plastics present in the input feed decides if depolymerization or random fragmentation of the hydrocarbon will take place. Hence, the cleaner and more homogeneous the input stream, the cleaner is the output from pyrolysis. The process can be done using a number of technologies, some of the common ones being fixed-bed gasifier, a cyclone gasifier, fluidized beds and plasma furnace.

Gasification, on the other hand, is an endothermic process which takes place in the presence of oxygen (or air) and requires higher temperature (above 700 °C at atmospheric pressure) (Ragaert et. al., 2017). The process produces a gas containing CO<sub>2</sub>, CO, H<sub>2</sub>, CH<sub>4</sub>. A mixture of H<sub>2</sub>, and CO is called syngas. Syngas has a wide range of applications, from uses for alternate fuel to producing olefins which can be used for plastic production. An advantage of gasification is that the process does not depend on how well the waste is sorted. It is a harsher treatment of the plastic waste than the pyrolysis, and it breaks it down into smaller components. However, the process is more energy demanding than pyrolysis because of the higher process temperature.

While both these technologies can accept wider and more impure plastic waste streams than mechanical recycling, they need to have large volumes of production to be economically viable (Ragaert et al., 2017). Chemical recycling is also a more energy intensive process when compared to mechanical recycling (Ragaert et. al., 2017).

### **1.3.6 Regulations for using recycled plastics**

In Europe and Sweden, a number of laws are established to regulate the production of plastic-based products (The Swedish Ministry of the Environment, SOU 2018:84). The EU commission regulation 10/2011 have regulations controlling the type of material that can be used and can come in contact with food products. There is also the EUs chemical regulation, REACH (Regulation (EC) No 1907/2006), which has banned the use of certain chemicals in the production of any plastic product. Hence, these regulations have an impact on where and for what recycled plastic materials can be used.

## **1.4 Earlier or ongoing research**

The production and dependence of plastics, leading to the accumulation of waste has been recognised as a problem that needs to be addressed. There have been research and national studies focused on understanding the nature of the problem.

In the paper “Plastic recycling in the Nordics: A value chain market analysis”, Milios & Holm Christensen (2018) identified barriers and opportunities for plastic recycling. They mapped out the value chain for the plastic waste and identified barriers and opportunities for plastic recycling at each part of the value chain. This was done by looking at interactions between two parts of the value chain, e.g. waste handling to sorting facility. The study was done through literature review and through interviews of actors in the value chain. Based on the interviews it was considered that value chain coordination, investments in innovation and technology developments were most important. Barriers identified for plastic recycling were connected to supply and demand for recycled plastics. The low demand was identified to be dependent on the price, insufficient traceability and design deficiencies in the recyclability of products.

In the Swedish Ministry of the Environment SOU 2018:84, the aim was to identify the environmental problems from usage of plastic products throughout its lifecycle. One of the focus areas was material recycling. The study identifies problems in today’s system with mechanical recycling, for example sorting restrictions and too many different types of plastic. Furthermore, they describe the advantages and disadvantages that could arise if chemical recycling would be implemented in Sweden.

Morandin et. Al (2016) investigates the implementation of chemical recycling of plastics in their paper, “Thermochemical recycling of plastics for production of chemical intermediates at a Swedish chemical complex site”. They study the impact of production of intermediates from two plastic waste streams using chemical recycling. The results indicate that chemical recycling could lead to reduction of global GHG emissions and reduction of import of fossil fuels.

With this thesis, one of the aims was to explore the challenges for plastic recycling in a system with both chemical and mechanical recycling in place with the focus on Västra Götaland, something not addressed in previous research. Furthermore, the thesis also studies the barriers and drivers involved in transitioning to the new system from the current system, which has not been seen in previous studies.

## **1.5 Arriving at The Research Question**

This thesis has been carried out at Challenge Lab, which is, a student driven change arena where master’s students can work on a thesis addressing sustainability and sustainable transitions. The aim was to create a space where students from different educational backgrounds can collaborate to address complex sustainability challenges in the society (Holmberg & Larsson, 2017). The students are given the opportunity to explore challenges from different perspectives and based on this formulate questions (Holmberg & Larsson, 2017). By not starting from a pre-defined question the students can be a part in sustainable transition.

The process at Challenge Lab includes both identification of a research question that represents a sustainability challenge with an associated leverage point grounded in a local/regional context (phase 1) and a process of, together with societal stakeholders, addressing the research question (phase 2). For readability, this thesis focuses on phase 2, and a more extensive description of Challenge Lab and the phase 1 process of arriving at a research question is presented in Appendix A.

One of the tasks in Phase 1 was to come to a collective conclusion on the principles that define sustainability. These are the principles on which all the theses done in the Challenge lab would be based upon. The framework to defining the principles is based on Holmberg & Larssons (2018). This framework includes four perspectives on sustainability: Ecological, Economic, Social and lastly human needs and wellbeing. While being relevant as independent categories, there also exist interdependencies between all of the dimensions (Larsson, 2019).

The principles identified in this year, 2019, is given in Table 2.

*Table 2 Sustainability principles defined in Challenge lab*

<p><b>Wellbeing</b></p> <p>Question addressed: “What is a good life?”</p>	<p><b>Social</b></p> <p>Question addressed “How can we live together?”</p>
<ul style="list-style-type: none"> <li>• Leisure</li> <li>• Intellectual</li> <li>• Freedom</li> <li>• Spiritual</li> <li>• Purpose</li> <li>• Nature</li> <li>• Safety</li> <li>• Institutions (social structure)</li> <li>• Self-actualization</li> <li>• Social</li> <li>• Love and belonging</li> </ul>	<ul style="list-style-type: none"> <li>• Embracing the interdependent nature of our human society, every individual has the sense of responsibility and involvement.</li> <li>• The foundation of our society is sufficiency.</li> <li>• All our interactions are meaningful and honour the humanity in all of us.</li> <li>• Equal rights and opportunities, the freedom to direct our own lives</li> <li>• Fair distribution of resources and knowledge with a culture of sharing and generosity.</li> </ul>
<p><b>Economic</b></p> <p>Question addressed: “How can capital be managed in the future?”</p>	<p><b>Ecological</b></p> <p>Question addressed: “How can societies activities fit within nature’s carrying capacity?”</p>

<ul style="list-style-type: none"> <li>• Resource management that allows all humans to fulfill their needs.</li> <li>• Long lifetime in man-made capital (durable, resource-efficient, circular).</li> <li>• Optimal use of non-renewable natural resources.</li> <li>• Use renewable resources within the natural regeneration capacity.</li> </ul>	<ul style="list-style-type: none"> <li>• No systematic accumulation of emissions and waste in nature from society. (and if needed, restore).</li> <li>• Use only the amount of resources that are renewable, not depleting resources.</li> <li>• Support and preserve biodiversity.</li> </ul>
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Once the principles were identified, it was necessary to find out what the current system with respect to the area of focus looks like. By comparing the current system to the defined sustainability principles, the gaps present in the current system were identified. For the area of plastics and plastics recycling in Västra Götaland, the following gaps were identified:

- Most plastic waste today is incinerated: This creates a dependence on primary oil-based plastic material, which depends on fossil raw materials for its production. Material recycling could help move away from this dependency.
- Extensive material sorting is necessary for mechanical recycling: For the mechanical recycling that exists today there is a need to sort the waste based on, e.g. colour, type and grade. Sorting is essential to assure that the secondary raw material is of good quality. However, sorting is not perfect and there are technological challenges that exist that cannot extensively sort all plastics.
- Lack of interest in accepting secondary raw material because of quality: Plastic production depends on high quality raw material. Because of this, there is hesitation to accept secondary plastic raw material to produce plastics from.
- There are a lack of collaboration for implementing new technologies: There are new ways of material recycling being researched upon by different institutes in the region but there appears to be a lack of collaboration or initiatives between them for efficient use of these methods for a more efficient circular flow of the material in the system.
- Material recycling is not prioritized in the region: The local waste handling strategy has not accounted for chemical recycling process of plastics as an option for plastic recycling. As plastics have the potential to generate a lot of energy, the regional plans, at the moment, prefers the incineration of plastics. However, it was also highlighted from stakeholders during dialogues that this was not a sustainable solution.

Based on the sustainability principles, the following leverage points were identified:

- What: What is the problem to solve?
  - Improve the material recycling rate of plastics. Reduce the dependence of fossil fuels for plastic production.
- Where: What “lock-in” to address? What local problem?
  - Chemical recycling has been viewed as a potential waste handling strategy to address plastic waste. The focus for this thesis will be on both the current waste handling system and chemical recycling.

- Who: What actors/organizations are interested in this issue? What ongoing processes to connect to?
  - Actors interested:
    - \* Researchers addressing the existing problem with plastics
    - \* Researchers studying the technology for material recycling from plastic waste
    - \* Region
    - \* Chemical industry
    - \* Waste handling sector
    - \* Recycling industry
    - \* Urban development collaborative arenas
  - Processes connected to:
    - \* Chemical recycling (Gasification or pyrolysis)
    - \* Mechanical recycling

The above-mentioned steps would lay the foundation to the topic of focus and the research question addressed in this thesis. Talking with various stakeholders during phase 1 lead to an understanding that this topic would be relevant to investigate. They mentioned that they would be interested in receiving compiled information on challenges throughout the plastic waste value chain. With one of the thesis authors being from the master program Industrial Ecology and the other from Materials engineering, the topic of sustainable handling of plastic waste combined both competences.

## 1.6 Research Question

While mechanical recycling is cheaper, chemical recycling can address the issues regarding quality and contaminated material. However, chemical recycling is an expensive recycling alternative. Hence, if chemical recycling were to be implemented, it will have to complement the existing mechanical recycling process for it be economically feasible (The Swedish Ministry of the Environment, SOU 2018:84). However, the existing challenges or a new set of challenges could present itself in this new plastic waste handling system. This raises two important questions:

- *What would be the challenges to sustainable material recycling of plastic waste if chemical recycling is implemented as a complement to mechanical recycling in Västra Götaland?*
- *What are the barriers to and drivers for transitioning from the current system to this new system?*

These are the main research questions studied in this thesis work. However, to answer the first question, it was necessary to find answers for the following three sub-questions:

- *What could be defined as the criteria for sustainable material recycling of plastic?*
- *What are the challenges in the current plastic waste value chain in Västra Götaland?*

- *What new challenges could arise if a new system, with both mechanical and chemical recycling, were to be implemented in Västra Götaland, and which are still present?*

## **1.7 Scope and limitations**

The aim of this thesis is to shed light on how to increase material recycling of plastics in the region of Västra Götaland, Sweden. It will be assumed that chemical recycling is a valid and suitable complement to today's mechanical recycling.

The scope of the thesis was initially limited to the plastic waste recycling chain in Västra Götaland, Sweden. However, for situations and aspects where centralized decision-making is in place, there might be a need to look both into the national context in Sweden and to the EU.

The data collected for the thesis has been from one actor from different parts of the value chain. The data collected was also generalised to give a holistic view of the whole system.

The thesis process time is limited to 20 weeks. However, the first four weeks of this was earmarked for formulating the research question. The time to address this research question was therefore limited to 14-15 weeks. Given the time constraints during this project, only one stakeholder from each part of the chain was interviewed. Hence, the data acquired and presented is only based on the perspective of those who participated.

The challenge lab is an arena where the thesis topic is created by the students in the lab. The process is iterative and based on information collected over time. This means that the scope and the limitations can change or be added upon throughout the process.



### **2.1.1 Step 1: Frame conditions for a sustainable future on a level of principles**

In the first step of backcasting, the goal is to frame a sustainable future based on values (Larsson, 2019 & Holmberg, 1998). Defining the framework for a sustainable future serves as a guiding principle for all the other steps in backcasting.

This step was used when addressing the first objective in the research question, “What could be defined as the criteria for sustainable and efficient material recycling of plastic?”. When addressing challenges hindering sustainable recycling, it is necessary to first determine what sustainable recycling ought to include. Based on the general sustainability principles created together with the other participants in the Challenge lab, a new framework was created to address recycling of plastic. The framework was also adapted to fit within the goals of 2030 (Västra Götalandsregionen & Länsstyrelsen i Västra Götalands län, (n.d.)) and 2045 (Government Offices of Sweden Ministry of the Environment and Energy, 2017).

This framework is defined in order to compare the current and the new system to see what the challenges in these systems to sustainable recycling of plastic waste are.

### **2.1.2 Step 2: Analyse gaps between the present situation and the sustainable future**

The second step of backcasting is to identify and map the current system (Larsson, 2019). This is done in order to better understand the starting point for the transition. The inventory from this step will be used as a foundation for both the third and fourth step as a way to connect the current situation and gaps with the preferred outcome (Holmberg, 1998).

For the thesis, this step was used to map the current system in order to understand how plastic waste is handled. By comparing this system with the defined sustainability criteria, the second objective in the research question, “What are the challenges in the current plastic waste value chain in Västra Götaland?” was addressed.

### **2.1.3 Step 3: Identify leverage point interventions for bridging the gaps**

The third step of backcasting is to find leverage points and interventions for bridging the gaps between steps 1 and 2 (Holmberg & Larsson, 2017). Meadows (1999) describes leverage points as places within a complex system, where one small shift in one part of the system can produce a bigger change in the whole system. Holmberg (1998) suggests that the goal with this step is not to specify the future in detail but to be open-minded towards new options. Hence, a direct solution is not the outcome of this step.

Ongoing interest, from researchers, pilot plants and the region, on chemical recycling indicates that implementing a chemical recycling facility might help address the

problems related to plastic waste. In the thesis, by acknowledging chemical recycling for handling the plastic waste, a new plastic waste value chain is introduced. However, the step further explores what potential challenges to sustainable recycling this new system would face when handling plastic waste. This was done by comparing this new system with the defined sustainability criteria. Hence, the thesis approach strays away from the method defined by Larsson (2019). This is then used to address the third objective of the research question, “What challenges could arise if a new system, with both mechanical and chemical recycling, were to be implemented in Västra Götaland?”

#### **2.1.4 Step 4: create strategies for realizing the leverage point interventions**

The fourth step in backcasting is to link the current situation with the future sustainable suggestion defined in step 3 (Holmberg, 1998). This also involves strategizing how to go from the current situation to this suggested system (Holmberg & Larsson, 2017).

In this thesis, the approach defined above is not strictly used. The link between the current and the new suggested system is presented as drivers for the transition. However, instead of working on strategies to reach the suggested system, the barriers hindering the transition is presented. This addresses the fourth objective in the research question, “What could be the drivers and barriers to transition from the current plastic waste value chain to the new system?”.

## **2.2 Value chain and stakeholder mapping**

Kaplinsky & Morris (2001, p.4) explain value chains as “all activities required to bring a product or service from conceptualization through all phases of production, delivery to final consumers and final disposal after use”. They further describe that the concept with value chains suggests simplicity, whereas the reality could be a bit messier. Value chains could also be used to understand the stages involved in the flow of the material, thereby helping in understanding the challenges for material recycling. At different parts of the value chain, stakeholders add value to the product leading to an increased end value (University of Cambridge, 2018).

Two different systems were mapped to understand the flow of plastic waste. The first was the current value chain and the other was a suggested new waste value chain. The approach to mapping each of these systems were different. The current system exists and could be mapped based on literature alone. The new system was mapped based on understanding where and how chemical recycling would fit in if it were to be implemented. This was done by studying literature on the technology and from interviews with researchers and stakeholders in the current system who work with or are interested in this new system.

It was only after the mapping was done that the challenges for plastic recycling at each stage could be identified. The mapped value chain also plays a key role in mapping the relevant stakeholders necessary for data collection. Understanding the value chain also enables to identify the exact drivers and barriers to transition to the new system at each part of the value chain.

Based on the value chain mapping, relevant stakeholders in the chain were identified. These were mostly stakeholders that were active in the current plastic waste value chain. Snowball sampling also played a key role to identify stakeholders that were connected to the field of plastic waste. Yin (2011) explain snowball sampling as when one stakeholder is asked to recommend other stakeholders. For snowballing to be useful it is important to have a good purpose, meaning that the recommended person can provide something useful (Yin, 2001). Finally, after analysing the gathered data, the gaps that needed to be filled to get a holistic view of the value chain were identified. The last group of stakeholders contacted was to fill these gaps.

## 2.3 Literature survey

A literature screening was done during the whole thesis process. In the beginning stages, literature was used to help formulate the research question. It was used to understand what had already been done and what aspects were missing. The literature also provided some guidance on how to structure the method and results.

Brynman (2012, p.98) describe that the purpose of exploring existing literature in early stages are to address:

- “What is already known about this area?”
- “What concepts and theories are relevant to this area?”
- “What research methods and research strategies have been employed in studying this area?”
- “Are there any unanswered research questions in this area?”

During later stages of the process, literature was used as a complement to the interviews. Missing pieces of information and unclear references were investigated and confirmed from literature.

Relevant literature addressing the thesis questions was found using different online sources. Some of the literature was also recommended by stakeholders. This search lead up to a combination of academic papers, formal documents and trade publications.

To get further background, lectures on the topics of plastic pollution, plastic packaging in food industry and industrial symbiosis were attended. Furthermore, a study visit to a sorting facility was done, in order to gain additional information. Summaries of the lectures and the study visit can be found in Appendix C.

## 2.4 Stakeholder interviews

A total of 15 interviews were conducted with the purpose of gathering information about plastic waste recycling. The focus was on the interviewee’s role in the chain. Given that each stage had different barriers, a semi-structured approach was used when interviewing. Before the interview, the area of expertise of the interviewee was looked into. While most of the questions were similar for all the interviews, certain specific questions were asked based of the area of expertise of the interviewee.

Semi-structured interviews are one type of qualitative interviews (Bryman, 2012). In these types of interviews, the interviewer often has a list of specific topics to address, often called an interview guide. However, the interviewer can change the order of questions during the interview and ask follow-up and probing questions.

The interviews were between 30-90 minutes each, depending on the topic and the stakeholders time constraints. The Interviews were conducted either in person (eight interviews), on skype (three interviews) or through telephone (four interviews).

Most of the interviews were recorded, after approval from the stakeholder, and transcribed. Brynman (2012) argues that reasons for the interviews to be audio recorded are that it is not only important what people say but also how they say it. Moreover, the interviewer should not be distracted from taking notes but be alert to ask follow-up questions. All interviewees were guaranteed anonymity before beginning the interview. A summary of each interview can be found in Appendix D.

## 2.5 Framework for Identifying barriers

The data gathered from the interviews had to be categorised for easier and a more generalised understanding of what the challenges to recycling were. The framework used for this is based on the paper “Barriers to circular economy: Evidence from the European union” by Kirchherr et. Al. (2018). The paper broadly divides their identified barriers into four distinct categories. The categories presented are: cultural, market, regulatory and technological, as explained in Table 3.

These defined categories can be considered as “nested”, meaning each of these categories can influence the other categories as well. For example, defined cultural barriers can have an influence on how the regulations are framed, leading to regulatory barriers. The barriers observed in the market can influence and determine the technology barriers. Kirchherr et. Al. (2018) also mentions interaction points between the defined categories. They explain how “lack of data on impacts”, a technological barrier, could affect the market interest in implementing a circular economic business model. This in turn could lead to lack of funding to initiate the process and hence could have very little influence to address necessary changes to regulatory barriers. All of these lead to lack of interest or awareness from the consumer, which relates to the cultural barriers.

*Table 3 Framework used to analyse data (Kirchherr et. Al., 2018)*

Category	Definition (Kirchherr et Al., 2018, p. 266)	Description
Cultural	“Lacking awareness and/or willingness to engage with CE”	<ul style="list-style-type: none"> <li>• Consumer preferences.</li> <li>• Cultural strategies, visions, missions and goals.</li> </ul>
Regulatory	“Lacking policies in support of a CE transition”	<ul style="list-style-type: none"> <li>• Lack of smart regulations for transitioning.</li> <li>• Lack of supportive policy instruments.</li> </ul>

Market	“Lacking economic viability of circular business Models”	<ul style="list-style-type: none"> <li>• Low prices on primary oil-based material.</li> <li>• Cost of circular economy business model.</li> <li>• Lack of subsidies to assure economic viability.</li> </ul>
Technological	“Lacking (proven) technologies to implement CE”	<ul style="list-style-type: none"> <li>• Lack of ability to deliver high quality remanufactured products and circular design.</li> <li>• Lack of data on for example impacts.</li> <li>• Too few large scale demonstration projects.</li> </ul>

### 3 Result and discussion

In this section the results and discussion that addresses the research questions are presented. The result of the thesis presents a holistic view of what a new system with chemical recycling could look like if chemical recycling was used to address plastic waste. Also studied is the influence of culture, technology, regulations and market on the new suggested system. The result could later be used when creating strategies for transitioning towards a new system for handling plastic waste.

#### 3.1 Sustainability criteria for efficient plastic recycling

The sustainability criteria were framed in order to address the first sub-question “What could be defined as the criteria for sustainable and efficient material recycling of plastic?”. These criteria were divided into wellbeing, social, ecological, economic based on the same categories on which the sustainability principles were earlier categorised as mentioned in relation to Table 2. The criteria for sustainable plastic recycling are presented in Tables 4 to 7. These were later used to identify the challenges to sustainable recycling in the current and in the new system.

*Table 4 Sustainability criteria for plastic waste recycling: Human need and Wellbeing*

Human need and Wellbeing: What is a good life?	
<b>Challenge lab principles</b>	<b>Adjusted to address efficient recovery of material from plastic waste</b>
<ul style="list-style-type: none"> <li>• Freedom</li> <li>• Nature</li> <li>• Safety</li> <li>• Institutions (social structure)</li> <li>• Social</li> </ul>	<ul style="list-style-type: none"> <li>• No incineration of fossil-based plastic.</li> <li>• Reduce emissions from plastic production and waste handling.</li> <li>• No leakage of plastic in nature.</li> <li>• Everyone should be able to have plastics for things they need.</li> <li>• Support human wellbeing by providing necessary material.</li> <li>• Support safe use of material.</li> </ul>

*Table 5 Sustainability criteria for plastic waste recycling: Economic*

Economic: How can capital be managed in the future?	
<b>Challenge lab principles</b>	<b>Adjusted to address efficient recovery of material from plastic waste</b>
<ul style="list-style-type: none"> <li>• Resource management that allows all humans to fulfil their needs.</li> </ul>	<ul style="list-style-type: none"> <li>• Recover secondary raw material allowing all humans to fulfil their needs.</li> </ul>

<ul style="list-style-type: none"> <li>• Long lifetime in man-made capital (durable, resource-efficient, circular).</li> </ul>	<ul style="list-style-type: none"> <li>• Keep the already existing plastics for as long as possible (e.g. re-use, recycle or recover).</li> <li>• Avoid taking up raw material (fossil fuel) for plastic production.</li> </ul>
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*Table 6 Sustainability criteria for Plastic waste recycling: Social*

Social: How can we live together?	
<b>Challenge lab principles</b>	<b>Adjusted to address efficient recovery of material from plastic waste</b>
<ul style="list-style-type: none"> <li>• The foundation of our society is sufficiency.</li> <li>• Fair distribution of resources and knowledge with a culture of sharing and generosity.</li> <li>• Embracing the interdependent nature of our human society, every individual has the sense of responsibility and involvement.</li> <li>• The foundation of our society is sufficiency.</li> <li>• All our interactions are meaningful and honour the humanity in all of us.</li> <li>• Equal rights and opportunities, the freedom to direct our own lives.</li> </ul>	<ul style="list-style-type: none"> <li>• Avoid taking up raw material (fossil fuel) for plastic production.</li> <li>• Recover secondary raw material allowing all humans to fulfil their needs.</li> </ul>

*Table 7 Sustainability criteria for plastic waste recycling: Ecological*

Economic: How can capital be managed in the future?	
<b>Challenge lab principles</b>	<b>Adjusted to address efficient recovery of material from plastic waste</b>
<ul style="list-style-type: none"> <li>• Resource management that allows all humans to fulfil their needs.</li> <li>• Long lifetime in man-made capital (durable, resource-efficient, circular).</li> </ul>	<ul style="list-style-type: none"> <li>• Recover secondary raw material allowing all humans to fulfil their needs.</li> <li>• Keep the already existing plastics for as long as possible (e.g. re-use, recycle or recover).</li> <li>• Avoid taking up raw material (fossil fuel) for plastic production.</li> </ul>

## 3.2 System Mapping

The plastic value chain describes the plastic waste from when it is disposed by the end-user until it is made into a new product. Both the current and the new suggested plastic waste value chains were mapped in order to provide a holistic overview. Furthermore, these value chains were used to identify stakeholders connected to each part.

### 3.2.1 Current system

Since the current value chain exists, the mapping was done by studying literature on the flow of plastic waste. In the current system, after the consumer discards the product to the collection unit, the waste handling company picks up the collected waste. This collected waste is sent to be sorted into different types of plastics, which is done by the sorting facilities. After the sorting phase, the plastic is recycled and then used to produce new plastic products for consumers. The recycling process used in this system is mechanical recycling. Some of the waste do not go through sorting or recycling but instead ends up being incinerated for energy recovery.

The current system is represented in Figure 4. This mapped system was used to address the objective “What are the challenges in the current plastic waste value chain in Västra Götaland?”.

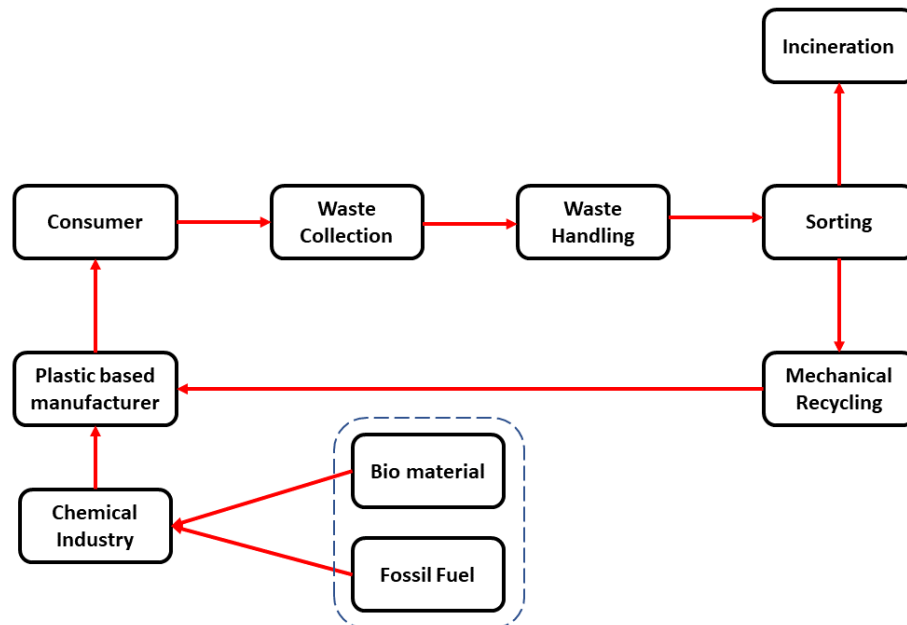


Figure 3 Schematic representation of the current plastic waste value chain

### 3.2.2 New suggested system

The new system suggested in this thesis is one where chemical recycling is used as a complement to mechanical recycling. In this system, the collection, waste handling and sorting stages may not be affected by implementation of chemical recycling. However,

after the sorting phase, the plastic will either be sent to be mechanically recycled or chemically recycled. This could in turn increase the amount of plastics sent for recycling while gradually phasing out the plastics sent to energy recovery from incineration. The mechanically recycled material is sent to a manufacturing company to produce new plastic products. The chemically recycled material will go to the chemical industry where it will be used to make new plastic (this is assumed in our study although it can in principle be used for many other purposes), which would be used by the plastic manufacturing companies to make new products. Figure 5 represents what the plastic waste value chain might look like in this new system. Having mapped this new system, it was used to identify relevant stakeholders and address the third sub-question “What challenges could arise if a new system, with both mechanical and chemical recycling, were to be implemented in Västra Götaland?”.

This suggested system was decided after the initial interviews where it was concluded that chemical recycling cannot be set up as a standalone solution. It will have to complement the mechanical recycling that exists today. However, this is only one suggested system that could help with better material recycling. There might be other solutions or systems favoured in reality.

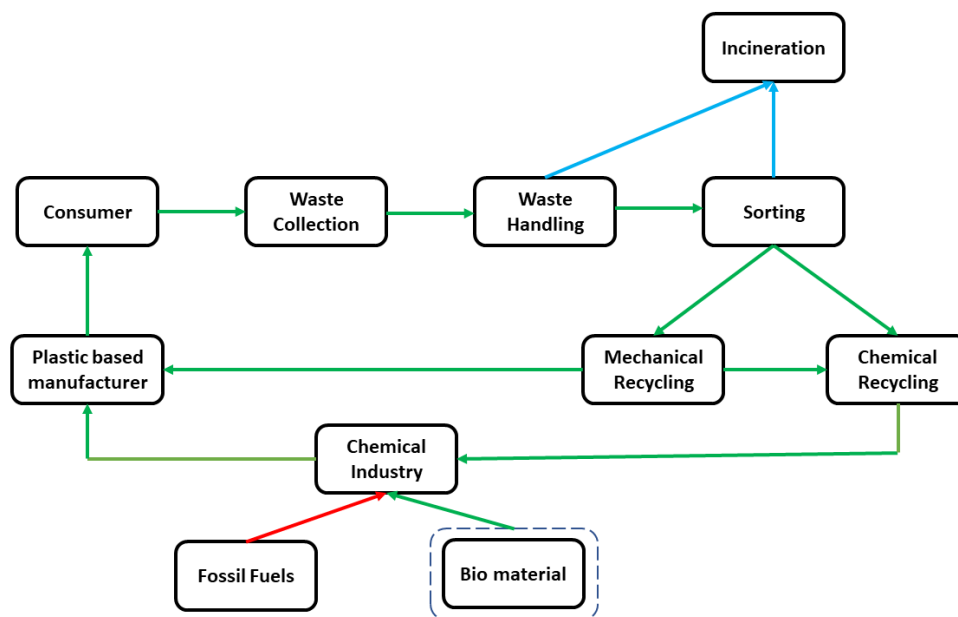


Figure 4 Schematic representation of the suggested new plastic waste value chain. Green indicates best possible route, blue is a route that is expected to gradually reduce under ideal conditions and red is the route to be avoided.

### 3.3 Stakeholder mapping

During this process 16 stakeholders related to the topic were identified, see Table 8. These stakeholders come from different types of organisations, both from businesses, municipalities and academia. The stakeholders were directly connected to the waste value chain, regional planners involved in policies addressing the flow of the plastic waste or were researchers studying technologies or problems addressing plastic waste. 15 of the 16 stakeholders were interviewed and a study visit was conducted with a

plastic waste sorting company. Data analysed to address the research question in the thesis was based on the interviews conducted with these stakeholders.

Table 8 Identified stakeholders

<b>Position</b>	<b>Organisation</b>	<b>Type</b>	<b>Area of expertise</b>	<b>Medium contacted by</b>
Project leader	Urban development collaborative arenas	Business – Private	Chemical recycling	Face-to-face interview
Project leader	Research institute	Academia	Mechanical recycling	Phone interview
Project leader	Public Sector	Municipality	Waste collection and handling	Face-to-face interview
Project leader	Chemical Industry	Business – Private	Chemical industry and chemical recycling	Phone interview
Regional planner	Public Sector	Municipality	Region	Face-to-face interview
Researcher	Recycling industry	Business – Private	Sorting, Mechanical and chemical recycling	Face-to-face interview
Researcher	Research institute	Academia	Mechanical recycling	Skype interview
Researcher	Research institute	Academia	Chemical recycling	Skype interview
Researcher	Industry & Research Institute	Academia	Mechanical recycling	Face-to-face interview
Researcher	University	Academia	General view of problem with plastics	Face-to-face interview
Researcher	University	Academia	Holistic view of plastic waste value chain	Phone interview
Researcher	University	Academia	Mechanical and chemical recycling	Face-to-face interview

Researcher	University	Academia	Chemical recycling	Face-to-face interview
CEO	Chemical Industry	Business – Private	Chemical industry and chemical recycling	Phone interview
Process Engineer	Waste handling company	Business – Public	Sorting	Study visit
Managing Director	Plastic waste sorting company	Public – Private	Waste collection and handling	Skype interview

### 3.4 Challenges to sustainable recycling

The data collected from the interviews were analysed to identify the challenges present when handling plastic waste. These challenges were distinguished between the current and the new systems based on the source of the collected data. Many of the challenges were unique for each part of the value chain. Hence it is seen as necessary to present the observed challenges by dividing it based on where in the value chain the challenge presents itself. However, even though challenges were unique, they were seen to directly influence the later stages in the value chain thereby affecting the entire chain as well. Detailed information about the Challenges to sustainable recycling can be found in Appendix E.

The data gathering has been through interviews of stakeholders. All additional information gathered through, e.g. literature, will be referenced to separately. However, given the time constraints, the interviewed stakeholders were limited to just one actor from each part of the value chain. Hence there could be other challenges to sustainable plastic recycling or barriers and drivers to transition to the new system that may not have been discussed during the interviews. In this respect, the data gathering was not designed for to be exhaustive but merely to provide knowledge for all parts of the value chain.

#### 3.4.1 Challenges for sustainable plastic recycling in the current system

The results presented in this section are to answer the question “What are the challenges in the current plastic waste value chain in Västra Götaland?”.

##### **Consumer to collection**

The first stage in the waste value chain is when a plastic product has no value for the end-user and hence is discarded. The waste is discarded into some sort of collection bins, depending on the type of product and location. The consumer is expected to sort

the waste according to the regulations in Sweden. For example, the consumers should sort the packaging plastics separately since it should be collected by the producers. Small household plastic, such as toothbrushes, are sorted as household waste and larger municipal waste, such as garden chairs are to be brought to allocated collection units.

Today the producers offer pick-up from some centralized stations for the consumers packaging waste. There is also the possibility for multi-apartment buildings to have the producers picking it up directly, which the apartment owners need to pay for. However, under the new EPR scheme, this will have to be paid by the producers.

Today much of the plastics that, by regulation, should go as sorted packaging plastic ends up as a household waste. The household waste is collected and sent for incineration whereas the plastic packaging is sent to be sorted for recycling.

It is seen by the municipality, that the sorting at household is not done as expected, which affects how much plastic is collected to be recycled. For many consumers, “plastic is just plastic” and they don’t have knowledge about different plastic materials.

Sorting of plastic packaging is relatively new and more complicated, compared to e.g. glass and it takes time for consumers to fully understand how to do it correctly. Some consumers are also aware of the lack of efficient plastic material recycling today. This makes them feel less motivated to separate the material from other household waste. There are consumers who view energy recovery as a justified solution to handling plastic waste and hence discard plastic as mixed household waste.

Plastic waste is regulated under multiple types of legislation depending on which waste stream it belongs to, e.g. packaging, household, WEEE etc. With all these different streams it can be difficult for consumers to understand what goes where. Collection bins for these specific wastes are not located everywhere and this could lead to consumers disposing these products into different collection streams.

With the new EPR scheme the producers will need to collect the sorted plastic packaging waste closer to the consumers. However, there is no regulation that forces the house- and apartment owners to set up these packaging waste collection units. In cities today, land to set these collection units is also seen as a problem. This could further delay and complicate the regulation meant to keep collection units “close to consumer”.

However, for industries (end-users), handling of waste is expected to be done by these actors themselves. Hence, they are free to use any collection system, which likely leads to them choosing the most economically beneficial option available for them. This could lead to their waste traveling long distances to the waste handling facility, leading to logistics-related emissions.

### **Collection to waste handling**

The waste in the collection units is handled by a waste handling company, which could either be private agencies or municipality owned agencies. In some cases, different actors handle different waste streams. The actors that handles the different waste streams can choose which waste handler they want, there could in this situation end up

being long transportation distances between collection and handling unit. This long-distance logistics of the waste adds to logistics-related emissions.

Even though material recycling is placed above energy recovery in the waste hierarchy (see Figure 1), in reality, a lot of plastic waste ends up being sent to incineration by the waste handling company. This is mostly due to the wrong sorting by consumers, leading to the waste handling companies getting the waste streams they are not responsible for. For example, the agency that sorts household waste is not responsible for plastic packaging waste, however when packaging does end up with the household waste, they become responsible for it nevertheless. The plastic packages that ends up in household waste is hence being sent to incineration. Furthermore, there are no regulation that addresses how to handle the wrongfully sorted waste.

### **Waste handling to sorting**

The plastic that is not directly sent to incineration is firstly taken to a waste handling plant where an initial brief sorting is done. After the initial sorting, the plastic is sent to a sorting facility for extensive sorting based on grades, colour and type. In Sweden there currently are few sorting facilities for plastic waste with one of these being run by the packaging companies and the others private companies. With scattered population and few sorting facilities the plastic waste leads to logistic-related emissions. In some cases, the waste is also exported and sorted outside of Sweden.

Today, parts of the plastic product that are not plastic, e.g. metals and woods, are not removed before the product is sent to the sorting facilities. Almost 20% of the waste sent to a plastics sorting facility is not plastic or any polymer that the sorting facility is meant to sort. This is because of bad sorting at the consumer level and also design of products, where recyclability at the end of life of the product is not prioritised. Moreover, plastic products with contaminants or toxins are not cleaned properly before arriving at the sorting facility, compromising the quality of entire batches of the sorted plastic.

### **Sorting**

At the plastic sorting facilities, the plastic waste is sorted based on the type and colour. In Sweden there have been issues regarding trust towards the plastic sorting facilities. In the recent past, data about sorted and recycled plastic waste had been consciously manipulated to show better recycling rates. The plastic waste data that was shown to be sent for recycling was instead sent for incineration. This not only affected the reliability of the overall data presented in the past but also the trust between the actors involved in this part of the chain.

There are many different types of plastics arriving at the sorting facilities and the existing sorting technology cannot handle all types. For example, biodegradable plastic and black plastic are difficult to detect. A lot of the plastics ends up in a “mixed plastic” batch, which has a low economic value and is sent to incineration. The waste share that does end up as secondary raw material is about 16% and that is very low.

Today there is no market for recycled plastic in Sweden. The sorted and the mechanically recycled plastic is exported to central Europe. Here the best-case scenario is that the recycled plastic is downcycled and made into products of lesser value. However, there are also a risk of it being incinerated or landfilled. This is because there is no regulation regarding sorting companies keeping track of the sold and exported plastics. Sorting of the plastic waste involves cleaning and drying, which consumes time, water and energy.

### **Sorting to mechanical recycling**

The sorted plastic from the sorting facility is sold to mechanical recycling companies, also called compounders. The quality of the sorted plastic directly affects the quality of the recycled plastic. If the plastic itself is not correctly sorted, e.g. based on type, colour and grade, it compromises the quality of the entire sorted batch. This also leads to the compounder being hesitant to buy sorted plastic waste.

The price for sorted and recycled plastic is different depending on the grade of the plastic. Today some types of plastics have no economic value in being recycled, e.g. plastic foams, and hence no Swedish compounder will buy it. This mean that it is either incinerated in Sweden or exported, where it could end up being incinerated or landfilled.

With the multiple waste streams that exists there can be an issue for the recyclers to get enough sorted plastic, leading to less amount being recycled. The plastic also needs to be transported between the sorting facility and the recycling plant. This is often a long distance meaning that there would be emissions from logistics.

### **Mechanical recycling**

At the mechanical recycling plant, secondary raw material is recycled from the sorted plastic waste. These recycling plants handle only specific streams of the plastic creating a lower market for them. This further leads to low input volumes and then low and irregular supply of raw material for plastic production.

Hazardous elements present in the input, e.g. chlorine from PVC fragments, cannot be removed during the recycling process. Presence of these elements restricts the market for this secondary raw material. Furthermore, not all types of plastics can be efficiently recycled. There is a limit to how many times plastic can be mechanically recycled before losing its properties and become unusable leading to economic value loss.

### **Mechanical recycling to plastic product manufacturer**

The mechanically recycled plastic is sold to industries manufacturing plastic products. There is a hesitance towards buying recycled material based on uncertainties over quality. As mentioned by a stakeholder “There is this issue of quality that industry puts up as an argument as to why they don’t choose recycled plastics”.

For manufacturing of plastic products, the quality demands are often quite high for the input material. Unable to meet these demands, mechanically recycled plastics are often downcycled, leading to a tremendous loss in their value.

Apart from problems with the quality, recycled plastics are more expensive than primary oil-based plastic material due to the various processes involved in recycling the material from the waste.

There is also a lack of certificates assuring the quality of recycled plastics. There is also a question as to who would conduct and bear the expenses of the quality tests. Lack of certification further restricts use of the secondary raw material to make plastic products. There is also the question of who handles the quality tests, which would add additional expenses to the already expensive material. These quality uncertainties are one of the main reasons as to why mechanically recycled plastics are not allowed to be used for food packaging. It is also why the market for recycled plastic in Sweden is almost negligible. Furthermore, as stated under the EU regulations, it is not allowed to use recycled plastics for food packaging.

### **Plastic product manufacturer**

The plastic product manufacturers are key to creating a market for recycled plastics. Today the price of oil-based plastic is much lower than recycled. The prices of secondary raw material is expected, by consumers, to compete with that of oil in order to have a wider market and acceptance. There is also a lack of policies supporting the intake of secondary raw material.

The plastic manufacturing industry plays a vital role in ensuring circularity of plastics. However, according to the stakeholders, there are not enough regulations on designing for circularity. The companies are free to use laminates, plasticizers and flame retardants for production, which makes it harder to recycle plastic. While there are regulations that hold the producers accountable for handling the waste, it does not clearly specify what has to be done to address the waste.

## **3.4.2 Challenges in the new system**

The results presented in this section are to answer the question “What new challenges could arise if a new system, with both mechanical and chemical recycling, were to be implemented in Västra Götaland, and which are still present?”

Since the stages up until sorting of plastic waste would be unaffected by the implementation of chemical recycling, it is assumed the challenges seen in the current system would still exist. Hence the same data is not mentioned in this section. The stages from sorting onwards is what will be covered. More detailed results can be found in Appendix E.

### **Sorting**

There is still some uncertainty regarding how extensive the sorting will have to be in this new system. A brief initial sorting would still be needed to decide what goes for mechanical or for chemical recycling.

There is no guarantee that the market for sorted plastic in this new system will be better than it is in the current system. This could mean that the sorting companies could continue to export the plastic and if they sell it, there is still no need for them to keep track of where the sorted waste ends up.

### **Sorting to mechanical recycling**

The sorted plastics has to be dried and cleaned before being sent for mechanical recycling. If the waste streams are still segregated, the volume of sorted plastic sent for mechanical recycling would still be low. The sorted plastic also needs to be transported, often long distances, leading to logistics-based emissions.

### **Sorting to chemical recycling**

Plastics that are difficult to recycle mechanically, especially the mixed plastic waste, must be redirected to chemical recycling. The sorted plastics must be dried and cleaned before being sent for chemical recycling. There are different processes when it comes to chemical recycling, e.g. pyrolysis and gasification. The plastic sent for gasification does not need any sorting, which questions the need for sorting in the value chain. However, pilot test conducted using pyrolysis indicate that some amount of sorting will be required incase pyrolysis is chosen as the technology to recycle plastic waste.

To be economically sustainable, the chemical recycling industry has to have high input volumes. This demand has to be met by the sorting company, which could be a problem. There are other countries setting up chemical recycling plants, each of which would require a high input volume of waste. This would create a problem as to where the sorting company has to direct their sorted waste.

### **Chemical recycling**

Today there are no regulations that address chemical recycling as an option for material recycling. With today's regulations, the chemically recycled material might still not be allowed in certain products, e.g. toys and food packaging, even if the quality is the same as that of primary oil-based plastic. This is because the secondary raw material from chemical recycling might still be categorised as recycled material and those are not allowed to be used to produce certain products.

Since there are many countries working on setting up a chemical recycling plant, there would most likely be an international competition between these plants on who gets the plastic waste. Many of the planned recycling plants are being set up in Northern Europe. This is a large challenge, since the plant would be dependent on high input volumes in order to be economically sustainable.

In the chemical recycling process, different types of plastics behave differently. The output from the recycling plant depends on what type of plastic is fed to it. Some grades of plastics contain elements that are not favorable for certain technologies, e.g. chlorides are not favorable for pyrolysis. Hence, there will be a need for pre- and post-treatments to remove the undesirable elements. This creates an extra step making for a longer material recycling process and thus making it energy demanding and expensive.

### **Chemical recycling to chemical industry**

Chemically recycled raw material (pyrolysis or syngas) can match the quality obtained from crude oil. However, it costs much more to purchase recycled plastic compared to oil. If there are no political subsidies or regulations that supports the use of recycled material, e.g. taxes on oil or subsidies to purchase recycled plastic, the acceptance of recycled material will still be very low.

Currently there are no certificates addressing the quality of the secondary raw material. If it stays the same, there would still be hesitation for the chemical industry to accept the recycled material. The same question of who pays for certification would still be a problem. The chemical industry also requires constant high feed of raw material to meet the current production rates. The high feed rate is expected to increase through the years. It is not clear if the chemical recycling will be able to meet that demand.

Logistics is another challenge to be addressed. Depending on the location of the plant, the recycled raw material has to be transported to the chemical industry. This could further add to expenses and logistics-based emissions.

### **Chemical industry to plastic product manufacturer**

Today there are no policies that promote the plastic producers to buy recycled material and hence the plastic producer still might prefer primary oil-based plastic material. For the plastic product manufacturers, it will be more expensive to buy chemically recycled plastic than plastic based on primary oil. There are also regulations that hinder recycled material to be used in certain products. If these stay the same, the plastic product manufacturers would still not be allowed to use chemically recycled plastics to manufacture certain products. This would further reduce the market for recycled plastics.

### **Mechanical recycling to plastic product manufacturer**

Mechanically recycled plastics are not allowed to be used for some products in Sweden. Hence, there is a very limited market. There is no guarantee that this would change in the new system. Mechanically recycled plastics might still end up being exported elsewhere where it could still be downcycled. Certificates addressing quality, as in the current system, would still be a problem. There might be no changes in this stage when compared to the current scenario when addressing mechanical recycling.

### **Plastic product manufacturer**

For the plastic product manufacturers, the quality and price of the raw material used is crucial. The lack of certifications on quality means that acquired recycled plastic would need to be quality tested, which would add on expenses. Currently there are no regulations addressing design of products for circularity and if this stays the same, the recycling process will still be a problem. The design of products also how much of sorting is done by the consumers after end of use of the product.

## **3.5 Barriers and drivers for transition to the new system**

Literature and data collected from the stakeholders were used to understand the feasibility of a transition. The data collected was analysed to identify what could drive towards and hinder or be an obstacle to transition from the existing system to the new system. This is used to address the question “What could be the barriers and drivers to transition from the current plastic waste value chain to the new system?”. These barriers and drivers were also categorized into what part of the value chain the data was relevant for. More detailed results can be found in Appendix E.

### **3.5.1 Barriers hindering transition to the new system**

In this section, the barriers to transition towards the new system from the current system is addressed.

#### **Collection to waste handling**

To transition to a new system, with the same amount of waste streams as today, could be challenging. Each waste stream has different collection and waste handling systems which could lead to it being complicated to meet the demand in the following stages in the value chain.

#### **Waste handling to sorting**

A barrier for transitioning from incineration to more material recycling could be the large amount of investments on incineration that has already been made in Sweden. The question that could arise is whether or not it would actually be of interest to incinerate less because of all previous investments on it. There is also the possibility that the waste handling companies would still prefer to send the waste abroad.

#### **Sorting**

There is a possibility that this new system would eventually lead to transitioning to a system that only employs chemical recycling. Extensive sorting may not be required for chemical recycling depending on the chemical recycling technology adapted. This raises the question of whether sorting companies would be in favor of having chemical recycling implemented.

#### **Sorting to mechanical recycling**

The transition to a new system with chemical recycling, could lead to a competition on who buys the plastic waste. If chemical recycling is favored, then there is a possibility that mechanical recycling industry will start losing its business and slowly phase out hindering a transition to the suggested system, if it should include both chemical and mechanical recycling.

#### **Sorting to chemical recycling**

For the transition to a system with chemical recycling, there is a need for a high input volume of plastic waste to the chemical recycling plant. Today’s waste streams are

divided into smaller streams, e.g. packaging, household, WEEE and automotive, with their own collection and handling systems. This would hence mean that to reach the high input volumes needed the chemical recycling plant needs to be able to get plastic from all different streams. If transitioning to the new system could negatively affect the sorting industry, there is a possibility for recycling companies to acquire plastic waste from the sorting industry.

### **Chemical recycling**

Since chemical recycling is not implemented in Sweden yet there are currently no regulations that addresses it directly. This include lack of control over the waste stream and lack of adopted regulation on how chemical recycled materials can be used. Currently there are different waste streams and there are different actors handling each of these streams. This can be a problem for a chemical recycling plant, which would need large volume of input waste to be economically sustainable. Regulations will have to be changed to take into consideration the secondary recycled material from chemical recycling.

Another crucial barrier is the uncertainties regarding ownership of a chemical recycling plant. There is today no business model for setting up a commercial chemical recycling plant. Hence it is seen to be a huge risk to invest in a chemical recycling plant.

In order for chemical recycling to be economically profitable there is a need for high input volume. With multiple countries in northern Europe, planning to set up chemical recycling plants there might be international competition on who gets the plastic waste.

The maturity of technology is still very low and and there is no one who really knows when it could be implemented in full scale. It might take years before the plant is set up and the scenario then might not be the same as is assumed today.

For the chemical recycling plant in west Sweden, the process to be opted for is yet to be determined, e.g. pyrolysis, gasification or something else. There are still uncertainties about certain parts of the process, e.g. handling contaminants, pretreatment of the plastic waste and post treatment of the output from the chemical recycling plant. It is also to be noted that chemical recycling is an energy intensive process, leading to questions on energy supply to the plant. These uncertainties need to be figured out before setting up a chemical recycling plant on a commercial scale.

### **Chemical recycling to chemical industry**

The major barrier influencing transition to a new system in this step of the chain is the acceptance of chemically recycled material into the chemical industry. Today there are no policies that economically support the chemical industry to use recycled plastics. The secondary raw material will be expensive because of the long process involved. Without any economic policy instruments, high price of the secondary raw material could hinder transitioning to the new system.

There is also a need for constant volume inflow of material for it to work in a viable way. The chemical industries themselves have high volume demands and it is uncertain

if chemical recycling could meet that demand. While it could help reduce consumption of fossil based raw material for plastic production, it might not be able to completely meet the chemical industry demands.

A chemical recycling plant has not been tested at large and commercial level yet. There are also no policies addressing syngas or pyrolysis oil as a new type of raw material, for example for usage in food packaging. The policies today say that recycled plastics can be used for some products, but this is not updated to address the output from chemical recycling. There is also no certification set in place assuring the quality of the secondary raw material. All of these affect the acceptance of the secondary raw material from chemical recycling plant to the chemical industries.

### **Chemical industry to plastic product manufacturer**

It will be expensive to buy chemically recycled plastic for the plastic product manufacturers. There is a lack of policies supporting the plastic producers to use chemically recycled plastic instead of plastic based on primary oil. The market for recycled plastic today is very low, and it is uncertain if the new system would change that. Hence there might not be a market for recycled plastic even with the new system.

### **Plastic product manufacturer**

Today's regulation does not differentiate if the material is mechanically or chemically recycled. It also restricts the usage of recycled plastic in some type of product, e.g. food packaging and toys. However, one of the advantages with having chemical recycling is the possibility of meeting the quality of primary oil in plastic production. Hence the current legislation acts as a barrier for fully utilizing chemically recycled material.

## **3.5.2 Drivers for transitioning to the new system**

In this section, the drivers to transition towards the new system from the current system are addressed.

### **Waste handling to sorting**

In interviews, it was told that the waste handling companies are in favour of increased material recycling. A crucial driver here is the 2030 sustainability goals in Västra Götaland saying that fossil fuels should not be used for energy. This means that primary oil-based plastics is not preferred for heating and incineration. During interviews with stakeholders, it has also been seen that the municipalities want to reduce the amount of plastic waste directed towards incineration as well. This because they don't see incineration as the best way to handle plastic waste. A solution for material recycling will be favored above incineration.

### **Sorting**

There is still some uncertainty if this new system will have a positive or negative effect on the sorting industry.

One positive impact for the sorting companies could be a guaranteed market for the sorted plastic and hence would lead to increased business opportunities. The sorting companies today have the required technologies to sort for higher demands and hence could easily adapt to a new system. So, in this new system, there could be larger business possibilities and larger market without having to invest in new technologies.

### **Sorting to mechanical recycling**

One of the 2030 goals of Västra Götaland is to reduce usage of fossil-based material, including plastics, for energy recovery. This could push for a transition where the plastic suitable for mechanical recycling is sent that way instead of going to incineration.

### **Sorting to chemical recycling**

A driver for this stage to transition towards a new system is the availability of a new market for mixed plastic waste. The sorted waste that was initially sent for incineration could be redirected to the chemical recycling plant. If the recycling plant is set up in Sweden, then the sorted waste that is being exported, could be recycled within the country. This could reduce transportation costs and logistics-based emissions.

### **Chemical recycling**

Chemical recycling is not yet implemented in Sweden. However, there is a collective interest from multiple actors across all parts of the value chain when it comes to collaboration and implementation of this technology. Apart from the actors in the material recycling chain, the interest is also observed from research institutes, academia and municipalities. There are multiple ongoing tests, projects and pilot plants being worked upon both on national and international scale. Also, according to Morandin et Al. (2016), the total GHG emissions from chemical recycling is also observed to be lower when compared to incineration.

### **Chemical recycling to chemical industry**

The output from chemical recycling (pyrolysis oil or syngas) is very close to primary oil when it comes to purity. This means that the chemical industries have an alternate source of raw material while they transition to meet the 2030 and 2045 goals. These secondary raw materials can be used in their production without having to upgrade or invest in new technologies within their plant. This also means that the plastic made from chemically recycled raw material could be used in food packaging, if the legislation is adapted to the new system.

These raw materials could potentially be used not just in the production of plastics but also in other industries within the chemical cluster, creating a wide market for chemical recycling plant. If the chemical plant is placed in a location near a chemical industry, access to their raw material would be easier, creating less logistic-related complications.

## **Chemical industry to Plastic product manufacturer**

Secondary raw material from chemical recycling can meet the same quality demands of primary oil-based plastics. At the same time, there are both company and regional goals in favour of using more recycled material for production. The chemically recycled plastic could hence be a way to meet these goals without compromising the quality of the product manufactured.

The possibility to use the mass balance principle in accounting for the origin of a mixed feedstock would be an important driver for switching out the primary oil material to more recycled material. To sell good quality products based on recycled material could act as a good marketing tool.

The mass balance principle would be an important driver to slowly help increase acceptance of recycled material while slowly phasing out dependence on crude oil based raw material. This could be used by the plastic product manufacturer to maintain the quality of their product and help with marketing to the consumers.

## **Plastic product manufacturer**

It is observed that the consumers favour recycled products even if it means having to pay extra for it. The companies themselves have goals to increase how much of recycled material is used in their production. Hence there is a driver to increase the acceptance of recycled material as they need to meet the demands of the consumers.

## **3.6 Discussion on method**

The framework used for the thesis was backcasting, which was chosen based on the complexity of the problem. The project aimed to explore a new system that does not exist at the moment. The system also consists of many actors with multiple connections between the actors. As the research progressed, the application of backcasting provided a structure for addressing the research question. Overall backcasting can be seen as an appropriate tool to use for this thesis.

System mapping, done through value chain mapping, aimed to provide a holistic understanding of the current and the new suggested system. These mappings helped to understand the connections between different parts of the chain and connections between actors. It made for a better understanding of how all parts of the chain affects each other. What should be noted is that a value chain mapping is to be seen as a simplification of the system in reality, which is much more complicated. There could be some processes or connections that might be missing.

The purpose of system mapping was to get a brief overview of the important actors involved. This was vital in order to understand the key actors to contact in the initial stages. It was also important to understand that there are aspects outside the mapped value chain, e.g. policies, research etc, that are just as important as the actors in the value chain itself.

The data collected was analysed based on barriers to circular economy as defined by Kirhherr et Al. (2018). Even though the barriers were broadly categorised into cultural, market, regulatory and technological, it is mentioned that each of these categories influence the others as well. The data gathered during initial interviews were observed to fall under these four categories. However, results presented in section 3 is not divided into these categories. Instead the relevant connections between the categories were made to present an overall answer addressing the research questions.

Overall the process has been iterative and changes have been made based on data acquired. This meant for example that the research question was updated multiple times in order to better suit the purpose of the thesis. Also, the main framework for approaching the research question was updated multiple times. For example, the backcasting approach was decided upon during the later stages of the process because of its fit with what had already been done and how it could guide remaining work.

## 4 Conclusions

To conclude, the data mentioned in the Results section is here concisely presented to clearly address the research questions:

1. What would be the challenges to sustainable material recycling of plastic waste if chemical recycling is implemented as a complement to mechanical recycling in Västra Götaland?
  - The acceptance of mechanically recycled material is low today, there is no telling if this would be different in a new system
  - All types of recycled plastics, irrespective of how it is recycled, fall under the same regulations. This could affect the market acceptance of recycled plastics, and the full potential of chemically recycled plastics might not be utilized. Hence, necessary changes in policies and regulations to address acceptance of the secondary raw material might be necessary.
  - Consumer behavior related to how the waste is discarded also hinders how much of the material is available to be recycled.
  - Given that the recycling plant will need high input volume, the project must not limit itself to accepting waste streams from only the region and must consider importing waste as well. Thus, strategic location of the plant might be needed in order to reduce logistics-based emissions.
2. What are the barriers to and drivers for transition from the current system to this new system?
  - Even though the chemical recycling has been studied in research groups or pilot plants, there is no business model for scaling it up on a commercial level.
  - There seems to be multiple actors interested in chemical recycling but there is still the question of who would be willing to own it. Different actors seem to have different perspectives on who they think should own it.
  - There are large risks involved when investing in this new technology. Current lack of a market for recycled plastic might still exist; with no market, the whole project might not really “take off”.
  - The secondary raw material will be expensive when compared to oil but, currently, there are no policies encouraging use of recycled material. Regulations also seems to be a major factor hindering this transitioning.
  - There has been interest on similar projects in different countries, most of them being from northern Europe. Hence, there is a likelihood of competition on who handles the plastic waste stream as these plants will need large input flows.
  - National and regional goals clearly mention the need to move away from use of fossil based raw materials and to reduce overall GHG emissions. Chemical recycling has the potential to help the recycling and the chemical industry meet these goals.

For further research, it is suggested to investigate the possibilities on how to implement a commercial chemical recycling plant in the region. This includes investigating a potential business model that addresses the role of each actor in the value chain.

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# Appendix

## Appendix A

### The Challenge Lab

This thesis is a project done in Challenge Lab, Chalmers, a student driven change arena where master's students can work on a thesis addressing sustainability and sustainable transitions. The Challenge lab was established in 2014 with the aim to create a space where students from different educational can collaborate to address complex sustainability challenges in the society (Holmberg & Larsson, 2017). For this transition, there is a need for different actors to collaborate and for parts in the knowledge triangle, see figure 2. The different actors are in this case the triple helix constellation between academia, business and society. The knowledge triangle is education, research and innovation.

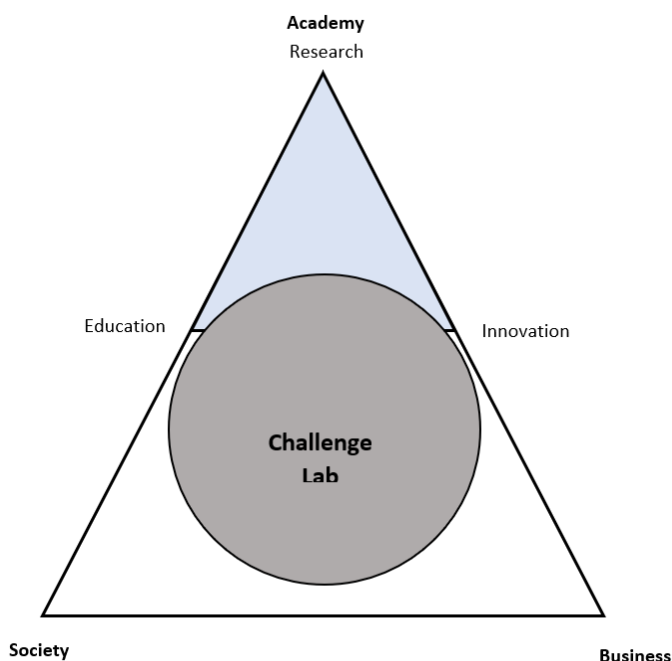


Figure 6 The triple helix of academia, society and business (Holmberg & Larsson, 2018)

Challenge lab offers a space for the students with different educational backgrounds. The students are given the opportunity to explore challenges from different perspectives and based on this, formulate questions on which the entire thesis would be based upon (Holmberg & Larsson, 2017). By not starting from a predefined question the students can be a part in sustainable transition. They are perceived to be natural and hence through dialogue with stakeholders can address fundamental questions. This also means that the students can take ownership of questions that often fall between what individual actors can do through their own activity.

The tool used in the Challenge lab is backcasting. This year, 2019, the areas of focus have been Mobility, food and materials, resources and energy in Västra Götaland, with plastic recycling being the topic addressed under the materials, resources and energy thematic area.

## Selecting challenge to address

Backcasting was used as a tool to reach the research question. Larsson (2019) define the steps in backcasting as follows:

- Step 1: frame conditions for a sustainable future on a level of principle
- Step 2 analyse gaps between the present situation and the sustainable future
- Step 3: identify leverage point interventions for bridging the gaps
- Step 4: create strategies for realizing the leverage point interventions

Backcasting was used instead of traditional forecasting since it tries to move away from the beliefs of today's system. Hence, this approach considers the changes and possibilities that sustainability could involve in the future. This could further be justified by Dreborg (1996), who describes it to be appropriate when:

- "The problem to be study is complex and affecting more than multiple sectors and levels of society."
- "There is need for major change."
- "Dominant trends are part of the problem."
- "Problem to great extent is a matter of externalities."
- "The time horizon is long enough to allow considerable scope for deliberate choice."

At the Challenge lab the backcasting process was done through the inside-out and the outside-in perspective. Larsson (2019) describe the inside-out perspective as a subjective perspective which includes reflecting upon oneself and one's surrounding. The inside out perspective focuses on personal development skills like leadership, trust, communication and also the strengths, weaknesses and values that an individual prioritizes. Larsson (2019) further describe the outside-in perspective as an approach using objective theories and tools. The outside-in perspective involves understanding the system we live in to map out problems, connections and similarities between different parts of society.

### Step 1: Frame conditions for a sustainable future on a level of principle

In the first step of backcasting, the goal is to frame a sustainable future based on values (Larsson, 2019 & Holmberg, 1998). Defining the framework for a sustainable future serves as a guiding principle for later activities in the lab. Only taking the current trends as a starting point, instead of defining the required criteria for a sustainable future, might lead to the whole course of working for this transition to go off stray (Holmberg, 1998).

In Challenge lab, the first step was done in two steps:

- Defining personal values (Inside-out perspective)
- Defining the future sustainability principles (Outside-in perspective)

### Inside-out

According to Ryan & Deci (2000), Motivation can be divided into extrinsic and intrinsic motivation. Extrinsic motivation is when there is a need for some sort of

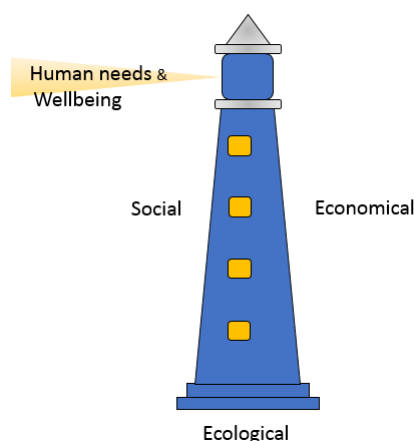
external stimuli to motivate a person. This could for example be fear, judgement or rewards. Intrinsic motivation refers to those who are self-motivated to carry on working. According to Senge (2015), self-motivation and being able to see larger systems are the foundations to what makes a leader guide a system's transition. In addition to this, other important skills are listening, cooperation and encouraging the team.

In the Challenge lab, the focus was to create intrinsic motivation by having a value workshop. During this workshop the students were asked to share and reflect upon their strengths, weaknesses and values that are important for them. The goal of this was build trust amongst the team, enabling cooperation and teamwork to help look at larger system. Apart from these, intrapersonal skills like listening, speaking and observing were also practiced simultaneously during these activities.

To be intrinsically motivated it is seen that competence, autonomy and relatedness play a big part. Competence refers to an individual being able to carry on and complete a task without being demotivated. Autonomy here refers to being able to carry on the task without depending on any external factors as a direct consequence of their actions. Relatedness refers to being able to experience a connection or an interest with the environment around (Ryan and Deci, 2000).

### Outside-in

To create sustainability principles Holmberg & Larssons (2018) lighthouse framework, see figure1.2, was used. This framework includes four perspectives on sustainability, the ecological, the economical, the social and lastly human needs and wellbeing. The human needs and wellbeing is presented as the light and the ecological aspects as the fundamental basis for all human activities. The economic and social dimensions lie between the human need and wellbeing and the ecological dimension (Holmberg & Larson, 2018). While being relevant as independent categories, there also exist interdependencies between all of the dimensions (Larson, 2019).



**Figure 7** The sustainable lighthouse (Holmberg & Larsson, 2018)

Analyse gaps between the present situation and the sustainable future

In the Challenge lab the students created a joint framework of principles. This was done by initial individual brainstorming followed by group discussions. This resulted in principles for all four aspects of sustainability. The result was a collective set of principles that was agreed upon by the whole team. These were meant to serve as a guide for the next stages in the process.

## **Step 2: Analyse gaps between the present situation and the sustainable future**

The second step of Backcasting is to identify and map the current system (Larsson, 2019). This is done in order to better understand the starting point for the transition. The inventory from this step will be used as a foundation for both the third and fourth step as a way to connect the current situation and gaps with the preferred outcome (Holmberg, 1998).

In Challenge lab, the second step was done in two steps:

- Map the socio-technical systems and root causes (Outside-in perspective)
- Multi-stakeholder dialogues (Inside-out perspective)

### **Outside-in: System mapping**

For mapping the socio-technical system one approach could be to use Geels' (2005) Multi-Level Perspective. Here the system is broken down in three levels, macro, meso and micro, for better understanding and mapping.

According to Geels (2005) the different levels are:

- The macro level, or the landscape level, is where the system is well established and stable. Changes to this level cannot be done at will and is often really slow. The influence of actors on this level is also very minimal (Geels, 2005).
- The Meso level, or the regime level, is established from socio-technical regimes with collaboration from actors from different dimensions of society. The stability of innovations is dynamic, with a possibility of new innovations arising but the growth is incremental and is path dependent (Geels, 2005).
- The micro level, or the niches, involves generating and developing radical new innovation and ideas that could potentially change the system. They are usually in their very early stages of development and hence have very little effect on the system. For innovations from the niche level to have an impact on the regime or to enter the landscape, there needs to be an understanding of where in the regime would it be accepted (Geels, 2005).

In the Challenge lab, the mapping was done for the thematic areas of food, mobility and energy, materials & resources. The aim with the system mapping was to better understand the current situation and as a way to prepare for the upcoming dialogues.

For each thematic area the students were asked to brainstorm individually, thinking about keyword describing the existing system. These were written down on post it notes, which were grouped into niches, regimes and landscapes. The keywords were then grouped based on the topic and compared with the sustainability principles. With the initial mapping of the system done, relevant questions were framed for the intended stakeholder dialogues. The inspiration to framing powerful questions were drawn from Vogt, Brown & Isaacs (2003).

## **Inside-out: Stakeholder dialogues**

Isaacs (1993) describes dialogues as a healthy environment to share information and collaborate with different actors in order to work towards sustainable transitions. Dialogues help foster an environment for communication and collective learning.

Isaacs (1993) furthermore explain that a dialogue is not aimed to seek agreement but is intended to help increase coherence, shared thinking and knowledge.

In the Challenge Lab the aim of stakeholder dialogues were to verify the systems mapping and to add missing aspects in the mapping. Furthermore, the dialogues were a chance to find points of potential, such as lock-ins, to be used for leverage point identification.

The dialogues were held in a fishbowl setting with an inner and one outer observing circle, see figure 4. The inner circle consisted of the facilitators, active dialoguers and the stakeholders. The outer circle consists of participants who took notes or were meta-listeners.

Dialogues in 7 topics were conducted. They are:

- Mobility of people
- Mobility of goods
- Food
- Circularity
- Equality
- Energy
- Climate 2030

As addition to these, a summary of the dialogues conducted in the courses Leadership for Sustainability transition (SEE025) and Managing Stakeholders for Sustainable Development (ENM130) were also referred to.

## **Step 3: Identify leverage point interventions for bridging the gaps**

The third step of backcasting is to find leverage points and interventions for bridging the gaps between steps 1 and 2 (Holmberg & Larsson, 2017). Meadows (1999) describes leverage points as places within a complex system, where one small shift in one part of the system can produce a bigger change in the whole system. Holmberg (1998) suggests that the goal with this step is not to specify the future in detail but to be open minded toward new options. Hence, a direct solution is not the outcome of this step.

In Challenge lab this step was done with:

- Creating leverage points (outside-in perspective)

## **Outside in: Leverage point creation**

In the Challenge lab, having completed steps 1 and 2, the leverage points were identified. These were first divided into the following thematic areas:

- Innovation strategy

- Materials and energy
- Mobility

The approach to the leverage points were framed by addressing the following questions:

- What? What is the bigger problem to solve? For example, what is the gap to address?
- Where? What “lock-in” to address, what local problem?
- Who? What individuals and/or organizations have expressed interest in this issue? What ongoing processes could it connect to?

The points addressed were also done by taking into account personal interests and program requirements the student is from.

### **Challenge to address**

In this section the result from the first three steps in the backcasting process are presented. These results are what narrows down to the initial research question. The results were used to narrow down to one area of focus and an initial research question. In table 1.1, the sustainability principles, as defined by the students, are presented.

**Table A.1:** Sustainability principles defined in Challenge lab

<p><b>Wellbeing</b></p> <p>Question addressed: "What is a good life?"</p>	<p><b>Social</b></p> <p>Question addressed: "How can we live together?"</p>
<ul style="list-style-type: none"> <li>• Leisure</li> <li>• Intellectual</li> <li>• Freedom</li> <li>• Spiritual</li> <li>• Purpose</li> <li>• Nature</li> <li>• Safety</li> <li>• Institutions (social structure)</li> <li>• Self-actualization</li> <li>• Social</li> <li>• Love and belonging</li> </ul>	<ul style="list-style-type: none"> <li>• Embracing the interdependent nature of our human society; every individual has the sense of responsibility and involvement.</li> <li>• The foundation of our society is sufficiency.</li> <li>• All our interactions are meaningful and honour the humanity in all of us.</li> <li>• Equal rights and opportunities, the freedom to direct our own lives</li> <li>• Fair distribution of resources and knowledge with a culture of sharing and generosity.</li> </ul>
<p><b>Economic</b></p> <p>Question addressed: "How can capital be managed in the future?"</p>	<p><b>Ecological</b></p> <p>Question addressed: "How can societies activities fit within nature's carrying capacity?"</p>
<ul style="list-style-type: none"> <li>• Resource management that allows all humans to fulfill their needs.</li> <li>• Long lifetime in man-made capital (durable, resource-efficient, circular).</li> <li>• Optimal use of non-renewable natural resources.</li> <li>• Use renewable resources within the natural regeneration capacity.</li> </ul>	<ul style="list-style-type: none"> <li>• No systematic accumulation of emissions and waste in nature from society. (and if needed, restore).</li> <li>• Use only the amount of resources that are renewable, not depleting resources.</li> <li>• Support and preserve biodiversity.</li> </ul>

For the area of plastics and plastics recycling in Västra Götaland the following gaps were identified:

- Most plastic waste today is incinerated: Burning away plastics creates a need to depend on primary oil-based plastic material, which depends on fossil fuels for its production. Material recovery could help move away from dependency.
- For material recovery today sorting is needed: For the mechanical recycling that exists today there is a need to sort the waste based on, e.g. colour, type and grade. Sorting is essential to assure that the secondary raw material is of good quality.
- Lack of interest in accepting secondary raw material because of quality: Plastic production depends on high quality raw material. Because of this, there is hesitation to accept secondary plastic raw material to produce plastics.
- There are a lack of collaboration for implementing new technologies: There are new ways of material recovery being researched upon by different institutes in the region but there appears to be a lack of collaboration or initiatives between them for efficient use of these methods for a more efficient circular flow of the material in the system.

- Material recovery is not prioritised in the region: Local waste handling strategy has not accounted for chemical recycling process of plastics as an option on plastic recycling. As plastics have a potential to generate a lot of energy, the regional plans, at the moment, prefers the incineration of plastics. However, it was also highlighted that this was not a sustainable solution.

Based on the sustainability principles the following leverage points were identified:

- What: What is the problem to solve?
  - Improve the material recycling rate of plastics. Reduce the dependence of new material for plastic and instead close the loop on what is already out in society.
- Where: What “lock-in” to address? What local problem?
  - Considering there is development in application of new technology for material recycling of plastics and there is interest from different actors, in developing and applying it practically in society today.
- Who: What actors/organizations are interest in this issue? What ongoing processes to connect to?
  - Actors interested:
    - \* Researchers
    - \* Region
    - \* Chemical industry
    - \* Waste handling sector
    - \* Recycling industry
    - \* Urban development collaborative arenas
  - Processes connected to:
    - \* Chemical recycling (Gasification or pyrolysis)

Based on the identified sustainability principles, gaps and leverage points an initial research question was framed.

## Appendix B

**Table B.1:** Adaption of backcasting to address research question

Step	As defined by Holmberg (1998, p. 33)	Approach in thesis
Step 1	“Define criteria for sustainability based on principles.”	a) Define criteria for sustainability for efficient recycling of material from plastic waste
Step 2	“Describing the current situation in relation to the criteria for sustainability”	b) Map the current system. This includes only mechanical recycling for material recycling  Present the challenges to meet criteria defined in a).
Step 3	“Envisaging and discussing the future”	c) Map new suggested System This includes a combination of mechanical and chemical recycling for material recycling for plastic waste.  Address the challenges from b) the new system could meet.  Present the possible challenges to meet criteria defined in a).
Step 4	"Finding strategies for sustainability"	d) Possible barriers and drivers for transition from b) to c).



## Appendix C

This Section has a summary of additional lectures and field visits attended for the thesis.

### Lecture: Reducing plastic pollution

The lecture was held as part of a series of lectures addressing global sustainable development. This lecture was conducted by a researcher working with the economics and regulatory aspects of plastic waste accumulation and pollution. The theme for this lecture was titled “reducing plastic pollution”.

The points covered were as follows:

- Plastics are useful material making products lighter, more durable while being lighter. It has the potential to help work towards the following sustainability goals defined by the UN:
  - Goal 2: Zero hunger
  - Goal 3: Good Health and wellbeing
  - Goal 6: Clean water and sanitation
  - Goal 11: Sustainable cities and communities
  - Goal 13: Climate action
- However plastics still contribute to working against the following sustainable development goals:
  - Goal 3: Good health and wellbeing (b)Goal 6: Clean water and sanitation
  - Goal 12: Responsible consumption and production
  - Goal 13: Climate action
  - Goal 14: Life below water
  - Goal 15: Life on Land
- Packaging is the biggest user of plastic products accounting for almost 40
- Plastics are also used to balance the demand in the clothing industry. Cotton alone cannot meet the demand. Hence the use of polymers like polyester and nylon is increasing. Fast fashion trend fueled by the fashion industry is the biggest contributor to this.
- Industry alone cannot be blamed for the production and use of plastics. Consumers use a lot of plastics on a daily basis. Industry follows and feeds the demand.
- Addressing the problem with plastics have to be holistic. The whole value chain has to be looked at.
- Reducing dependence of plastics by banning certain products all over the world (from plastic bags, single use plastics and straws). Move extended to possibly band top 10 products seen amongst ocean plastic waste.
- The market is international. Production, usage and waste handling flows freely between different countries and cant be limited to just within sweden. Plastic produced and used elsewhere can be discarded here.
- Biodegradable plastics are not and will never be a solution. It needs land and water for production to meet current demand. Also the products need industrial grade composting to decompose. Cannot be discarded by the consumer into the environment.
- The same land use can come into question when suggesting use of bioplastics. Plastics today in all areas use about 4000 different chemicals. No regulation to

completely regulate this. About 148 of them are confirmed toxins and not all of them are banned globally

## **Lecture: Plastic packaging in food industry**

The lecture was conducted by the sustainability head at a popular supermarket chain in the region. The lecture addresses the problems with plastic in general and also provides some insight about its effects on the supermarket industries. The following points were covered:

1. Use of “SIN list (Substitute It Now) to decide the material to use for their products. The list can be used to assess the impact of a certain material and then look for alternatives for it.
2. Some materials are legal to use but is known to be unsustainable. Need regulations to control production and use of such material.
3. It is impossible to reach circularity without improving recycling.
4. Cost of recycled plastics went from almost SEK 3000/ ton to almost nothing these days.
5. Use of primary oil-based plastic material is cheaper than recycled. Logistics adds to cost of recycled plastics.
6. While packaging companies are responsible for handling the packaging waste it is not compulsory for it to be recycled.
7. Need more deposit and collection of plastic products, including packing.
8. Regulation changes takes very long. Took 2 years to set up the “pant” system for “squash” bottles.
9. Voluntary deposit systems seems to have helped the PET recycling. Something on similar grounds could be set up for others as well.
10. Products produced today are often done so without thinking of how it could be recycled.
11. Collection rates are addressed as “recycled” in most regional and nation documents. Data can be misgiving.
12. Scandal in the sorting industry affected perception on how much of packaging was being recycled. Sorted plastic was sent for incineration but data indicated the same was sent for recycling.
13. New sorting facility only sorts 3 types of plastics. These are the only ones collected a lot more than the others.
14. Public procurement can help improve demand for recycled plastic products. Also making it mandatory to have part/parts of products made from recycled plastics and increasing taxes on fossil fuel based plastics can help drive towards more recycling as well.
15. Unnecessary packaging seen in supermarkets are there because there is a need to differentiate organic(bio based products) from the regular ones.

## **Lecture: Industrial symbiosis**

This lecture was held by stakeholder working close with the chemical industry. The lecture includes things such as:

1. What is industrial symbiosis?
  - a. The sharing of resources and by-product resources in order to add value and be resource efficient.

- b. If one industry produces by-products, they can sell that to another company.
- 2. Chemical industries in Västra Götaland have been collaborating during many years.
  - . They use each other's by-products. They are dependent on each other.
  - a. They have many years of knowledge and experience when it comes to collaborating.
  - 3. Who pays when industries collaborate?
    - . Ownership?
    - a. Maintenance costs?

### **Study visit to sorting facility**

This is a summary of the points discussed during the study visit to the sorting company. This is one of the facilities where plastic waste from multiple streams are sent to. The plastic waste here is sorted based on the type and grade of plastic and the colour.

Sorting is a complex process. The technology that exists today cannot sort the plastic waste efficiently. If people are serious about recycling, it should also be made harder to put products material that are hard to recycle into the market in the first place. The same can be said about material that use fossil fuel based raw material. There also also too many types of plastics in the market today. Products have different types of plastics in them making the sorting a complicated process.

In the sorting plant, about 20% of the waste received is not even plastics. Some materials are not worth sorting. The process can be expensive when compared to the volume of material recycled. E.g. foams and laminates. Some material like black plastics in general are just hard to detect during sorting.

Sorted plastic is mostly sent to Central Europe where it is mostly downgraded. They cannot be stored at the sorting facility because of health and safety hazards.

Some materials are expensive to sort. The cost of sorting is much lower than the cost at which the material is sold afterwards.

Recycled products cannot be used for medical and food products for fear of contamination.

Apart from policies, the general attitude of the industry is against recycled plastics. Oil prices are lower and can assure better quality when compared to products made from mechanically recycled products.

While people say that plastics going for incineration is preferred for heating, the incinerator firms get way too much plastic. Plastics have a high calorific value. Energy recovered is much more than what the incinerators can store or handle.

It is expensive to buy recycled material. So, in general money talks and matching the prices of primary oil-based plastic products is hard. However, there is a trend observed where consumers are starting to opt for recycled material.

Bioplastics make sorting hard. They are hard to differentiate from the regular plastic waste and affects the overall quality of batch.

Packaging is all collected under one single collection system even though there are so many different types and grades of material used which makes sorting complicated.

## **APPENDIX D:**

This section covers the summary of all the stakeholders interviewed for the thesis.

### **Interview questions**

- Can you describe your organisation and your role in the organisation?
- What do you see as the largest challenges in the current waste stream when it comes to plastic, e.g. logistics, policies, market, culture etc?
- Are you familiar with chemical recycling?
- What would be the challenges in system with chemical recycling?
- What would be barriers and drivers when it comes to implementation of chemical recycling?
- What role would/ could your organisation have if new chemical recycling plant were to come up in the region? Could there even be a potential of ownership?
- Is there anything that didn't come up in the interview that you'd like to add?
- Is there anyone we might have missed that you think we should contact?

### **Summary of interviews**

#### **Project leader Urban development collaborative arenas**

This stakeholder works as a project leader for a project working on setting up a chemical recycling plant. The project is still in its early stages.

#### Questions specific for this stakeholder

- What initiatives on chemical recycling do you see in the Sweden and in the world?
- With your project, are the focus on gasification or pyrolysis?
- On a regional level, how keen are politicians to have a chemical recycling plant?

#### Summary

The stakeholder believe that their project is the only initiative in Sweden on chemical recycling. There is some talk about doing something in Finland, Denmark, Holland, Canada and Spain. So, there are a lot of upcoming news about it, but the stakeholder doesn't know how far they have come. The stakeholder however thinks that plastics that could go to mechanical recycling should go there since it is more energy efficient.

The project that the stakeholder work on, has gasification as their main focus but they have not excluded the other alternatives. The focus on gasification depends on multiple aspects, but partly because of other projects in the same area that are ongoing. They also feel that they know more about gasification and have more knowledge about it.

One challenge to chemical recycling in Sweden, is that the technology need to be sorted out. There is also need to do an techno-economical evaluation, and hence narrow down and make a decision on what technology to go with. Another barrier is the logistics and infrastructure, policy and regulations questions. The stakeholder do not think that the region will invest in the infrastructure or in a pilot for a chemical recycling plant. They might support it, but they will not be the owners. The stakeholder speculates that the owner would be either one single company or a joint venture of different actors.

The mass balance principle is important when it comes to transitioning to a fossil free society and processes. This is important since there already is plants and it is not possible to just build completely new ones, need to make use of the ones that they already have. So, when phasing out the fossil raw material you mix it with some renewable raw material into the same reaction. That means that you will get out a mixture of both. The material will be both based on green and fossil raw material. With this mass balance principle, they can sell a green product and say that they have put in the same amount of green as it is in this product, however you cannot be sure that your product is made of green molecules. But this principle will help to transition and increase the market for new green products.

The stakeholder mention that the main challenges to implement a chemical recycling plant are the business model (e.g. ownership), some technical prerequisites and optimization of processes, need of economical incitements from politicians, and the waste monopoly. When it comes to pricing, they are dependent on political subsidies and legislations/ regulations that facilitate the use of recycled plastics. It could for example be higher tax on oil-based products.

The chemical industry needs raw material supply for their products and processes. This is not only for doing plastics, because if you put plastic waste into this plant and get the raw material, you can both make plastic but also chemicals. So, companies that don't produce plastics but produces chemical components they could also be interested in this plant.

The stakeholder thinks that politicians on a regional level are interested in this plant. They want to have industry in the region and that these industries produce products in a sustainable way. The industry provides the region with a lot of money and job opportunities, so the industry is extremely important for the region.

### **Project leader at research institute**

This stakeholder is a project leader at research institute working with e.g. plastics in cable and recycling of PVC. The stakeholder primarily has knowledge about mechanical recycling and not much about chemical recycling.

### Questions specific for this stakeholder

- What challenges do you see when it comes to sorting?
- How much influence do you think a product manufacturer have when it comes to recycling?

### Summary

The companies in Sweden that uses recycled plastics, they use scrap from production with quite high qualities. So, this mean that that they use mostly pre-consumer plastics and not so much post-consumer plastics. But the stakeholder believes that companies want to use more recycled plastics. There is for example a large automotive company that say that 25% of the plastic they use in cars should be recycled the year 2025. But then the sorting needs to be better so they can get the right quality for the automotive industry.

The stakeholder also thinks that the producers need to take on some responsibility when it comes to designing products that can be recycled. They also need to support the collection system for the product. The stakeholder believe that plastic product manufacturers have the most important role when it comes to plastic recycling. It is important that they think about how they mix materials and try to avoid materials that are difficult to recycle. Today it takes a lot of time to take out parts and it can be expensive and they could design in a better way so it is easier to take out big plastic parts from for example a car so it can be recycled.

### **Project leader municipality**

This stakeholder is working at a company that is a part of the municipality. This company are responsible for the household waste in one of the municipalities in Västra Götaland. They also coordinate the waste management plan since the plan is a bit broader than their responsibility regarding collection.

### Questions specific for this stakeholder

- When speaking about plastic recycling, one argument against it has been if we even need to recycle it considering the district depends on it for heating. What is his/her view about this?
- Does the region collaborate with other actors?

### Summary

The municipality is responsible for the household waste and the producers are responsible for the packaging waste. The stakeholder explains that the municipalities have a responsibility to inform the householders that they should give the packaging waste to the producers. The municipality have some cooperation with producers, but don't know how they will work in the future since there is a new legislation they will need to adapt to.

In the household waste “quite a lot” of plastic packaging still ends up there since the householders don’t sort it. Out of the household waste about 30% is still packaging and newspapers that should go to the producers instead. Regarding plastic, most of the plastic is in the packaging, there is not a lot of plastics that fall under households. There is of course things like toothbrushes and other products in the households, but it is not as dominant as packaging.

Plastic waste from packaging has not been sorted over such as long a period compared to e.g. glass. So, sorting plastic is a new thing and it takes time to learn. This also mean that there can’t be to many changes in the system, since it would make it even more confusing for the consumers.

When it comes to plastic waste there is a very complex system with different actors being responsible for different streams. The waste stream also consists of many different actors such as the ones who creates it, transportation and then facilities that treats it. However, regarding the EPR scheme the legislation has changed, they are now supposed to have more service to the households and collect closer. But in a region were most people live in apartments, the legislation is not very strong regarding that. If the apartment buildings have trash bins, the producers will pick it up, but The ones who build apartments are not forced to make space for the bins.

The stakeholder is not afraid that more recycling of plastic will affect the incineration and district heating since there are a lot of waste still landfilled in Europe... “I think will not run out of waste in the future even if we pick the plastic away”.

The stakeholder believes that there is a need for tax incentives or eco-design directives, where you need to use recycled content in your product.

### **Project leader chemical industry**

The stakeholder is working as project leader for a sustainable project that is a collaboration between some chemical companies.

### Summary

The chemical companies that the stakeholder works with are all connected to a cracker and depend on feedstock that comes from it. Today the feedstock that goes to in to the cracker is based on fossil feedstock. The chemical companies have a joint challenge, to switch this feedstock to more sustainable alternatives which could be e.g. renewable or recycled alternatives.

Today they cannot use mechanically recycled plastics for the products that they produce because the quality requirements are to high. But with the chemical recycling you get the same quality requirements as with primary oil based raw material.

When it comes to mechanical recycling one obstacle is that all plastic waste and al polymers is not possible to recycle by mechanical recycling. Another obstacle is that many producers choose different kinds of plastics in one product. Sorting is another obstacle; e.g. black plastics have not been able to be sorted out. The stakeholder think

that there is a new technology that is enabling this, but there is still some restrictions on this part. The quality loss of recycled materials compared to primary oil-based plastic material is also an obstacle. This means that there is no real demand for this type of recycled plastic, because of the low quality.

When it comes to chemical recycling, you need to take some further steps compared to mechanical recycling, requiring more energy and making for quite an expensive technology. There is also a need to make a decision on which of the techniques of chemical recycling to do. So, there is quite a lot of technology related issues, but there are also more political issues. The stakeholder believes that there should be some kind of political driving force for recycling, it should be better, there should be some incentives to recycle your material by mechanical recycling compared to energy recycling. There are issues regarding logistics since those facilities are often more favourable when they are bigger in size. This means that there is a need to find a way to transport very much plastic waste to one place.

The stakeholder thinks that the ownership of a chemical plant would be a collaboration between companies since it is such a high risk. This can for example be recycling companies, chemical companies and energy companies. . . “to make it fly, it needs some kind of collaboration, the ownership with support from government or something like that to make it come over the barrier, to make it fly “.

The stakeholder thinks that gasification is sensitive for scale up effect and that for a facility to fly it needs to be bigger. The stakeholder also believes that for gasification it is a quite long way to go. But the stakeholder thinks gasification is better if you want to stay at methanol for example and it is easier for it to work if not only producing chemical products out of it but if it is also used as fuel.

Mass Balance is very important, it is when let's say that we are putting in a specific amount of recycled feedstock to our system, we mix it in the same system as we have fossil based feedstock but we are only allowed to sell the same amount of recycled based product so to say as the amount of feedstock we put in. But when you buy as a customer you cannot be sure that it has ended up in your specific product. It is a certified system, so you know that you can be safe that it has been put in to the system but you don't know if it ended up in your product.

Chemical recycling is the future but is not sure if it will be in Sweden because of political conditions. The political conditions have to be right in order to make this fly in Sweden. Incentive for material recycling instead of energy recycling so that it's better economic wise that you material recycle over energy recycle. Also, investment support as it is such a big facility.

### **Regional planner for Municipalities**

This stakeholder acts in collaborative organisation for municipalities in the region near Gothenburg. In the organisation the stakeholder works for they work with networks with the municipalities where they together make plans on how to develop or change the waste management systems.

### Questions specific for this stakeholder

- When speaking about plastic recycling, one argument against it has been if we even need to recycle it considering the district depends on it for heating. What is his/ hers view about this?
- Does the region collaborate with other actors?

### Summary

The stakeholder mentions that when it comes to waste handling, they value pleased customers. They have been working on new goals which however is not set yet. In regards of plastic the goal are “the plastic waste from the households shall reduce with 50%.

The municipalities are in charge of the residual waste and not the packaging waste. However, some municipalities in the region have set up system where house owners can have sorting bins outside the house. This includes packaging which in reality is not the municipalities responsibilities. There is a new regulation that says that the producers need to set up systems close to all homes.

According to the stakeholder the municipalities are not really considering that incineration is an issue that speaks against more recycling “the municipalities are not really considering that as an issue. they don’t really care about the district heating, in my personal opinion on how is the discussions going. that is a separate system, apart from the waste management”. The stakeholder mean that all systems need to be optimised and the optimisation of waste management is not incineration. If there was a chemical recycling plant it would be the producer that would use it and not the municipalities, since their plastic waste is so limited. But the stakeholder also claims that they need to sort out more of the plastics from the residual waste, but that is what the goals they have set up is about.

### **Researcher A, from recycling industry**

The stakeholder works for a company that are involved in collection, sorting and mechanical recycling of, mostly, WEEE plastics but also from refrigerators and film plastics. They only collect from industries and not from households.

### Summary

Today there is not much plastic recycling at all, there is some mechanical recycling of plastic packaging. From the plastic product industry there are also some internal loops, but this is in a small scale.

The awareness of plastic recycling has become higher, large companies say that they want more recycled material. But then are standards that says that the material should be primary oil-based material. The stakeholder does not know if it is easier with chemical recycling since then the molecules are new again.

The chemical industry wants recycled raw material and the stakeholders company have raw material, but then nobody has the chemical recycling plant. For the stakeholders’

company a chemical plant is not their core business and probably not they would want to own. The stakeholder doesn't believe that the chemical industry would want to own it either. So, the question is who should run it? The stakeholder, for example, mention that it could be an energy company or an oil company. The stakeholder thinks that the region needs to help with the plant, help the transition to a pilot. The region needs to put up with some research money, could even be on a national level.

Chemical recycling will always be more expensive than mechanical recycling. However the with the chemical recycling you get more clean pellets. The stakeholder thinks that the authorities has to say that it is good. Now they have the goal that they should not incinerate any fossil 2040, which would give some pressure. Then you can get the plastic into a circular flow and if we meantime put in some bio based the product will more or less be based on bio. With chemical recycling it doesn't matter if the plastic is fossil or bio based, but biodegradable should not go into the same lines.

The stakeholder thinks that there needs to be demand to increase the recycling, both demand from plastic manufacturer companies but also from consumers. The demand has changed, everyone speaks about recycled plastic. So, the stakeholder believe that both consumers and legislation plays a vital role when it comes to recycling.

### **Researcher B, from research institute**

This stakeholder works as a researcher in a research institute. The stakeholder works with circular economy and has knowledge about the end of use phase when it comes to plastics

#### Summary

The stakeholder says that there are requirements for several industries to use more recycled materials and to produce recyclable products, e.g. in the automotive industry. But they see input of recycled materials as a risk because the chemicals that older products can contain for example flame retardants and phosphorus. This would hence make products that are not legal to put on the market anymore. The stakeholder thinks that the risk seems to overwhelming and hence they prefer using primary oil-based plastic material.

One other aspect that the stakeholder claims as a issue is the the fact that plastic is lightweight so if a company have a requirement to have a percentage weight that is recycled then they will not start with the plastic.

Recycled plastic is not viewed to be as valuable as plastics from primary oil-based sources, therefor people want to pay less for it. So a big obstacle is the perceived down-cycling and the compounding. The stakeholder hence mean that a need to understand what good are good uses of recycled plastics. For example some of the textile products that already exist that are made from recycled plastics and they are "quite nice".

### **Researcher C, from research institute**

Working in an industry-based research institute in Sweden. Focused on gasification and chemical recycling. The interview was structured more about technological drivers and challenges on chemical recycling. Did a literature study for one of the ongoing projects about setting up a recycling plant in the region? Earlier research was focused on biomass conversion to raw material that could be used for plastics but the organization used the same technology to address plastic waste.

#### Summary

Plastics today use a lot of elements in some way or the other. They could be used as paints, fillers, plasticizers etc. and this is what complicates mechanical recycling of plastics. These would have to be recycled through a thermochemical route. Some elements are problematic. Halogens can lead to corrosion if not handled properly. They can also release toxic gases during combustion, which should be avoided. Chlorides are easier to be handled in gasification than in pyrolysis. However, elements like sodium are problematic for gasification.

There are different processes one could use for chemical recycled. However, they have different challenges. The output yield varies based on the route selected. The type of material fed to the process also determines quality and type of output obtained. Some processes have additional processes in-between which makes them energy intensive to run. One common factor between the observed processes so far is that there are losses involved and the amount of recycled material recycled is lower than the amount fed.

There is also theories of using additional processes to improve the output yield. One such process is electrolysis involving splitting water molecule into hydrogen and oxygen. Both the split molecules can be used back into production to improve the yield. However, this one is in theory and the practicality of setting up this has not been tested.

Pyrolysis and gasification are two of the most common processes considered for chemical recycling. However, for pyrolysis you need a cleaner waste stream compared to gasification. Gasification is a more complex and energy intensive process as it needs higher heating temperatures. Gasification is economical on a large scale but pyrolysis can be set up in smaller units.

Energy required to keep such a chemical recycling plant is to be questioned. One could use the produced raw material or the plastic waste for the heating required to run the plant. Hence it is important to decide a proper business model before designing a plant.

### **Researcher D, from industry and academia**

Researcher who plays a big part in a strategic innovation program where the mission is to gather stakeholders within the field of sustainable material use. The program also funds projects around the same topic. The questions raised here in the interview were about ongoing projects and the potential of chemical recycling and what drives them.

#### Summary

They fund two types of projects: open call and strategic projects. Open call are for projects aimed at developing solutions – If you have an idea in mind, you can test it in a lab and get enough quality that can help scale up. Strategic involves developing knowledge for open innovations, not focused on solutions.

Projects involve: working with hazardous material in plastics, WEEE plastics, many on plastic recycling. Also, some on feedstock recycling (chemical recycling) to evaluate different technologies. One of the projects related to recycling plant in Stenungsund where they evaluate techno-chemical conditions for a refinery. These projects were first started back in 2016.

Challenges observed here for recycling are almost never the technical challenges. Policies and market are bigger. Industry is routed in such a way that the focus is to efficiently and inexpensively get as much out of the material as possible. Little effort put into designing to get material back.

Compared to metals, plastic recycling is very recent. The government helped metal recycling from the 60s while plastic recycling was started in the 90s. loss of value of plastic waste is much higher per ton than steel. There is also a market to accept steel. The use of plastics in products is gradually increasing as well. However, more effort is put to using recycled steel over recycled plastic to meet the overall recycled material consumption targets.

However, lot of companies are putting up roadmaps to get to use more recycled plastics because of vision 2030, best example being IKEA and Volvo. Some companies also delay applying this to their businesses. Company policies help reach those targets better. But for companies to set this up will take time. Electrolux took years to develop this and now have certification for material, suppliers etc. The purchasing department played an important role when they realized they could save money doing so and promote a sustainable image. These changes go much faster when it can be shown to save money. Companies however expect recycled material to be cheaper than oil but the reverse logistics here is expensive making oil cheaper any day.

EU is putting up laws based on which other countries in the EU are adapting to. But even though more companies want recycled material, recyclers have a hard time finding a market for their material. For industry quality and prices matter. Added to this, they want more than one supplier to supply globally, which is hard. Hence market and policies are decisive factors.

For certain products, plastic is expensive to remove and transport when compared to how much one can earn when it is sold, meaning there is little interest to want to recycle this. This is easier with industrial waste because it is more homogeneous.

Different waste streams are also handled differently. The word recycled also refers to how much to collected. The waste collected is sent to central Europe to be recycled. Actual recycled rate is low and of that recycled, those that end up being used in production is even lower.

Even if we improve recycling rate, the demand from industry is very high. Recycling today may not be able to meet that. This could be balanced with the use of bioplastics but you have to consider land use to cultivate the crops that would be used for bioplastics. That might cause other problems as well. There have been use of biodegradable plastics which might not be good cause it will not easily degrade in nature. However dependence of this is increasing, e.g. for 3d printing.

Some material might be complicated even for chemical recycling. E.g. halogens from PVC should be avoided for pyrolysis. Biodegradable plastic is hard to detect in sorting for and thermosets are hard to be mechanically recycled. Laminated are complicated as well.

Drivers for a change are seen as companies have seen the trend that customers want more recycled material in the products they buy. There are goals of not depending on primary oil-based plastics by 2030. The transition will be slow but it is there there.

### **Researcher E, from University**

This stakeholder works as a researcher at a university. The stakeholder mostly looks at plastic from a leakage perspective.

#### Summary

The recycling chain includes many different aspects, e.g. sorting and collection. To get a new material is just the end part in the chain. In Sweden they often say that we have a certain percent of recycling, when in reality it is collection percentage they talk about. So it is important to be mindful about what words that are being used.

People are not very good at sorting out the plastic, about half of the packaging is sorted wrong. The stakeholder thinks that it could be laziness or that people don't trust the recycling chain. Maybe people know that, e.g. black plastics are difficult to recycle, so then they believe it's better for it to be incinerated. It could also be difficult for people to know whether something should be sorted as packaging or as household waste. There is a miss match, for example if you buy take away packages, which should be sorted at home, but often you are not home when you buy take away products.

### **Researcher F, from University**

The stakeholder is doing research on circular economy in manufacturing. The research on plastic recycling is from a manager and policy perspective.

#### Summary

Mechanical recycling has its limits, there are many fractions of waste plastic waste that cannot be effectively treated with mechanical recycling. This means that some fractions that are collected for recycling, end up being downcycled or even incinerated because of ineffectiveness of mech recycling. However, those can effectively feed in chemical process because the plastic is broken down to its constituent monomers. It is much easier to take out the plastic component and get rid of other chemical components. This will result in a much purer material that can be used again to make new plastics.

For chemical processes to be economically effective they need to have a high feed/input of materials, especially since the technology is more expensive. This means implementing chemical recycling at a regional level is extremely difficult, nearly impossible. It would need to be large and have multiple channels for collecting material, nationally or even internationally.

One important aspect to chemical recycling is the price, the material has to go through a very costly process. You can find the same polymer type that comes from oil industry and that is 5-10 times cheaper. The low price on oil makes it impossible to compete with. Any type of process, be it mechanical or chemical recycling, has many add on costs. And for the market, it is always that the recycled product has to have equal or lower price than the primary oil-based plastic material.

However, if we look at the longer term, say 2045, Sweden has made a commitment to become fossil free country, which means even in the heating sector needs to find alternatives fuels (that does not come from fossil). This mean that plastic can't be incinerated anymore. So, this mean that there will not be any other option than recycling.

### **Researcher G, from University**

Researcher working on a project at a gasification plant in University. Has previously worked on mechanical recycling and has done a thesis on plastic waste from the oceans. Also worked on the GoBiGas project at Chalmers. The interview was aimed to get technical information on the technology

### Summary

Sorting will never be efficient enough. Sorting from the consumer level is not good and there are technological challenges for few grades and colours of plastic material when it comes to sorting in a sorting facility. Mechanical recycling is challenging because it depends on how the waste is sorted. Waste has to be sorted by grade and colour. Additional elements present in plastics also affects the recycling purity. These additional elements include impurities, fillers, plasticizers etc. Apart from those, the plastic could be in contact with contaminants which have to be thoroughly cleaned before recycling. Different types of plastics are used in a single product as well. There are Laminates which use different type of materials blended together in a single product. Given these conditions, there is a clear limit on how much you can mechanically recycle.

However, if there is uniformity in the waste stream, e.g. PET bottles, then those could be still handled by the current system and doesn't have to be sent to chemical recycling. For chemical recycling, pyrolysis is still dependent on how clean the stream of plastic waste fed to it is. Gasification does not depend on the purity of the input stream. So if one were to transition to a system with better material recycling, then there should be both mechanical and chemical recycling.

Sometimes technology is not always the solution. With a project around production of bio-methane, the technology was a success. However, the project did not scale up because the biomethane produced was more expensive than those imported from Denmark. There were incentives given by Sweden for those using that Biomethane because it was an alternate fuel source to fossil fuels. There was no way the prices from

the biomethane production plant could compete with those, proving that there needs to be some government intervention as well.

The product obtained from chemical recycling has to be tested to be used back into production. There are additional steps involved between chemical recycling and using that output back into production. Additional elements present in the stream, e.g. chlorine, Sulphur etc. have to be cleaned or removed in different processes. These elements also pose a threat to the plant itself leading to problems like corrosion or production of unwanted substances that could lead to gradual degradation of the plant. This cleaning could be a challenge as well because it would have to be done on large volumes. Setting this up is an investment as well, making the process even more expensive. The cleaning stage is not completely tested to handle waste stream on a commercial level.

Chemical recycling is better than incineration when it comes to emissions. Pollutants released from both chemical recycling processes are lower than that with incineration. However, the process is energy intensive. Both chemical recycling processes require constant supply of heat. It is not decided how that problem could be handled. Part of the plastic waste could be used but for an overall sustainable recycling process, the energy used has to be from renewables as well.

Prices of the secondary raw material affects the market. At the moment, different types of plastics have different prices. The cleaner the stream, the higher the quality and the price. With chemical recycling, each additional process adds to the price. A techno-economic assessment of the whole project is vital to how feasible a solution chemical recycling will be to handle plastic waste.

### **Researcher H, from University**

Researcher at university on gasification. Have knowledge about technology and about the holistic approach.

#### Summary

The stakeholder believe that chemical recycling is the future and hopes that in the future no sorting will be needed. The stakeholder hence thinks that the sorting companies potentially could be phased out. The positive aspects with chemical recycling is that the material don't need to be downcycled. With mechanical recycled plastic you can feel the degradation of quality with your hands. However there are still some business model aspects that needs to be sorted out before a chemical plant can be commercialized.

### **CEO, from chemical industry**

Working at this company. Also active in a joint collaboration in regards of sustainability with other chemical companies close by. The stakeholder is also on a board for the Extended Producer Responsibility.

#### Summary

The stakeholder describe that their vision is that 2030 their production should be based on renewable and recycled raw material. In the collaboration project is vision driven and they are working together in order to be stronger and gather other partners and collaborations to explore different opportunities. But it is up to each of the individual companies to actually take action and do the work.

The stakeholder say that they see that there is a need to be more circular and that it starts with design. It starts with design of the material and the product or the packaging. They try to cooperate through across the whole value chain, so it is about trying to find solutions for products that today are a bit more difficult to recycle.

From a lifecycle perspective there is better to do mechanical recycling first. However the stakeholder see more push and initiatives coming on chemical recycling now, much more than a year ago. There are still different technologies available and the stakeholder does not know which one is the best and how it would be developed. Regarding ownership of a chemical recycling plant the stakeholder think that there are some different options that can be explored. One option could be that one company is the owner, for example if you make syngas one company might be able to use that. It could also be a joint venture both with companies from the chemical industry but also energy companies and waste handling companies.

The stakeholder thinks that one of the most important things when it comes to recycling is to have a long term access of feed stock. The waste legislation in Europe need to encourage recycling and chemical recycling. The stakeholder think it is possible to work on a circular economy in Europe for plastic. The retailers and everybody also want to have this circular economy so it is a push to go there from many different angles. There is legislation pushing for higher recycling rates , but the stakeholder still think more could be done when it comes to waste legislation in Europe.

### **Managing Director, from waste handling company**

Key actor working in waste handling company in the region. Their stage involves collection of waste from consumers and then redirecting the waste to sorting or incineration. They own some of the incinerator plants in the region. The question asked where to get an understanding of the effects of consumer behavior on the next stages of material recycling. Questions addressing the role of incineration were also asked.

### Summary

Municipalities are responsible for the waste treatment in Sweden for household waste. The consumers pay a fee to handle this waste.

Producers have something called producer responsibility, especially for plastic products. This is done by adding a small fee to the consumers when they buy the product. But if the waste is not sorted by consumers then it ends up being incinerated. The waste handling facilities do not sort plastics out of the waste streams that are not meant to have plastics. There is about 17

When plastics are sent for waste to energy treatment, there is a gate fee that has to be paid as well. Waste to energy recovery also releases carbon dioxide, most of it is from the plastics. So there has to be some way to recycle material over energy recovery.

For Industrial waste, they have to contact a waste handling actor to handle their waste. There is no restriction on who they collaborate with. It could be actors away from their location.

Plastic products are made with a mix of different plastics, metals and other type of materials. This makes it hard to separate and sort. Production of polymers for different industries compared to just plastic produced and collected is different. This needs to be studied when working with chemical recycling.

There are also plastics that cannot be recycled mechanically or even produced because of the use of toxic materials. The ones that have been produced already could be recycled using chemical recycling.

Packaging is supposed to be handled by different actor altogether but it ends up with private waste handling company which is not technically responsible for them. One strategy to discourage waste to energy recovery is by trying to raise the cost of incineration. However there are multiple actors involved and the industries are free to opt for some other agency which could provide cheaper rates. Waste to energy plants in Sweden accounts for 5 %

Lack of market here in Sweden for acceptance of recycled plastic also hinders how much of a driver there is to recycling more of the material than to recover energy. There are also countries elsewhere that offer low prices for landfilling. Some companies or countries opt for this solution and the plastics sent there has been seen to be accounted for material recycling statistics. Regulations are not strict enough to make recycled products for a reasonable cost. Anything is recyclable but it takes time, energy and money to do so. There is also no ban on using fossil fuel based products as well.

However, with the closure of nuclear plants in the country, there might be some more demand for energy recovery but if there are other better reliable options, that would be opted but plastics could provide some fraction of it too. There is some discussion about enforcing a ban of incineration of material that are based out of fossil fuels. Given that there is a lack of market for recycled plastics, this could be a problem if this is suddenly enforced with no clean solution to handle plastic waste.

In the current system, in the sorting facility, about 40-50% Plastic waste for incineration have a few other problems as well. There is problems of corrosion which could degrade the incinerators. Plastics also have high calorific value. So when more plastics are accepted, the other fractions of waste might have to be rejected because there is a limit on how much energy can be recycled as well.

Are steering elements (policies and regulations) addressing the end of stage processes (recycling and energy recovery). But there is not enough being done at the beginning of the chain. That could be vital to helping steer towards sustainable usage and consumption of plastics.



## APPENDIX E

In Appendix E, the result is presented. The result is presented in the based on four categories; cultural, regulatory, market and technology.

### Current system

In this section the challenges to meet the sustainability criteria in the current system is presented.

**Table E.1:** Consumer to collection

Category	Challenges
Cultural	<ul style="list-style-type: none"> <li>• Consumers know that there is no effective recycling of plastic. This is influencing how they sort.</li> <li>• Consumers do not sort the waste efficiently.</li> <li>• There is a lack of knowledge on what and how to sort. For the consumers “plastics are just plastics”.</li> <li>• Sorting plastics is relatively new compared to other products like glass or paper.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• Plastics come under multiple different waste stream, e.g. household waste, packaging waste and WEEE.</li> <li>• The trash bins in the public is only for municipality waste.</li> <li>• Land acquisition to set up collection units becomes a problem with crowded cities.</li> <li>• New EPR doesn't take that into consideration</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Industry waste handled by industry. They are free to partner with any waste handling actor and price becomes a defining factor. Which could lead to long transportations.</li> </ul>

**Table E.2:** Collection to waste handling

Category	Challenges
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Cultural	<ul style="list-style-type: none"> <li>• Different waste stream is leading to wrongful sorting which is leading handling company being responsible for the type of waste they are not suppose to be responsible for. Hence, packaging waste that ends up in household waste is incinerated.</li> <li>• Distributed location of collection and handling units always brings problems related to logistics.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• No regulations to address plastic sent for incineration. Plastic waste not sorted by consumers are incinerated.</li> <li>• Too many waste streams with different collection and handling systems.</li> </ul>

**Table E.3:** Waste handling to sorting

Category	Challenges
Cultural	<ul style="list-style-type: none"> <li>• Material that are not plastics (e.g metals, wood et.c) not removed before sending it to plastic sorting facility. They account for almost 20</li> <li>• Plastic products with contaminants or toxins are not cleaned properly compromising the entire batch. Location of sorting plants raise logistic-related problems.</li> </ul>

**Table E.4:** Sorting

Category	Challenges
Cultural	<ul style="list-style-type: none"> <li>• Data of plastic that is sorted to be recycled is based on trust. Previous instances of manipulation noted. Plastic meant for recycling were sent for incineration elsewhere reflecting wrong data on how much of the material was actually recycled and recycled.</li> </ul>

Regulatory	<ul style="list-style-type: none"> <li>• Sorting companies don't have to keep track of exported/sold plastic. They could end up being incinerated elsewhere.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• There is no market in Sweden for recycled plastic. Hence sorted plastic is exported to central europe, where it is said to be mostly downcycled.</li> <li>• Too many different plastics are used in society both by consumers and manufacturers making it hard to sort.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Too many plastics to sort and technology cant handle everything. Hence there exists a "Mixed plastic" batch which has low value and is mostly incinerated.</li> <li>• Black plastics hard to detect and sort</li> <li>• Has to be cleaned and dried. Consumes time, energy and water.</li> <li>• Mixing of different plastics during sorting can compromise the quality of the whole sorted plastic batch.</li> <li>• Biodegradable plastics hard to detect and mixes with regular plastic waste.</li> </ul>

**Table E.5:** Sorting to mechanical recycling

Category	Challenges
Market	<ul style="list-style-type: none"> <li>• Different prices for different grades of plastics. Some plastics have no economic value in being recycled.</li> <li>• Logistics - Moving from sorting to recycling facility</li> <li>• Different waste streams have to be sent to different recycling centres for recycling</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Plastic has to be sorted based on grade and colour. Mixing of different plastics during sorting can compromise the quality of the whole sorted plastic batch resulting in recycled plastic of poor quality.</li> </ul>

**Table E.6:** Mechanical recycling

<b>Category</b>	<b>Challenges</b>
Market	<ul style="list-style-type: none"> <li>• Mechanical recyclers handle only specific streams of the plastic creating a lower market for them.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Presence of hazardous elements in plastic not cleaned out by mechanical recycling.</li> <li>• Mechanical recycling cannot accept all types of plastics.</li> <li>• Limit on how many times plastic can be mechanically recycled before it loses its properties and becomes unusable leading to drop in its economic value.</li> </ul>

**Table E.7:** Mechanical recycling to plastic product manufacturer

<b>Category</b>	<b>Challenges</b>
Cultural	<ul style="list-style-type: none"> <li>• Hesitance to change the tried and tested way of production which do not consider using recycled raw material</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• There is a lack of support/subsidies to use recycled material for production</li> <li>• For some products recycled plastics can't be used, e.g. for food packaging. This mean that it is difficult to sell recycled plastic to these industries.</li> <li>• There is a lack of certificates assuring quality of recycled plastics.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Today, it is cheaper to use primary oil-based material for plastics than to use recycled material.</li> <li>• There is no real market for recycled plastic in Sweden at the moment. No demand for recycled plastic.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• There is very strict quality demands of the for some input material.</li> <li>• Mechanically recycled plastic is almost always downcycled.</li> </ul>

**Table E.8:** Plastic product manufacturer

<b>Category</b>	<b>Challenges</b>
Cultural	<ul style="list-style-type: none"><li>• Plastics made from oil is cheaper than recycled plastics and companies often will only buy recycled material if it is cheaper.</li><li>• Profit oriented approach with lower goals on intake of recycled raw material (25% material in Volvo where as 100% at IKEA).</li></ul>
Regulatory	<ul style="list-style-type: none"><li>• There are rules for plastics that come in contact with food. Hence they can't use recycled plastics.</li><li>• The producers do not need to design for recyclability. E.g. There are too many types of elements in plastics and no regulations controlling it (except if it is banned) (Groh,2019).</li><li>• When it comes to the EPR scheme, the rules are vaguely formulated and do not clearly specify using recycled material.</li></ul>
Market	<ul style="list-style-type: none"><li>• Acquiring recycled plastic would need quality tests which would add on to expenses.</li></ul>
Technological	<ul style="list-style-type: none"><li>• There is a lack in design for recyclability.</li><li>• There are many different actors involved in designing a product. (The Swedish Ministry of the Environment, SOU 2018:84)</li><li>• The design of products is often complicated. There is e.g. use of laminates, plasticizers, flame retardants etc. making sorting a complicated process.</li></ul>

**New Suggested system**

In this section the challenges to meet the sustainability criteria in the new suggested system is presented.

**Table E.9:** Consumer to collection

<b>Category</b>	<b>Challenges</b>
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Cultural	<ul style="list-style-type: none"> <li>• Consumers do not sort the waste efficiently.</li> <li>• There is a lack of knowledge on what and how to sort. For the consumers “plastics are just plastics”.</li> <li>• Sorting plastics is relatively new compared to other products like glass or paper.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• Too many waste streams, e.g. household waste, packaging waste and WEEE.</li> <li>• The trash bins in the public are only for municipality waste.</li> <li>• Land acquisition to set up collection units becomes a problem with crowded cities. New EPR doesn't take that into consideration.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Industry waste handled by industry. They are free to partner with any waste handling actor and price becomes a defining factor. Which could lead to long transportations.</li> </ul>

**Table E.10:** Collection to waste handling

Category	Challenges
Cultural	<ul style="list-style-type: none"> <li>• Different waste streams are leading to wrongful sorting which is leading handling companies being responsible for the type of waste they are not supposed to be responsible for. Hence, packaging waste that ends up in household waste is incinerated.</li> <li>• Distributed location of collection and handling units always brings problems related to logistics.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• No regulations to address plastic sent for incineration. Plastic waste not sorted by consumers is incinerated.</li> <li>• Too many waste streams with different collection and handling systems.</li> </ul>

**Table E.11:** Waste handling to sorting

Category	Challenges
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Cultural	<ul style="list-style-type: none"> <li>• Material that are not plastics (e.g metals, wood et.c) not removed before sending it to plastic sorting facility. They account for almost 20</li> <li>• Location of sorting plants raise logistic-related problems.</li> </ul>
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**Table E.12:** Sorting

Category	Challenges
Cultural	<ul style="list-style-type: none"> <li>• If sorting is still required in the new system, then data of plastic that is sorted to be recycled is based on trust alone, which could be manipulated as seen in current system.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>• Sorting companies don't have to keep track of sold plastic. They could end up being incinerated elsewhere.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Market acceptance uncertainties still unestablished.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Has to be cleaned and dried. Consumes time, energy and water.</li> </ul>

**Table E.13:** Sorting to mechanical recycling

Category	Challenges
Market	<ul style="list-style-type: none"> <li>• Logistics - Moving from sorting to recycling facility</li> <li>• Different waste streams have to be sent to different recycling centers for recycling</li> </ul>

**Table E.14:** Sorting to chemical recycling

Category	Challenges
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Market	<ul style="list-style-type: none"> <li>• Do the sorting companies want to increase chemical recycling (lose business)</li> <li>• Sorting companies have to consistently meet high volume demand for chemical recycling</li> <li>• Possibility of international/national competition to handle all of the plastic waste which could bring down input volume.</li> </ul>
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**Table E.15:** Chemical recycling

Category	Challenges
Regulatory	<ul style="list-style-type: none"> <li>• No regulations that address chemical recycling as an option for waste handling.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Competition between countries</li> <li>• Input volume has to be high for the system to be economically sustainable, which is not guaranteed.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Time taken to explore the full potential of the system is unknown. There are aspects of the technology that still needs “Fixing”</li> <li>• Different plastics behave differently. The output from the process depends on the type of plastic fed to it. Some grades have elements that are not favorable for some processes (E.g. Chlorides for pyrolysis).</li> <li>• The process is Endothermic and hence needs energy to sustain. Hence can be energy intensive.</li> <li>• Pretreatment and post treatment at the plants will be required to remove undesirable elements.</li> <li>• Maintenance - Who does it and who pays for it.</li> </ul>

**Table E.16:** Chemical recycling to Chemical industry

Category	Challenges
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Regulatory	<ul style="list-style-type: none"> <li>• Chemically recycled secondary raw material is expensive. No subsidies at the moment when buying recycled plastic.</li> <li>• There is no certification to address quality of secondary raw material.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• At the moment, using oil in the chemical industry is cheaper. Recycling is a long process and the secondary raw material will be much more expensive.</li> <li>• Chemical industry requires constant and high feed of raw material. It is not known if chemical recycling can meet those demands, which is seen to be increasing by the year.</li> <li>• Depending upon the location of the chemical recycling plant, there might be need further logistics based problems.</li> </ul>

**Table E.17:** Chemical industry to plastic product manufacturer

Category	Challenges
Regulatory	<ul style="list-style-type: none"> <li>• No policies that promotes usage of recycled plastics for production.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• With the chemical industry spending more to buy secondary raw material for plastic production, buying recycled plastic would be expensive.</li> </ul>

**Table E.18:** Mechanical recycling to plastic product manufacturer

Category	Challenges
Regulatory	<ul style="list-style-type: none"> <li>• There is no certification to address quality of secondary raw material.</li> </ul>

Market	<ul style="list-style-type: none"> <li>• There is still no tested or available market for mechanically recycled material and no guarantees of one in future.</li> <li>• For some products recycled plastics can't be used, e.g. for food packaging. This mean that it is difficult to sell recycled plastic to these industries.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Mechanical recycled plastic might still be downcycled.</li> </ul>

**Table E.19:** Plastic product manufacturer

Category	Challenges
Regulatory	<ul style="list-style-type: none"> <li>• There are rules for plastics that come in contact with food. Hence they can't use mechanically recycled plastics.</li> <li>• No strict regulations for plastic products to be designed for recyclability. E.g. There are too many types of elements in plastics and plastic based products and no regulations controlling it (except if it is banned) (Groh,2019).</li> <li>• When it comes to the EPR scheme, the rules are vaguely formulated and do not clearly specify using recycled material</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Acquiring recycled plastic would need quality tests which would add on to expenses.</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• Products will still need to be designed for circularity to help with sorting and recycling at the end of life of the product.</li> <li>• There is a lack in design for recyclability.</li> <li>• There are many different actors involved in designing a product. (The Swedish Ministry of the Environment, SOU 2018:84)</li> <li>• The design of products is often complicated. There is e.g. use of laminates, plasticizers, flame retardants etc. making sorting a complicated process.</li> </ul>

### **Transitioning to new system**

In this section the barriers and drivers for transition from the current to the new system is presented.

**Table E.20:** Consumer to collection

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Cultural		<ul style="list-style-type: none"><li>• Knowledge about new recycling system, with more effective recycling, might encourage consumers to sort more.</li></ul>

**Table E.21:** Collection to waste handling

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Regulatory	<ul style="list-style-type: none"><li>• Transitioning to the new system with the same complicated waste streams as today, would be challenging</li></ul>	

**Table E.22:** Waste handling to sorting

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
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Cultural	<ul style="list-style-type: none"> <li>• Incineration plants are invested in by the region. May not be in their best interest to move away from incineration.</li> </ul>	<ul style="list-style-type: none"> <li>• Waste handling company representative in favour of material recycling even if it involves less business through incineration. “If it is good for the planet, then we should go for it. Its ok if I lose my job.”</li> </ul>
Regulatory		<ul style="list-style-type: none"> <li>• Cannot use fossil fuels (plastics too) for energy (2030 goals). This could push for sending more material for recycling than incineration.</li> </ul>
Market	<ul style="list-style-type: none"> <li>• In some cases the waste handling companies might still prefer to send the waste abroad.</li> </ul>	<ul style="list-style-type: none"> <li>• Sorting companies buy waste from waste handling companies. More business for the waste handling company.</li> <li>• If recycling companies have a high volume demand than the waste handling companies have larger business opportunities.</li> </ul>

**Table E.23: Sorting**

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Market	<ul style="list-style-type: none"><li>• Sorting companies could also lose business, if chemical recycling takes over.</li></ul>	<ul style="list-style-type: none"><li>• High volume demand from recycling companies means that there is a guaranteed market for the sorted waste, which would be good for their business.</li><li>• If recycling companies have high volume demand, which might have to be met by import of waste, sorting will be still be needed and increased sorting market might be good for their business.</li></ul>
Technological		<ul style="list-style-type: none"><li>• Existing sorting technology is sufficient to sort for higher demand. Also extensive strict sorting is not needed. Higher business possibilities and bigger market with no upgrade on technology.</li></ul>

**Table E.24:** Sorting to mechanical recycling

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Regulatory		<ul style="list-style-type: none"><li>• Cannot use fossil fuels (plastics too) for energy (2030 goals). This could push for sending more material for recycling than incineration</li></ul>
Market	<ul style="list-style-type: none"><li>• There might be a competition on who the sorted waste (or all of plastic waste) should go to.</li></ul>	

**Table E.25:** Sorting to chemical recycling

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Cultural	<ul style="list-style-type: none"><li>• Sweden is so based on incineration today which is a barrier to transitioning to chemical recycling (reason: heating is required).</li></ul>	
Regulatory	<ul style="list-style-type: none"><li>• New set of regulations not defined.</li></ul>	

Market	<ul style="list-style-type: none"> <li>• Do the sorting companies want to increase chemical recycling or will it jeopardize their business?</li> <li>• To have high input volume, chemical recycling needs to be able to get plastic waste from the different waste streams. If each stream chooses to work differently, then the market for chemical recycling will be small, making it less economical</li> <li>• The plastic waste stream is very segregated into smaller streams (Packaging, Household, WEEE, automotive etc.), which have their own collecting and handling systems.</li> <li>• Unless chemical recycling can get waste from everyone, the input volume might be small.</li> </ul>	<ul style="list-style-type: none"> <li>• There is a market for the mixed plastic.</li> <li>• The sorting companies have a market in Sweden, which</li> <li>• reduces logistic costs and emissions.</li> </ul>
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**Table E.26:** Chemical recycling

Category	Barriers	Drivers
Cultural	<ul style="list-style-type: none"> <li>• Hesitance from uncertainty of the technology. It isn't tried and tested to be commercially established.</li> <li>• Uncertainty based on maturity there is uncertain on how long it would take to establish a commercial chemical recycling plant.</li> </ul>	<ul style="list-style-type: none"> <li>• There has been shown to be a willingness to cooperate and collaborate between different actors.</li> <li>• New job opportunities would arise with a chemical recycling plant</li> </ul>

Regulatory	<ul style="list-style-type: none"> <li>No policies taking chemical recycling into consideration so far.</li> </ul>	<ul style="list-style-type: none"> <li>Chemical recycling can be a solution for fossil independent chemical industry/society. Is a way to meet the 2045 targets.</li> </ul>
Market	<ul style="list-style-type: none"> <li>There is uncertainties regarding the ownership of the chemical recycling plant. Chemical recycling has to have big volumes to be economically profitable.</li> <li>Multiple actors' collaboration might be needed to share the economic risk.</li> <li>There is no business model for setting up a commercial recycling plant.</li> <li>Multiple countries are setting up chemical recycling plant, all of which have high volume demands. Hence there might be international competition.</li> </ul>	<ul style="list-style-type: none"> <li>Ongoing interest in the process and technology from multiple actors and research institutes handling a variety of research projects and small pilot tests.</li> <li>New projects have funding to run tests as well.</li> </ul>

**Table E.27:** Chemical recycling to Chemical industry

Category	Barriers	Drivers
Cultural	<ul style="list-style-type: none"> <li>The model is not tested and this could lead to hesitance to accept this at the chemical industries.</li> </ul>	

Regulatory	<ul style="list-style-type: none"> <li>• There are no policies to economically support chemical recycling.</li> <li>• No policies addressing Syngas or pyrolysis oil for production in chemical industry (Current policies address recycled contaminated plastic cannot be used in certain products)</li> <li>• There are no certifications on quality</li> </ul>	
Market	<ul style="list-style-type: none"> <li>• There is a need for a Constant Volume inflow on material.</li> <li>• The secondary raw material will be expensive because of the long process involved.</li> <li>• “Even with all waste collected, they cannot meet demand of industry” and “demand for plastics is only increasing by the year”.</li> </ul>	<ul style="list-style-type: none"> <li>• The quality of the recycled material can match oil for purity/quali</li> <li>• The secondary raw material produced has a potentially wide market</li> <li>• Since quality close to primary oil-based plastic material, can be used for food packaging.</li> <li>• If located near chem plant, then easier to access raw material. Lesser logistics required.</li> </ul>

**Table E.28:** Chemical industry

Category	Barriers	Drivers
Cultural		<ul style="list-style-type: none"> <li>• There are already ongoing collaboration.</li> <li>• There seems to be willingness to change existing system.</li> </ul>
Regulatory		<ul style="list-style-type: none"> <li>• Chemical recycling can be a solution for fossil independent chemical industry/society. Is a way to meet the 2045 targets</li> </ul>
Market	<ul style="list-style-type: none"> <li>• There are high demand in volume input.</li> </ul>	<ul style="list-style-type: none"> <li>• The raw material source is within the country. Hence no logistics based complications</li> </ul>
Technological	<ul style="list-style-type: none"> <li>• There are multiple process for chemical recycling with different benefits and challenges.</li> <li>• While parts of the technology is tried and tested, at small pilot plants and for different applications, the large scale process for commercially recycling plastics is not tested.</li> </ul>	<ul style="list-style-type: none"> <li>• No changes to existing production method is required to accept the recycled raw material</li> </ul>

**Table E.29:** Chemical industry to plastic product manufacturer

Category	Barriers	Drivers
Regulatory		<ul style="list-style-type: none"> <li>• Company and regional goals are in favour of using more recycled raw material for production. Chemical recycling can help achieve those goals without compromising on the quality</li> </ul>
Market	<ul style="list-style-type: none"> <li>• Plastic made from chemical recycling will be expensive because of the longer process involved in it's material recycling.</li> <li>• Market uncertainty. Currently the market for recycled plastics is almost negligible and it is uncertain if that would change even with a new system</li> </ul>	<ul style="list-style-type: none"> <li>• The mass balance principle could make it easier to switch out virgin material gradually.</li> <li>• With chemical recycling the producers can sell good quality products from recycled material. Could be used as marketing tool.</li> </ul>

**Table E.30:** Plastic product manufacturer

<b>Category</b>	<b>Barriers</b>	<b>Drivers</b>
Cultural		<ul style="list-style-type: none"> <li>Many companies are promoting usage of recycled material in their products and increasing the goal margins by the year. Thus, it is seen that there is a potential market in the future.</li> </ul>
Regulatory	<ul style="list-style-type: none"> <li>The regulations today don't allow for using recycled plastics in some products. The regulation does not differentiate between mechanical and chemical recycling.</li> </ul>	
Market	<ul style="list-style-type: none"> <li>Market uncertainty. Currently the market for recycled plastics is almost negligible and it is uncertain if that would change even with a new system.</li> </ul>	