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Chemical recycling

a potential solution for Sweden's plastic recycling industry in the transition to a circular economy?

A Multi-level Analysis

by

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Abstract

Although Sweden collects and sorts a large share of plastic waste, a significant part of the separately collected plastic packaging waste is being incinerated and only 8 % of the plastic waste is being recycled into new products. As plastic is the main cause of greenhouse gas emissions from waste incineration, a systematic shift is needed to decrease incineration. Currently, Chemical recycling (CR) is being developed to break down plastic waste to smaller molecules, which can be built up to new plastics and/ or chemicals depending on technology. However, there are no-full scale CR projects in Sweden but a few demonstration projects covering depolymerisation of PET bottles, gasification and pyrolysis in Stenungsund. This study uses the multilevel perspective (MLP) framework to understand and contextualize Sweden's plastic recycling industry and the chemical recycling sector´s opportunities and obstacles. The results show that the current industry is facing multiple obstacles related to both economical, technical and regulatory aspects. Sweden's recycling industry is characterized by having an overcapacity of incineration, a malfunctioned market for recycled plastic, a resistance to change and a policy framework and infrastructure that does not facilitate the development of CR. How a transition to a circular economy of plastic will look like and which transition pathway Sweden will take will highly depend on whether the recycling industry can overcome the identified challenges within the current industry.

Key words: Plastic recycling; Chemical recycling; Circular economy; Transition; Multilevel framework

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Abbreviations

CCU - carbon capture and utilization

CE - circular economy

CR - chemical recycling

GHG - greenhouse gas

IVL - the Swedish Environmental Research Institute

LCA - life cycle assessment

MLP - multi-level perspective

PE - polyethylene

PET - polyethylene terephthalate

PP - polypropylene

PS - polystyrene

SEPA - the Swedish Environmental Protection Agency

WFD - Waste Framework Directive

1. Introduction

1.1 Background

The mass production of plastic started already in the 1940s, and with plastic's unique properties and usage, one might think that plastic is fantastic (Knoblauch, 2009). However, every year, more than 380 million tonnes of plastic is produced globally where half is used as single-use plastic such as shopping bags, straws and bottles (Ritchie & Roser, 2018). As a result, plastic pollution has become a global concern as waste ends up in oceans, on landfills and in rivers (Parker, 2019). With current linear framework of take-make-waste, we could have more plastic than fish in the oceans by 2050 (Ellen MacArthur Foundation, 2016). The global plastic waste crisis has prompted the call for a systemic shift towards a circular economy for plastics, meaning that we keep the value of plastic in a "closed loop" with no leakage to the natural environment (Ellen MacArthur Foundation, 2016). Waste management and the recycling industry is the most practiced way to promote a circular economy as recycling is considered to be the best solution to keep plastic in a closed loop. However, it has also been criticized for its limitations (Ghisellini, P., Cialani, C., & Ulgiati, 2016; Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M., 2015) and a wide range of bottlenecks (Hahladakis & Iacovidou, 2019). Current recycling capacities and technologies such as mechanical recycling cannot deal with the millions of tonnes of contaminated, multi-layer and mixed plastic waste produced every year. The technology is accompanied with degraded plastic properties (i.e down cycling), which emphasize that alternative ways to recycle plastic needs to be found (Ragaert et al. 2017).

To support a sustainability transition towards a circular and resource-efficient economy, waste management and chemical sectors are anticipated to play important roles, especially since new technological innovations within recycling are being developed (Lee et al. 2021). Chemical recycling (CR) has emerged as a niche innovation within the industry with high potential to close the material cycle as it can convert plastic polymers into "chemical building blocks" (i.e polymers or monomers) that are then used again as a raw material in chemical processes making new plastics (CEFIC, 2020a). This means that CR can handle plastic waste that today goes to incineration that mechanical recycling cannot handle (Ritchie & Roser, 2018). However, whether this new technology can be a complement to mechanical recycling will highly depend on whether Sweden's recycling industry can overcome current obstacles and push for an attitude change towards seeing all plastic waste as a valuable material (SEPA, 2021a). Despite being a leader in waste management and a strong innovation nation, 51% of the plastic waste handled in 2017 was in the form of unsorted streams and not suitable for mechanical recycling. The majority (85.5%) was sent to incineration with energy recovery (waste-to-energy), hence valuable resources are being lost and CO2 emissions are released to the air (Ljungkvist Nordin et al. 2019). As plastic is the main cause of greenhouse gas (GHG) emissions from waste incineration, a systematic shift is needed to decrease incineration as it is not part of circular thinking and increase recycling rates (SEPA, 2021a). Especially because Sweden's long-term goal is to have zero net GHG emissions by 2045 and recycle 55% of the plastic packages by 2030 (Ministry of the Environment and Energy, 2017).

Even if the unsustainable situation with plastic has led to a growing interest in studying alternative recycling technologies such as CR (Angyal et al. 2007; Kumar et al. 2011; Okuwaki, 2004), less focus has been given to Sweden. The majority of studies within CR focus on the benefits and downsides with the technologies from an EU perspective and its potential is discussed from an environmental perspective, taking a life-cycle analysis (LCA) or material flow analysis approach. Few attempts have been made analyzing Sweden's recycling industry and the new technology of CR from a transition perspective using the Multi-Level framework (MLP) which is a commonly used approach when analyzing sustainability transitions. With the MLP a comprehensive 3-level analysis can be made and one can gain an understanding of Sweden's plastic recycling industry and the CR sector´s opportunities and obstacles and the interactions between the current industry, CR sector and external forces. By gaining insights from experts in the field as well as knowledge from previous projects, it is possible to understand what role CR can play as a potential solution in the transition towards a circular economy.

1.2 Aim & Research Questions

The aim of this study is two-fold. First, to fill in the gaps of the literature and analyze current obstacles within Sweden's recycling industry viewed from different stakeholder perspectives. Second, investigate whether CR of plastic can be a possible solution for Swedish in the transition towards a circular economy of plastic. Further, considering the complexity of a new technology such as CR and the movement towards a circular economy, this study does not aim to deliver final solutions to the waste management problem in Sweden. It rather aims to provide evidence that current obstacles facing the plastic recycling and CR sector are complex and can differ between stakeholders.
To do so, the following research questions seek to be answered;

- ➢ How can the CR be understood under the MLP?
- ➢ What are the main challenges for developing the CR sector, and how do these perspectives differ across stakeholders?
- ➢ Which role can CR play in the transition to a circular economy in Sweden?

To answer the research questions, data is collected from both previous national project reports published by SEPA covering CR developments and semi-structured interviews with industry experts. This study employs the MLP framework, a well established framework within the sustainability transitions research (Geels, 2002; Geels & Schot, 2007). By using the MLP as an analytic framework, the interview data, from industry experts, can be analyzed from the three-levels of regime, niche and landscape, that describes the characteristics, dynamics and current obstacles within the plastic recycling industry as well as the potential of CR.

When considering the collected data and methodology, it is important to highlight the limitations with this study. When collecting data from interviews, both the researcher and participant bias needs to be taken into account and to further increase the data validity a review of previous project reports covering CR in Sweden has been triangulated with the interview data.

Further, this study does not focus on technical aspects of CR or evaluate a specific technology. No global comparison is being made comparing different countries as CR developments are national and context dependent, hence only a Swedish perspective is taken. The results of this study might therefore be of interest to all actors within the plastic value chain in Sweden and practitioners within innovation and sustainability. Likewise, policymakers might also be interested in the results and

analysis to gain a deeper understanding of how CR can enable circularity and what the main obstacles are to further develop the technology. As we need an urgent transition to a circular economy and speed up the work towards SDG 12, Sustainable consumption and production, this study will also contribute with knowledge and insights regarding the work with Agenda2030.
Finally, as this study focuses on the industry perspective, a discussion about the role of households is limited.

1.3 Outline of the study

This study consists of seven parts including the introduction, literature review, theoretical approach, the case of Sweden, methodology, theoretical analysis & discussion and finally, conclusion. The following section of background is necessary to fully understand the current plastics waste recycling system in Sweden and its imperfections. In addition, a general presentation of CR is given to cover current developments, technologies, actors and regulations. The literature review presents sustainability transition research, and the MLP framework followed by current research within the field of CR globally and in Sweden. As the MLP is used as an analytic framework in this study, a more detailed explanation of the MLP is given under section four, theoretical approach. The research design, sample, data collection method and analysis is then described in section five. In the theoretical analysis & discussion section, the Swedish recycling system is being analyzed within the MLP framework based on the collected data and the main results are presented. Finally, section seven provides the reader with conclusion and policy recommendations.

2. Literature review

The following literature review provides an overview of the literature within sustainability transition research and the developments within the MLP framework. As the MLP has been applied as an analytic framework within multiple industries, waste management- and CR- research is being reviewed. Finally, based on the current MLP- and CR- studies, a research gap is identified and discussed.

2.1 Sustainability transition literature & MLP

Sustainability transition studies have received increased attention over the past decades within social-sciences and emphasizes the need for fundamental changes in systems and structure (Geels, 2002; Smith et al. 2010; Markard & Truffer, 2008; Grin et al. 2010). Most of the literature focuses on different sectors such as energy (Geels et al. 2011, Schreuer et al. 2010), transportation (Yuan et al. 2021), the water sector (Gleick, 2003) and food sector (Meynard et al. 2017). Hence sustainability challenges emerge and can be identified in all industries with strong path-dependency and lock-ins (Åhman & Nilsson, 2008). Technological development and radical changes will therefore be crucial to cope with in the prevailing sustainability challenges (Markard et al. 2012; Markard & Truffer, 2008).

Within the broad transformation literature that combines insights from Science, technology and society (STS) studies and evolutionary economics (Nelson & Winter, 1982; Van den Bergh & Growdy, 2000) there are 3 main approaches; System transformations, Structural approaches and Enabling approaches. The system transformation is therefore the broader framework within sustainability transition studies that can further be divided into transition management (Kern & Smith et al. 2008; Loorbach, 2010), niche management (Kemp et al. 1998; Raven & Geels, 2010) and the Multi-level perspective (Geels, 2002; Geels & Schot, 2007; Smith et al. 2010).

Within the sustainability transition literature, the MLP framework (Geels, 2002) is built upon the concepts of 'technological regimes' and 'technological trajectories', first introduced by Nelson & Winter (1982) and then further enhanced by Rip & Kemp (1998) were they focused on the micro, meso and macro perspective. Meanwhile, Geels further developed the MLP framework and provided an analytical and heuristic concept to understand complex dynamics and transitions of socio-technical regimes (Geels, 2002). It has since then been a tool to analyze and "understand the complex dynamics of sociotechnical change" (Geels, 2002, p.1259). The central concept of socio-technical regimes consists of actors, networks, institutions, norms and regulations (Geels, 2004; Markard et al. 2012). Not only does the concept include changes from a technical dimension, it also includes changes in user practices and institutional (e.g., regulatory and cultural) structures. (Markard et al. 2012). Frank Geels was interested in understanding how traditional industries (eg. ship building) transformed over time by looking at the interplay between new actors and technologies with the current industry and dominant technologies. The framework of Geels (2002) has been dominant as he introduced the MLP, which conceptualizes overall dynamic patterns in socio-technical transitions, widely applied to a variety of studies in sustainability transitions both in the global north and in the global south.

The MLP framework has been applied in multiple studies covering industries such as metals (Jackson et al. 2014), iron and steel (Karakaya et al. 2018), renewable energy (Finn et al. 2020) and waste management (Salmenperä, 2021; Lozano & Gasparatos, 2019; van Dijken, 2019). Waste management emerges as one of the dominant fields, especially covering plastic due to the pressing global environmental concerns of plastic pollution (Lozano & Gasparatos, 2019; van Dijken, 2019; Salmenperä, 2021). Salmenperä (2021) compared the recycling society in Austria, Sweden and Finland and analyzed potential pathways for a circular economy. Common for all countries were the lock-in´s (at the regime level) excessive incineration capacity, malfunction of market for recycled plastic and lack of product design for recyclability. The author also argues that the recycling market is global and not limited to the borders of one country hence the incentives for national politicians to increase recycling rates may be too weak (Salmenperä, 2021).

2.2 Chemical recycling studies/ case studies

During the past few years, the applicability of CR to promote a circular economy has been driving CR research (Meys et al. 2020, Ragaert et al. 2017, Hong & Chen, 2017), the global socio-political debate (CEFIC, 2020a; ZeroWasteEurope, 2020) and various projects have been launched. In the scientific literature CR is considered as tertiary recycling, meaning that it covers both the recovery of plastics and the production of fuels and other substances (Lee & Liew, 2021; Solis & Silveira, 2020). Thus, the concept of recycling is broader than defined in the Waste Framework Directive (European Parliament, 2008). However a number of studies (Manžuch et al. 2021; Solis & Silveira, 2020) highlights that the definition of CR is unclear and that there is a lack of consistency within the regulatory framework. The European Chemical Agency report from 2021 concluded that the lack of clarity and consistency within the definition of CR can lead to a confusion about the potential of CR in a circular economy (Manžuch et al. 2021).

The majority of research within CR analyzes the benefits and downside using LCA as well as current technological development (Jeswani et al. 2021; Meys et al. 2020; Solis & Silveira, 2020). Lee et al. (2021) investigated stakeholders' perception of CR, the advantages, obstacles and its role in the transformation to a circular economy in Germany. The results highlight that the main advantages of using CR relates to resource conservation and reduction of CO2 emissions, meanwhile the main obstacles include high cost, process efficiency, input considerations and a lack of a regulatory framework (Lee et al. 2021). The need for a clear regulatory framework to support developments within CR is also emphasized by BASF, the leading chemical producer in Germany (BASF, 2020). At EU level, Zero Waste Europe (2020) highlights the need of funding and investments to support CR technology to ensure a transition to a circular economy. The European Chemical Agency report from 2021 also highlights the lack of clarity and consistency when it comes to the definition of CR and it leads to a confusion about the potential of CR in the circular economy.

There are a few studies that focus on the implementation of CR in Sweden and its potential (Solis, 2018; Fråne et al. 2015; Thunman et al. 2019a; Solis et al. 2021; Lassesson et al. 2021). Solis (2018) concluded that the main challenges are of economic and political nature, and include low supply and demand for recycled plastics, need for clear regulatory framework and uncertain costs. Whether there will be a successful full scale implementation of CR will highly depend on new developments of business models that can generate economic benefits to all actors in the plastic recycling chain (Solis, 2018). However, Thunman et al. (2019a) take a more technical approach and argues that it is both technically and economically feasible for a full scale implementation of CR by using the existing infrastructure of the petrochemical cluster in Stenungsund. The study shows that switching feedstock from virgin fossil fuels to plastic waste confers economic advantages. To ensure that these CR facilities get enough input material, mixed or sorted plastic waste, there is a technical possibility to mix plastic waste with biomass, hence lowering the amount of plastic waste needed. However, the economic feasibility of a full transformation will highly depend on the context and regulatory framework of business and the political drivers related to reducing CO2 emission from incineration facilities (Thunman et al. 2019a). Both Solis (2018) and Thunman et al. (2019a) highlight the importance of developing and investing in CR since it will play an important role in the transition to a circular economy in Sweden.

Whether CR can increase recycling rates is further discussed in the SEPA report from 2021. The main obstacles identified are similar to obstacles facing mechanical recycling, i.e high costs, how to stimulate the demand for recycled plastics and how to steer plastic waste streams away from incineration (SEPA, 2021b). Different policy recommendations have been discussed in the report by Bjerkesjö et al. (2021) with the aim of increasing recycling rates for plastic. The study consisted of two workshops with industry experts and relevant actors within the plastic value chain in Sweden. The main concerns from the discussions is the low demand for recycled plastics and the unclear definition whether CR can be considered as material recycling. The policy recommendation that was considered the most important to spur investments in CR were; a regulatory clarification that CR is considered as material recycling and a requirement that new plastic products must consist of a share (%) of recycled plastic (Bjerkesjö et al. 2021).

Lassesson et al. (2021) looked into possibilities of developing a CR facility in Sweden, what kind of plastic waste streams could be relevant and identified the main obstacles. The results shows that current infrastructure is based on virgin plastic production and treatment methods such as mechanical recycling and incineration. Hence the industrial actors interviewed in this study pointed out that they see a lack of long-term perspective and policy instruments that can steer away from fossil raw materials and away from the incineration of plastics, towards recycling (including CR) (Lassesson et al. 2021).

To be able to examine whether CR will be successful or not, the environmental aspects need to be considered. This is why the majority of studies within CR take a Life-cycle approach (CE Delft, 2019; BASF SE, 2020; Davidson et al. 2021; Meys et al. 2020; Jeswani et al. 2021; Shen et al. 2010). CE Delft (2019) found that the climate change benefits differ per CR technology and input waste stream. However, a combination of mechanical and CR will increase recycling targets and reduce the emissions coming from incineration and landfills (CE Delft, 2019). BASF (2020) compared incineration with chemical recycling and found that chemical recycling (pyrolysis) of mixed plastic waste emits 50% less.

Rahimi & García (2017) argues instead that it is hard to evaluate the full environmental impact due to the novelty of the technology (Rahimi & García, 2017). Jeswani et al. (2021) found that pyrolysis is better than incineration in terms of CO_2 emissions but the analysis revealed that the environmental impact depended on the quality and composition of plastic waste. They concluded also that pyrolysis should be considered as a complementary technology to mechanical recycling as it would prevent plastic waste going to incineration. Pyrolysis is the most researched CR method in LCA studies and is often highlighted as the best CR technology (Davidson et al. 2021; Shen et al. 2010). These results are supported by Meys et al. (2020) who compared the performance of different CR technologies and concluded that CR (pyrolysis) is better in terms of saving GHG emissions compared to incineration but still mechanical recycling is prefered over CR due to the high amount of energy that is needed (Meys et al. 2020).

2.3 Research Gap

However, few attempts have been made analyzing the obstacles within the recycling industry and chemical sector in Sweden using the MLP framework since most prior studies are taken from an environmental perspective hence using LCA or Material flow analysis. Yet, the majority of studies also take a technical approach, therefore, this study aims to emphasize the transition literature and the MLP. Whether or not CR can be a potential solution in the transition to a circular economy in Sweden, it is of high priority to study the current industry and niche innovation of CR using the MLP framework. Much of the research within waste management and the circular economy is focused on technological issues and fails to take a systemic approach into account.

3. Theoretical Approach

This section provides the reader with an in-depth description of the Multi-Level Perspective (MLP) framework as part of the sustainability transitions theory. Further, some of the main critiques to the MLP found in the transition literature are explained.

3.1 The Multi-level framework

The MLP is based on 3 central pillars; the *sociotechnical regime, the landscape,* and *the niches* (Rip & Kemp, 1998; Geels & Schot, 2007; Geels, 2002) The *socio-technical regime* is the central piece of the MLP (see *Figure* 1) and represents the current system consisting of established actors, industrial networks and current rules and regulations. Thus, their knowledge, practices and current state of technology, cultures and behaviors also characterize the socio-technical regime. Innovation in an already existing regime is mostly in line with already existing technologies and mainly incremental improvements happen, i.e no radical change takes place (Geels, 2002). A socio-technical regime creates stability due to linkages between heterogeneous groups and shared cognitive routines. Key characteristics of the socio-technical regime are resistance to change, path-dependency and lock-in mechanisms (Geels, 2002). The lock-in mechanisms can be sunk investments in machines, infrastructures or more in general mis-matches between the current regime and niche development (e.g lack of appropriate infrastructure, regulations or consumer practices) (Geels, 2002).

The *landscape* is the external larger context that influences the national systems and contains a set of heterogeneous factors, such as oil prices, economic growth, the climate crisis, political coalitions, norms and cultural values. Changes at the landscape level usually is a slower process than at the socio-technical regime level, hence the landscape developments are illustrated with long thick arrows (see *Figure* 1). Changes at the landscape level will put pressure on the current socio-technical regime and create openings for new technologies. However, if the landscape puts a weak pressure, niches will need to be mature, and likely exist in high numbers to pose a threat to the current socio-technical regime (Geels, 2011).

The *niches* are the incubation spaces or “protected spaces” where innovation takes place by actors at the fridge of the regime. Some examples of these spaces include R&D laboratories and different demonstration projects. Niche-actors such as start ups, scientists and entrepreneurs and small tech-networks hope that their new innovative technology can eventually be used in the current regime or even replace it. However, as the current regime is stabilized by lock-in mechanisms and niche-innovations may have lack of infrastructure, not enough supportive regulatory framework, it may not be easy (Geels, 2002). Kemp et al. (1998) and Geels & Schot (2007) focus on niche innovation and highlight that building social networks and including more actors is important to expand the resource base of niche innovations. Yet, learning about market demand, infrastructure requirement and what kind of policy instrument is needed.

The relationship between the landscape, the regime and the niche are usually represented by a nested hierarchy as illustrated in *Figure* 1 by Geels (2002) where the regimes are embedded within the landscape and the niches within the regimes. One could also interpret the niches that form the micro-level, the regime forms the meso level and the landscape, the macro level of analysis.

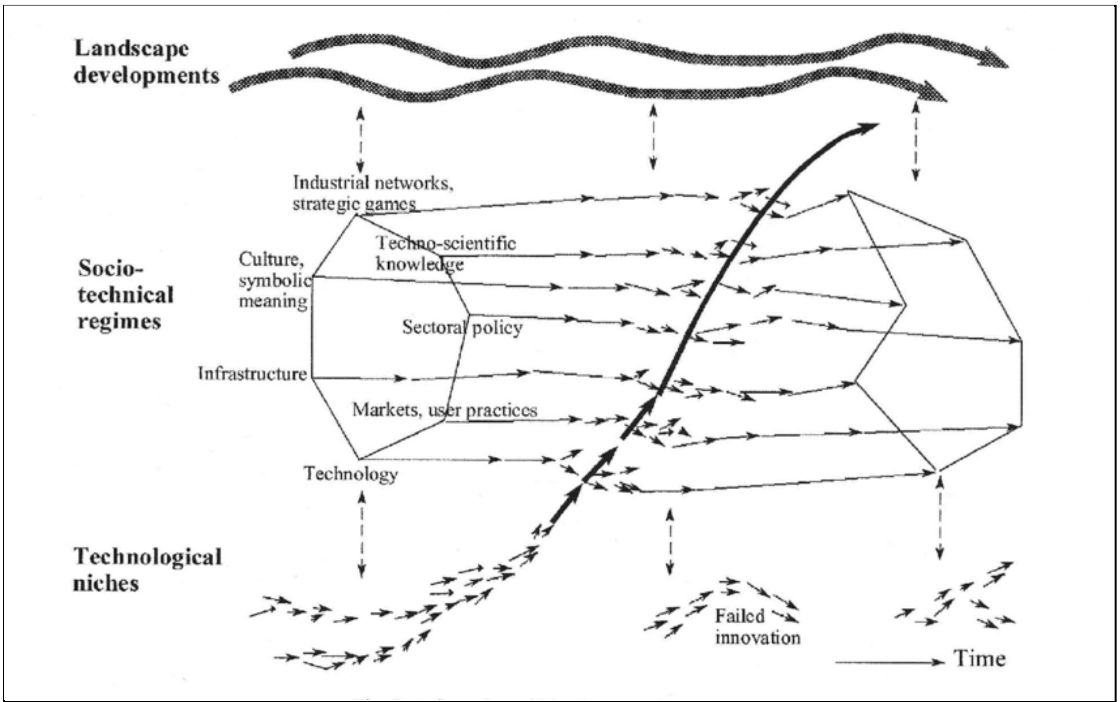

Figure 1 - The Multilevel perspective (Adopted from Geels, 2002 p.1263)

If conditions are adequate, meaning that the landscape puts enough pressure on the current regime and niches are mature, niche innovation may challenge the regime and "windows of opportunity" are created (Geels, 2006). Therefore, an important point of the MLP is that new technology can not only be successful if one considers developments only within the niche (Geels, 2002). A transition of a system is then defined as "regime shifts" that are triggered by the interaction between the landscape and the niches of the regime. New technologies in their early phase developed within the niches usually connect with established technologies in order to solve bottlenecks. Thus, old and new technologies act in symbiosis rather than in competition (Geels, 2002). Nevertheless, Geels & Schot (2007) argues that the relationship between niche innovations and the current socio-technical regime can both be *competitive* (aiming to replace it) or *symbiotic*. The latter is a similar understanding to Geels (2002) where the niche innovation can be adopted as a competence-enhancing add-on to the existing socio-technical regime to improve performance.

Different transition pathways can be identified depending on how the interaction evolves between the niches, the regime and the landscape. Timing (the niche "readiness") and the nature of the niche interaction (substitute or complementary) is therefore important. Geels & Schot (2007) identified five different transition pathways based on the timing and interaction; Reproduction; Transformation; De-alignment & Re-alignment; Technological substitution and Reconfiguration.
Reproduction process - lack of external landscape pressure and the regime remains stable. Due to the stability of the current regime it has sufficient problem-solving potential to deal with obstacles and over time incremental change will help boost performance (Geels & Schot, 2007).
Transformation path - If the landscape pressure is moderate and the niche innovation is not yet fully developed, "new regimes grow out of old regimes through cumulative adjustments and reorientations" (Geels & Schot, 2007, p. 407). An important factor is the outside actors where social movements or

scientists play a key role as they draw attention to negative externalities, which the regime insiders tend to neglect (Fens, 2020).
De-alignment & re-alignment path - There is a large change in the landscape that quickly puts pressure and creates problems in the regime, eventually causing the regime to collapse and de-align. Uncertainty arises in the current regime and multiple niche-innovations are highlighted by outsiders. One of the niche innovations will be dominant allowing for the re-alignment of a new regime (Fens, 2020; Geels & Schot, 2007).
Technological substitution. - high landscape pressure and mature niche innovation will break through and replace the current regime thanks to "windows of opportunity". A radical niche innovation exists and replaces current technology (Geels & Schot, 2007).
Reconfiguration pathway - Radical innovations that are symbiotic to the current socio-technical regime and can be accepted if the niche innovation can solve current obstacles. This pathway is of high relevance to industries using multiple technologies, such as agriculture and hospitals, as the transition is not driven by the advancement of one innovation (Fens, 2020; Geels & Schot, 2007).

A transition is not a linear process due to the complexity hence it is more a result of interactions between changes happening at both the landscape, regime and niche level (Geels, 2019). A transition, especially to a circular economy of plastic, is also a slow process that will include stagnant periods and obstacles preventing the change. It is therefore important to understand the transition to a circular economy and what is needed to be able to remove lock-ins and for policy makers to govern it (Salmenperä, 2021). The majority of the literature that use the MLP as a analytic framework when analyzing sustainability transitions focus on specific subsystems (energy/mobility sector) and the empirical analysis are usually applied at national level (eg. energy transition in the netherlands). Case studies using the MLP goes from sailing ships to steamships (Geels, 2002), Switzerland's transition from industrialized agriculture to organic farming (Belz, 2004) to the energy sector in Scotland and renewable energy (Finn et al. 2020).

3.2 Critique to the MLP

The main critique to the MLP framework is that the analysis mostly focuses on a single regime that receives pressure from both niche innovations and the landscape (Raven, 2012). Raven (2012) and Genus & Coles (2008) highlights that it may be of relevance to analyze multiple regimes and the interactions between them in the context of sustainability transitions (e.g to a circular economy).
From an empirical point of view, Berkhout et al. (2004, p. 54) argue that it is not clear how these conceptual levels of socio-technical regime, landscape and niche should be applied empirically as a
a sociotechnical regime could be defined at one of several empirical levels. This implies that a regime shift can be viewed differently, what looks like a regime shift could be viewed as an incremental change instead (Berkhout et al. 2004; Geels & Schot, 2007).

4. The case of Sweden

In order to understand how the innovation of CR will develop in Sweden's recycling industry, it is necessary to fully understand the current plastics waste recycling system and its imperfections. This chapter introduces the current plastic recycling system in Sweden, i.e the main actors, processes, technologies and regulations. Moreover, CR is being introduced to provide an understanding of the innovation, the different technologies, current state of the market, involved actors and the environmental aspects.

4.1 Waste management in Sweden

Sweden is considered as a global leader when it comes to sustainable waste management (Folk, 2021). This is thanks to gradual changes in the delegation of responsibility and the development in waste management systems (SEPA, 2012). The legal basis of Swedish waste management follows the European waste legislation and the waste hierarchy (see *Figure* A1, Appendix A), meaning that the priority for managing waste consists of; prevention, re-used, recycling, energy recovery, and the least preferred option of landfill/disposal (European Commission, 2020).

The waste statistics from Ljungkvist Nordin et al. (2019) show that three of seven national recycling targets for packaging were met in 2020, for glass packaging, and metal packaging of aluminum and steel respectively (see *Table* 1). This indicates that recycling rates for plastic (plastic packaging) are substantially lower and far behind other common materials in our society.

Table 1 - Packaging put on the Swedish market, recycling rates and recycling targets (Ljungkvist Nordin et al. 2019).

Type of packaging material	Added to the market (tonne)	Recycled (tonne)	Recycled (%)	Recycle targets (%) by 2030
Glas	233 000	217 900	94%	90%
Plastic (incl. PET)	248 800	84 500	34%	55%
PET-bottles	27 800	23 900	86%	90%
Paper, cartongs	604 200	471 100	78%	85%
Steel	28 600	23 700	83%	70%
Aluminium	31 200	25 300	81%	50%
Pant-bottles of aluminium	23 500	20 400	87%	90%

Note: The data is based on the producer's responsibility for packaging in Sweden.

The collection system for plastic waste consists of both curbside collection programs, bring-sites and recycling centers but can differ between municipalities. After the plastic waste has been collected from curb-site, bring-site or from recycling centers, it is transported to sorting facilities where the plastic waste is being sorted (The Swedish Waste Management and Recycling, 2020). According to Ljungkvist Nordin et al. (2019) approximately 1.7 million tonnes of plastic waste was generated in Sweden (including imports) between 2016 and 2017, where 1.31 million tonnes was sent to incineration (waste-to-energy) and 6 thousand tonnes ended up in landfill (see Figure 3). Only 10-20% of the mapped plastic waste is being recycled as new raw material within the geographical area of Sweden (PET and plastic packaging). Plastic from electronics and parts of the collected plastic packaging quantities are being exported to other countries for recycling, mainly to Germany

(Ljungkvist Nordin et al. 2019). However, Sweden´s plastic waste exports have decreased since 2010 due to the Chinese import ban of plastic waste.

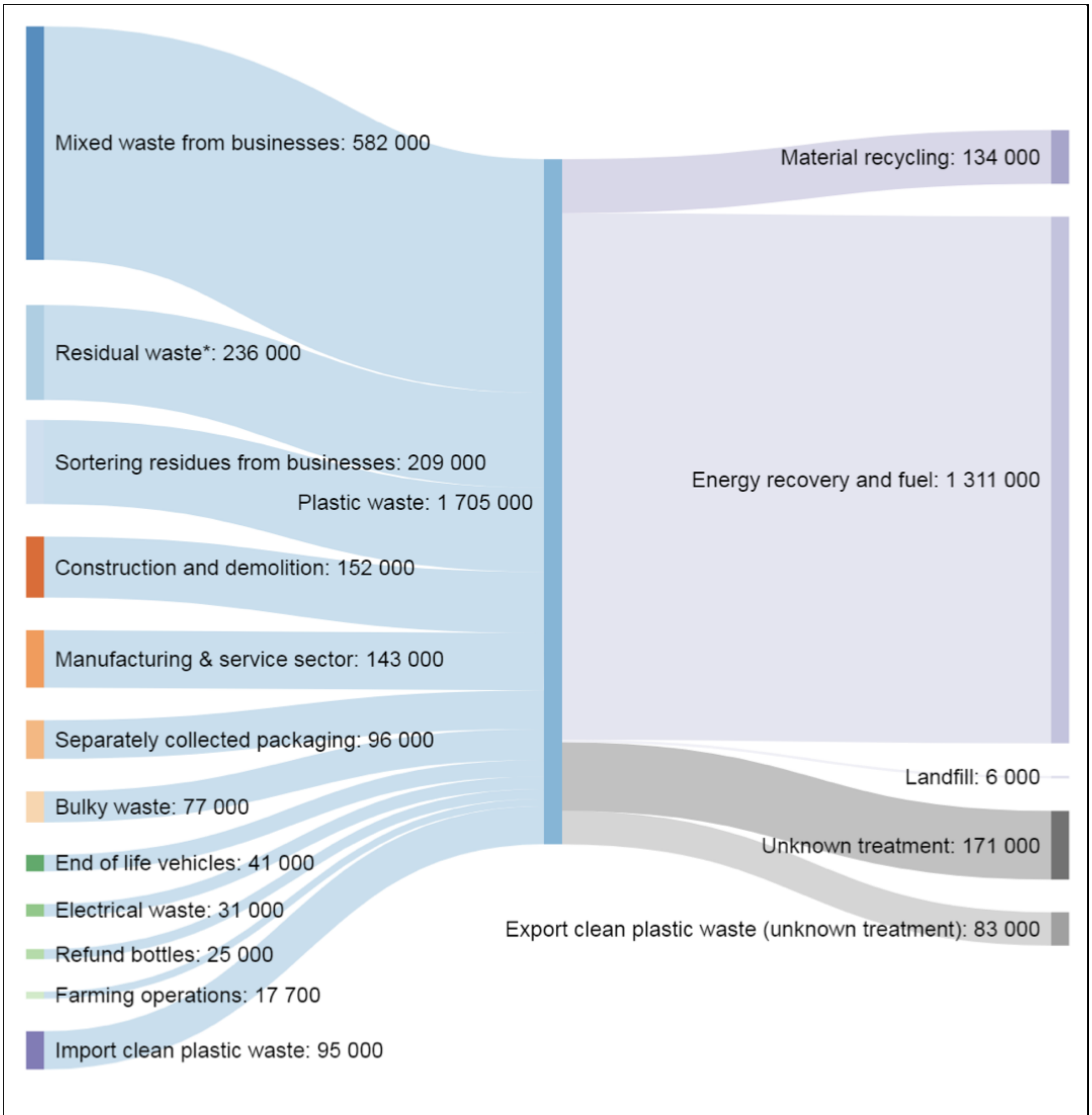

Figure 2 - Plastic waste flows in Sweden, an overview (Adopted from Ljungkvist Nordin et al. 2019, p.25)

The majority of Sweden's plastic waste is being incinerated together with other residual waste including household waste (Lassesson et al. 2021). Even if incineration is considered as a loss of valuable resources and release of GHG emissions, Sweden has developed their waste management infrastructure and is one of the leading countries when it comes to waste-to-energy plants where waste is a fuel used in Swedish district heating systems (Folk, 2021). Due to the excessive incineration capacity at the waste-to-energy plants, Sweden is importing waste to help produce electricity and heating for cities. To regulate the waste-to-energy plants from an environmental perspective, Sweden has introduced a tax on every tonne released GHG emissions. To cut these emissions, one strategy could be to decrease the fossil-based content in the waste or capture emissions at the plant by using

Carbon capture & utilization processes (CCU) (The Swedish Waste Management and Recycling Association, 2021a).

Although Sweden collects and sorts a large share of plastic waste, a significant part of the separately collected plastic packaging waste is being incinerated. A prerequisite for mechanical recycling is clean plastic waste streams, meaning high purity, no contamination, additives and fibers (Milios et al. 2018). In the project report by Lassesson et al. (2021), they concluded that these requirements are not met in several plastic waste streams and therefore not suitable for mechanical recycling. The highly contaminated, multi-layered and coloured plastic waste, that is not suitable for mechanical recycling, could therefore be a potential input material for CR (Lassesson et al. 2021). A concern with current technology is that food-packaging and plastic used within health care follow strict requirements for product safety, hence these products cannot be produced with recycled plastic. The technology of mechanical recycling is also accompanied by degraded plastic properties i.e downcycling, meaning that a plastic product can only be mechanically recycled up to 2-3 times (PET, 10 times) until it loses its properties (Ragaert et al. 2017). Another key aspect is that new plastic products put on the market are not designed for recycling as products today are a mix of different plastic types and colors. To enable higher recycling rates manufactures must be encouraged to use an eco-design strategy and therefore take the entire product life cycle into account (Lange, 2021).

The identified "moment 22" within the Swedish recycling industry is that plastic waste streams that go to mechanical recycling are too small to provide a sufficiently stable situation (in terms of quality and quantity) for potential buyers. Therefore, low demand for recycled plastic and no sufficient incentive will come from the user side in order for recyclers to increase the collection (Lassesson et al. 2021).

4.2 Actors & responsibilities

There are several actors involved in the Swedish waste management system (see *Figure* 3), actors that are responsible for collection and sorting waste, recycling and those that inform, make waste prevention programmes and reports on waste statistics.

For collection and sorting, households, producers and municipalities are the main responsible ones. According to Swedish law, each municipality is responsible to supervise the collection of household waste[1], meaning that they need to make sure that it is being collected and treated (The Swedish Waste Management and Recycling association, 2021). Their main policy instruments consist of a waste plan, a waste management fee and local regulations. Which waste fractions households need to separate their waste is regulated in the local waste regulations and can therefore different between municipalities (SEPA, 2020). Producers, on the other hand, need to make sure that all plastic packaging waste that they have placed on the Swedish market is collected and treated under the Extended Producer's Responsibility (EPR). The EPR is a governmental policy and a Swedish law that aims to create and improve waste and collection management. However, even though the EPR has contributed to an increased amount of collected material, the demand for recyclables has not been affected (Lassesson et al. 2021).

[1] refers also to waste that comes from businesses (restaurants, shops, offices, etc.)

The Swedish Waste Management and Recycling Association (Avfall Sverige) has 400 members from both the public and the private waste management and recycling sectors. One of their main tasks is to promote the exchange of experience and information between its members and collaborate with authorities, government departments, the Environmental Protection Agency and the Ministry of the Environment (The Swedish Waste Management and Recycling Association, 2021).

Swedish Plastic Recycling *(Svensk Plaståtervinning)* is one of the biggest sorting and collecting companies in Sweden where *The packaging and newspaper collectors (FTI)* work on behalf of Swedish Plastic Recycling and are responsible for all recycling stations in Sweden. Sorting takes place at Svensk Plaståtervinning's facility SiteZero in Motala, where about 50-55 percent of the total collected Swedish plastic waste is being sorted. With a maximum capacity of handling 120 000 tonnes of plastic waste per year makes the facility one of the biggest recycling plants for plastic waste in Europe (Swedish Plastic Recycling, 2021). The sorting process at Motala Sorting facility uses advanced technology to further separate and categorize the plastic packages into each category of plastic type (PP/HDPE/PET) and colors. The amount of plastic waste that cannot be sorted by this technology goes to incineration of waste-to-energy plants. *Stena Recycling* and *Ragn-Sells* are two of the biggest recycling companies in Sweden. The dominant technology is mechanical recycling and usually includes the process of sorting, washing, drying, grinding, re-granulating and compounding (Swedish Plastic Recycling, 2021).

Borealis and *Inovyn* are two main plastic producing companies in Sweden, where Borealis is the only polyethylene (PE) producer and Inovyn the only Polyvinyl chloride (PVC) producer. SEPA is the main responsible institution in Sweden responsible for gathering and publishing statistical reports on waste statistics. The waste statistics is categorized by industries, where households act as one, and further split up by waste streams (glass, plastic, metal, etc.). Plastic consists of two streams: PET plastic which is managed through a deposit system and other plastics (Meteyer, 2020). The problem with waste statistics is that one cannot compare different recycling rates over time due to a change in calculation method at EU level. Before 2020, Sweden's waste statistics followed the EU reporting under the Waste Directive where recycling means that the collected waste is either mechanically recycled or being incinerated (with energy recovery). As incineration is not recycling, the EU calculation methods changed and from 2020, incinerated plastic cannot be counted as recycled anymore. This means that the legislation changes will show recycling rates closer to reality and indicate how far Sweden is from its recycling target (Meteyer, 2020).

4.3 What is Chemical recycling?

Chemical recycling (CR) also called feedstock- or advanced recycling is the broad term used to describe emerging technologies that are increasingly being developed to deal with plastic waste that mechanical recycling cannot process. Chemical Recycling Europe (CRE), defines CR as "any reprocessing technology that directly affects either the formulation of the polymeric waste or the polymer itself and converts them into chemical substances and/or products whether for the original or other purposes, excluding energy recovery" (ChemRecEurope, 2019). A similar definition is made in The Waste Framework Directive (WFD) (European Parliament, 2008) but in the WFD, they define the waste hierarchy (see figure A.1, Appendix) to guide the prioritization of specific initiatives and technologies in waste prevention and management policy and legislation.

Based on the definition, the idea is to recycle plastics by changing their material structure and turn polymers back into monomers. This means that a plastic package can be broken down into its plastic "building blocks" (monomers) that can be then used to make new plastic products (Hann & Connock, 2020).

A simplified picture of the life cycle of plastic is shown below in *Figure* 3 and shows how CR technologies can help to move from a linear plastic economy to a circular economy. The different CR technologies, that will further be explained below, can complement mechanical recycling and potentially improve recycling rates and divert plastic waste from ending up at landfill or being incinerated (European Commission, 2019b).

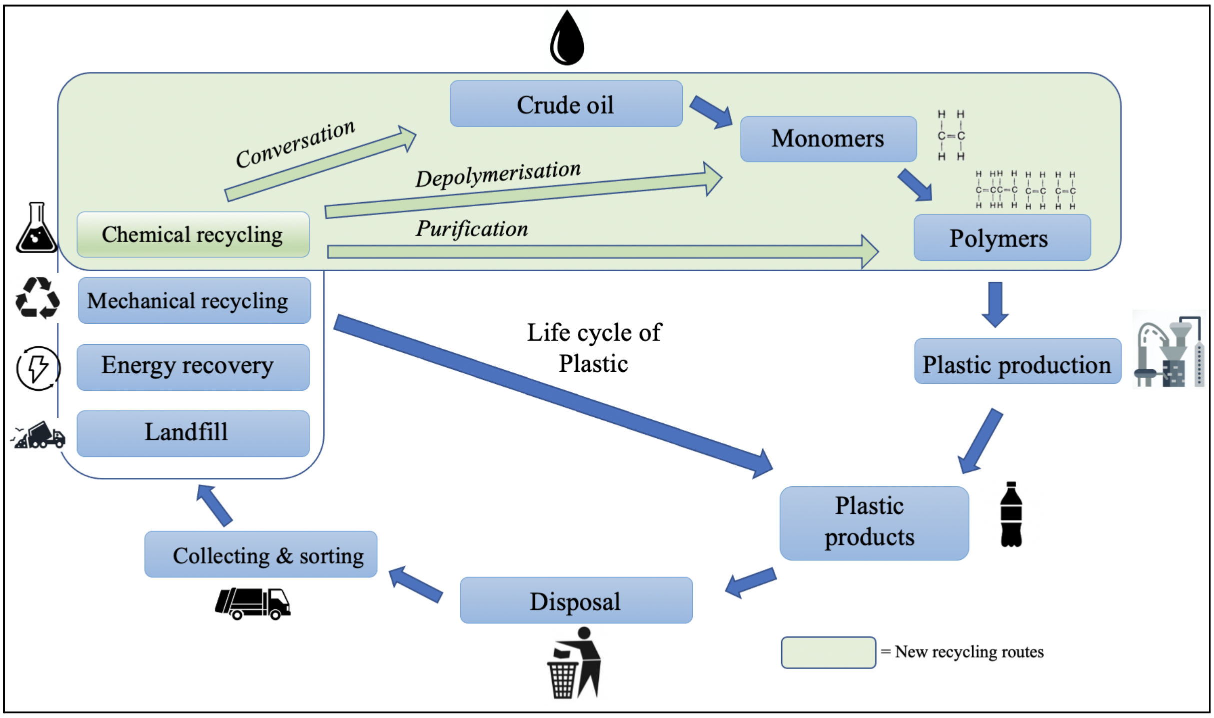

Figure 3 - Simplified flow of the plastic life cycle (Author´s own illustration based on CEFIC, 2020b & Ambrières, 2019).

CR technologies can be categorized into three categories based on the position of their outputs in the plastic supply chain;

1. *Dissolution*
2. *Depolymerisation*
3. *Conversation/Thermal Depolymerisation*

Dissolution is the process where heat and solvents are used to dissolve plastic waste and extract polymers to make new recycled plastic. During the dissolution process the structure of the polymer is not altered. It is only new additives that are added to the polymers to produce new recycled plastic (CEFIC, 2020b).

Depolymerization is the process where sorted plastic waste is broken down into monomers (basic building blocks) by using heat. Potential contaminants are isolated from the monomers and then they are fed back into the normal plastic production processes as a secondary raw material. The produced

plastic by using depolymerization have a similar quality as virgin plastic (those made from traditional fossil resources) (CEFIC, 2020b).
Conversation/Thermal Depolymerisation is the thermal degradation of plastic waste using different temperatures (300-900 degrees celsius) with oxygen (gasification) or without oxygen (pyrolysis) (Rehan et al. 2017). Gasification converts plastic waste into energy as the heated plastic produces a valuable synthesis gas, which can be used for electric power generation. Pyrolysis, on the other hand, uses no oxygen meaning that the heated plastic can generate hydrocarbons and therefore produce liquid oil (pyrolysis oil) which is similar to crude oil. This can be further refined into transportation fuels (Ragaert et al. 2017). However, depending on what type of plastic waste stream it is, different technologies are better suited for different types.

4.4 Chemical recycling developments

To foster developments, investments and cooperation between countries, the Independent Commodity Intelligence service, ICIS, launched the Recycling Supply Tracker that provides a comprehensive view of the CR market and ongoing projects. As of 2021, there are 145 ongoing global projects within CR but only 30 % are operating at a commercial scale (ICIS, 2021). A few large-scale projects have received funding from the European Commission Innovation Fund due to the potential of lowering GHG emissions and closing the material cycle for plastic. There have been a number of CR projects (pyrolysis) at national level but due to financial issues and lack of input material, the majority have been closed (ICIS, 2021).

Currently, there are no-full scale CR projects in Sweden that are commercialized. However, there are a few on-going demonstration projects, Depolymerisation of PET bottles, 10 000 tonne (to be in operation by 2024), Gasification in Perstorp, 15 000 pyrolysis oil (by 2025) and Pyrolysis in Stenungsund (that will further be explained below) (Josefsson, 2021).

A research group at Chalmers University of Technology discovered an efficient procedure of breaking down any plastic waste to a molecular level through gasification (add heating up to 850 degrees celsius). At the Chalmers Power Central facility, the gasses can be converted into new plastics of the same quality as virgin plastic and can currently handle 200 kg of plastic waste per hour (Thunman et al. 2019a). By experimenting, the goal is to evaluate the optimal technology that can be integrated into the Borealis cracker facility in Stenungsund and hopefully a new plastic refinery can be commercialized in 2025. The project is in collaboration with Stena Recycling, Borealis and Fortum Recycling and Waste, where Fortum will be the main actor responsible for bringing plastic waste to the Stenungsund chemical cluster (Lundberg, 2021). Thunman et al. (2019b) highlights that the transition to a circular economy of plastic is technically feasible with CR by taking advantage of existing infrastructure, e.g those at Stenungsund chemical cluster. Henrik Thunman, the professor in thermal-energy at Chalmers University who works with gasification technology mentions that the economic feasibility of a full transformation is possible only if the regulatory framework is in place (Thunman et al. 2019b).

SEPA have identified four different challenge areas in their action plan for sustainable consumption of plastic (2021), uncertain profitability, lack of incentives to design for recycling, uncertain market for recyclables and lack of standards, methods and trackability to ensure high quality of recycled material. All these obstacles identified by SEPA will affect supply and demand of recycled material. The uncertain market for recyclables is also related to the low cost of producing virgin plastic from fossil fuels since the environmental cost and the release of CO_2 emission is not fully included in the price for producing virgin plastic (SEPA, 2021b). Whether there will be investments within the CR sector will depend on ensuring plastic waste streams in the long run and the regulatory framework (Lassesson et al. 2021).

4.5 Waste & recycling regulations

The Swedish Environmental Code contains environmental legislation, including waste regulations in Chapter 15. It is largely embedded within the EU waste policy framework (Waste Directive 2008/98/EC) and the waste hierarchy (see Figure A1, Appendix 1) meaning that the waste hierarchy acts as the main level of prioritization when developing waste management processes (Milios et al. 2018). However, after the introduction of the EU Action Plan for a Circular Economy in 2015 at EU level, the policy framework in Sweden is in a constantly changing environment with plastic waste as a priority area for action.

The concept of circular economy has prompted the call for a large number of law and regulation reviews both within the EU and in Sweden. In 1991, the Swedish Government introduced a carbon tax of 250 SEK per tonne of CO_2 emitted, which increased in 2018 to 1150 SEK (Government Offices of Sweden, 2018). Further, the Extended Producer Responsibility (EPR) scheme was introduced for waste packaging meaning that all producers are legally responsible for collection and recycling plastic waste entering the market (Milios et al. 2018). In 2000, a landfill tax was introduced at a rate of 250 SEK per tonne of waste and in 2015 the amount doubled to 500 SEK per tonne of waste (The Swedish Waste Management and Recycling association, 2018). To prevent plastic waste from being incinerated, a incineration tax on municipal waste was introduced in 2006 (Sahlin et al. 2007). However, the tax was removed in 2010 due to its weak effectiveness. Salmenperä (2021) mentions that actors within waste management have different views on incineration, where municipalities consider it to be an enabler of clean cycles and private companies argue that incineration steals recyclables from them. Even if an incineration tax is put back on the political agenda (SEPA, 2021), the action plan for improving the plastic recycling rates is still unclear. SEPA (2021) highlights that the Swedish waste legislation framework focuses more on the collection of plastic waste rather than stimulating the demand of recycled material that is of high importance to achieve a circular economy. There is a strong need for a clear national, consistent policy framework that supports circular economy targets and promotes the use of recyclables (SEPA 2021b).

5. Methodology

This section describes the research design and approach used in this study followed by a more detailed explanation of the semi-structured interviews and the project report review. Further, a presentation of the data analysis procedure is explained followed by a discussion of the limitations and ethical considerations.

5.1 Research Strategy

The research strategy follows a qualitative approach consisting of semi-structured interviews with industry experts and a review of previous project reports (see *Figure* 4). An inductive exploratory approach is taken as CR is a new complex technology and because the empirical evidence covering circular economy and the CR sector is limited and inconclusive. By following this research strategy one can understand current obstacles and opportunities within the sector and how a possible transition to a circular economy of plastic can be possible. The qualitative strategy is chosen for this study because it can "*purposefully select participants or sites that will best help the researcher understand the problem and the research question*." (Creswell, 2014, p.45).

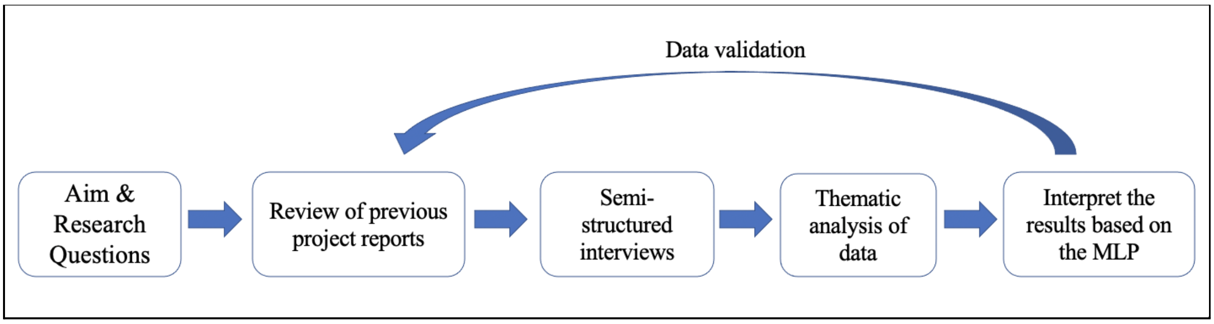

Figure 4 - Research Strategy (modified by the author).

The reasoning behind starting with a review of previous project reports covering CR in Sweden is that one gets an overview of the main actors and experts involved in CR related projects and publications. The researcher then identifies a good sample with relevant participants with right expertise. Following the research strategy the main data source comes from semi-structured interviews with experts which is then analyzed using thematic coding. The findings are supported by the results found in the previous project reports, hence multiple data sources are used to get a comprehensive understanding of the phenomenon in question. This is the logic behind data *triangulation* described by Olsen (2004) and to further get higher validity of the findings and a more complete picture of the problems facing the CR sector in Sweden.

As described in the theory section, the MLP is being used as an analytical framework to analyze my results and identify key characteristics within the Swedish recycling industry. Yet, it is also the guide to categorize my data sample, hence the interview sample consists of industry experts (IE) from the current recycling industry (socio-technical regime), the CR sector (niche) and from institutions/agencies covering the external forces (landscape). The data collection process is based on

Creswell (2014) and follows a procedure of raw data collection and transcription (dictation in Word), preparing and analyzing data, coding in themes (thematic analysis) and interpreting the results.

5.1.1 Previous project reports

To complement and support the collected data from the interviews I relied on findings from previous project reports that covered CR developments, possibilities and identified obstacles within the Swedish recycling industry. Since 2020, SEPA has requested project reports from the industry covering the new technology of CR and how it can contribute to a circular economy as they got the mission from the Swedish government to investigate how Sweden can increase material recycling for plastic[2]. The selected project reports are the following;

- Lassesson et al. (2021). *Chemical recycling of plastic - technology, flows and environmental aspects.* The project report has been produced by SMED and requested by SEPA (2021b) and took place between August and December 2020. The aim is to analyze the resource, environmental and climate impact of a CR facility and which waste streams could be relevant. Also identify obstacles and potential problems with the technology.

- Solis, et al. (2021). *Chemical Recycling for Circular Flows of Plastic Waste.* The project is a collaboration between Profu, KTH, Stockholm Exergi AB & Sörab AB (2021) and took place between January 2020 and April 2021, funded by Lidl Future Initiatives. The overall aim is to evaluate CRs potential as a commercial waste management alternative for a circular economy perspective.

- Bjerkesjö et al. (2021). *Policylab for chemical recycling of plastic.* The project has been requested by SEPA and produced by Johannebergs Science Park together with IVL (report U 6506, 2021) and took place in April 2021. The aim of the project is to come up with policy recommendations based on the waste management industry needs to increase recycling rates of plastic.

The main findings and conclusions can be seen in Table 2 below.

[2] Regeringsbeslut 2020-11-26

Table 2 - Summary of findings from previous project reports

Project report	Authors	Main findings
Chemical recycling of plastic - technology, flows and environmental aspects.	Lassesson H, Gottfridsson M, Nellström M & Rydberg T (IVL), Josefsson L (Johanneberg Science Park) & Mattsson C (RISE).	**Identified obstacles include**, lack of a long term vision in the current policy- and regulatory framework for CR and the process of getting permissions for developing CR facilities is too long. Important that CR can be counted as material recycling.
		"Mechanical recycling can efficiently recycle high-quality plastic flows to plastic material of slightly or significantly lower quality. Chemical recycling can in a less efficient way recycle lower quality plastic flows to higher quality plastic materials. In this way, they have a good potential to complement each other "
Chemical Recycling for Circular Flows of Plastic Waste.	Solis M, Sahlin J, Bisaillon M & Henrysson M.	The results shows that by developing the CR technology pyrolysis in Stenugnssund, the circularity of plastic will increase with 40% compared to todays practises.
		Identified changes within the plastic value chain if CR is developed; new actors and roles within the waste management value chain, and new challenges for every actor.
Policylab for chemical recycling of plastic.	Bjerkesjö P, De Jong A, Lassesson H, Nielsen T, Romson Å, Rydberg T, Steen L, Hermansson E & Josefsson L.	**The identified obstalces** found in the workshops are related to regulattions & standardisatiom, technical-, economic-, logsitic obstacles, access to energy and lack of public information.
		Based on these identified obstacles 9 potential policy recommendation has been developed; 1. Need of clear definition what is considered material recycling. 2. Need of change in tax rate for waste incineration. 3. Limit the amount of plastic that goes to incineration for new incineration facilities. 4. Facilitate the permit process for CR facilities. 5. Requirement of increased sorting and material recycling for plastic. 6. Facilitate the imports of mixed plastic waste. 7.Requirement for a minimum proportion of recycled raw material in plastic products. 8. Material recycling certificates 9. No tax on recycled material
		The priotarization that has been done based on a common understanding; 1. Clarification that chemical recycling is approved as a method for material recycling 2. Requirement for a minimum proportion of recycled raw material in plastic products

5.1.2 Semi-structured interviews

The purposeful sampling is reflected within the 3 levels of the MLP consisting of industry experts, IE, (socio-technical regime), CR experts (niche) and agencies/institutions within the regulatory external environment (landscape) (see *Table* 3 for details).

Table 3 - Sample of semi-structured interviews

Sample	Actors	Explanation	Company name
Socio-technical regime	Plastic producers	As virgin plastic is cheap and easy to produce, it competes with recycled plastic and affect the demand (Naturvårdsverket, 2020). Borealis is the biggest	Borealis
	Collecting & sorting companies	Key actor in the value chain. This step is important for the recycling to work and be efficient .	Renova
	Mechanical recycling companies	Mechanical recycling is the dominant recycling technology in Sweden and represent the current practise. Two of the biggest recycling companies will be selected based on number of employees and business tenure.	Swedish Plastic Recycling
	Waste Management networks & associations	As the socio-technical regime also refer to industrial networks, knowledge, culture and behaviours, it is important to include the broader network organizations within waste management in Sweden.	The Swedish Waste Management Association
Niche	Chemical recycling sector/pilot projects & associations	As analysing the potential of chemical recycling of plastic in Sweden is the main focus in this study, pilot projects and association covering the chemical industry will be selected.	Stenugnsund project IKEM
	Reasearch institutes & innovation center	As the innovation of chemical recycling was developed as a niche-lab experiment, scientist, resarch and innovation centers are crucial to include.	RISE Chalmers KTH
Landscape	Actors involved in the regulatory framework and put environmental pressure	The landscape is characterized by global trends, envionmental pressure and regulatory frameworks, The Swedish Environmental Protection Agency (SEPA) that conducts and coordinates Sweden's environmental work will be selected.	SEPA IVL

The sample size is based on the concept of data saturation, which is employed as guidance for purposeful sampling by Guest et al. (2006). Their paper suggested that between 6 and 12 in-depth interviews is enough to reach full data saturation, hence the sample was constructed within this range. The sample is very rich, because of diversity across industry experts and, therefore, covers the different features of the topic and depicts how they interrelate with each other in the plastic life cycle.

From the current industry sample (socio-technical regime) the following industry experts, IE were chosen;

- IE1, Production engineer at Borealis with 8 years of experience within plastic production and currently involved in the CR project at Stenungsund.
- IE2, Development engineer at Swedish Plastic Recycling with experience within material recycling and expert within design for circularity.
- IE3, Technical advisor for waste to energy at The Swedish Waste Management Association with over 10 years of experience in the waste management industry.
- IE4, Development Strategist within waste and recycling at Renova with over 23 years of experience in the waste management industry.

and from the CR sector (niche);

- CRE1, CEO at Josefsson Sustainable Chemistry AB with over 30 years experience within the plastic industry. Previous worked as a Professor of The Practice Hållbar Utveckling at Chalmers University.

- CRE2, Senior researcher at KTH and was involved in the project “CR for circular plastic waste streams” with Profu, Sörab and Stockholm Exergi.
- CRE3, Senior researcher & project manager at RISE with over 3 years of experience doing research about chemical recycling technology.
- CRE4, Head of Plastic Converting at IKEM, working as the link between policy makers and the member companies of IKEM. Has been working within the research area and at RISE for 7 years.
- CRE5, Professor at Department of Energy and Environment at Chalmers, working developing a new type of chemical recycling of plastic at Chalmers Power Central facility in Gothenburg.

and at landscape level;

- A1, Climate analyst at The Swedish Environmental Protection Agency working with analyzing the environmental aspects of plastic and recycling.
- A2, Project manager at IVL with over 5 years of experience working with different waste and recycling projects.

The *Interview guide* is based on Creswell’s (2018) sample interview protocol and can be found in Appendix B. Here, the questions are based on different areas such as; definition of CR, benefits and challenges of CR, cost, regulatory framework, future and scale up possibilities. These areas are all aspects that previous project reports have covered (Lassesson et al. 2021; Solis et al. 2021; Bjerkesjö et al. 2021). As a first step, a pilot interview was set up to check the open-ended question’s quality. All the participants were contacted through email and LinkedIn to schedule an online Microsoft Teams meeting that lasted about 30-40 minutes on average. The email and LinkedIn message covered a short description of the study, the aim, that the participation is voluntary, how the data will be used, stored and the recording procedure. Online meetings were preferred due to the Covid-19 situation even if physical interviews are a more natural setting. The interviews were conducted over a period of 3 weeks and took place from the 14th of March until the 30th of March 2022. The interviews were all recorded to ensure data accuracy and to avoid misunderstanding each respondent’s answer. The raw data obtained from the recorded interviews was immediately transcribed during the interview session as the researcher used the Word function “dictation”.

5.2 Analysis of the qualitative data

The data analysis follows the procedure presented by Creswell (2014) and includes the following; Raw data preparation (transcribing data from interviews), Organize data for analysis, Read and take notes of key findings, coding into different themes leading to a thematic analysis and finally interpreting the results. A thematic coding approach allows the researcher to map the main topics in the text without quantifying them (Bryman, 2014). Hence, the 11 interviews transcriptions are hand-coded using a thematic coding scheme consisting of four main themes with corresponding sub themes (see Table C.2, Appendix C). The sub themes were chosen as the researcher identified both common answers to the same questions and different perspectives related to the same theme.

5.3 Data Validation & Limitations

As the interviews were conducted over Teams and not in a face-to-face session, the researcher cannot capture body language and as explained by Bryman (2014), there could be a potential lower engagement. It's also more likely that technical issues arise during the interview session that could disturb the data collection process. In this study, a few interviews took shorter than expected and one interview session had some technical problems with internet connection from the participant side which means that some additional insights could be lost. However, remote interviews have been beneficial in this study due to the Covid-19 situation and since the participants lived in different cities in Sweden. Concerning the first step of contacting the participants, Bryman (2014) argues that the participants may not prioritize scheduling an interview session. However, the majority of the participants answered within a few days and the interview session took place a week after with no re-scheduled interviews. In total, 19 participants were contacted via email and/or LinkedIn with a response rate at 75%.

When conducting qualitative studies participant bias is the main disadvantage according to Creswell (2014) as interviews threaten the external validity of the findings. "*Social desirability bias"* can also occur meaning that the participants respond in ways that we feel are more appropriate or socially acceptable (Bryman, 2014). Moreover, as some of the participants are part of companies within the plastic value chain their answers might have been tailored favorably. Further highlighted by Oleinik et al. (2014), the researcher bias may arise when coding and analyzing the data. As the researcher in this study both use triangulation, a coding scheme, a systematic methodology and stayed close to the transcriptions, the bias has been minimized. However, it's further important to discuss a potential language barrier that may arise when translating the transcribed data according to Creswell (2014). Even if the researcher has advanced levels of English, the translation of quotes from Swedish to English could pose a threat and imply reducing the meaning of some concepts and extra words could be added to the original quote. This could potentially change the participants' voice (van Nes et al. 2010).

Further, qualitative reliability indicates that the researcher's strategy is consistent across different researchers and different projects (Gibbs, 2007) hence the transcripted data has been carefully analyzed so it matches the exact quotes from the interviews.

5.4 Ethical considerations

As a researcher faces ethical challenges when conducting a study, it's important to take these into consideration from the beginning of the study, during data collection until analyzing and when presenting the results. As qualitative research involves collecting data from people and about people, ethical considerations are important to discuss (Punch, 2005). To ensure that this study follows essential ethical considerations, Creswell's recommendations on how to address common ethical issues (2014, p.133) were followed. Prior to the data collection phase, all participants were informed about the general purpose of the study and how the data is to be used and stored via email and/or LinkedIn. This is important since the researcher must ensure that the information provided by the participant is kept confidential (Creswell, 2014). After receiving whose acceptance from participating in the study they were asked whether the interview could be recorded and that the recorded material is being deleted at the end of the study. During the data collecting process all participants received the same questions as the researcher followed the interview protocol carefully. As stated by Bryman (2014), it's also important that the interview guide include gentle, explicit, and not harmful questions, meaning that the researcher is ethically sensitive. To avoid researcher bias when later analyzing the data, multiple perspectives and contrary findings have been highlighted. In addition, fictitious names have been used for all the participants to respect privacy and anonymity (industry experts = IE; CR experts = CRE; agencies/institutions = A) (see Table C.1, Appendix C). Finally, a copy of the final report has been sent out to the participants so they could make sure that the quotations have been done correctly before publication.

6. Theoretical Analysis & Discussion

In this section the results are presented following the order of the research questions. First, the Swedish recycling industry and CR are conceptualized within the MLP based on the literature and data collection. Second, the main challenges facing the CR sector in Sweden are presented based on the interview data and previous project reports. Finally, how developments within the CR sector can enable a transition to a circular economy are discussed. As mentioned above, the participants cover industry expert = IE; CR experts = CRE, agencies/institutions = A.

6.1 Sweden's recycling industry & CR under the MLP

Socio-technical regime level

The recycling industry in Sweden can be conceptualized as a *socio-technical regime* consisting of established actors (consumers, firms, and other organizations within the value chain) using current state of technology, regulations, norms and knowledge. From the interviews and MLP literature, several characteristics of the current *socio-technical regime* explained by Geels (2002) can be revealed such as resistance to change, path-dependency and lock-in mechanisms.

First, a resistance to change to a circular economy from key actors in the value chain is identified where those are primarily profit- and efficiency-driven (CRE4, 21st of March 2022; CRE5, 14th of March 2022). CRE5 (14th of March 2022) argues that there is a "resistance to change within the current market" and that "there is a huge gap in interest between the society and the recycling industry " as both the regulatory framework and infrastructure is based on plastic made from fossil raw material. In contrast, IE1 (23rd of March 2022) clearly highlights that there is a driving force to work with more recycled material as "you will not have any customers unless you are not part of this transition and increase the use of recycled material". However, IE3 argues that all plastic producers talk about circularity, bioplastic, recycled plastic etc. But if you look deeper, the plastic producing companies are owned by oil companies who have a different interest and want to increase the plastic production as the demand for fossil fuels will decrease in the future" (IE3, 30th of March 2022).

Second, *technological path dependency* can be identified within a socio-technical regime (Geels, 2006). As mechanical recycling and incineration are the dominant waste management practices, hence current infrastructure is developed for these technologies (Bjerkesjö et al. 2021) and that incremental changes only take place. Third, *lock-ins* are also characterized within the current industry such as the overcapacity of incineration and the malfunctioning market for recycled material, also mentioned by Salmenperä (2021). The lack of demand for recycled plastic is something that is mentioned multiple times during the interviews, for example "low demand for recycled plastic"(IE4, 30th of March 2022) thus "hard for recycled plastic to compete" (IE3, 30th of March 2022). The price of recycled plastic is too expensive compared to virgin plastic which is a result of the underdeveloped current technology and expensive sorting technologies (Salmenperä, 2021). Fourth, another lock-in mechanism that is common in socio-technical regimes argued by Geels (2002) is related to the industry structure and mis-match between the current socio-technical regime and niche development in terms of infrastructure and regulatory framework. These features can be seen as current waste management infrastructure is developed for the dominant waste management practices, hence it will be difficult to redirect plastic waste streams to future CR facilities. This is further supported by the results found in Bjerkesjö et al. (2021). The characteristics of the current socio-technical regime as not having enough supportive regulatory framework (Geels, 2002) for CR is highlighted by a number of participants (A1, 23rd of March 2022; A2,18th of March 2022; CRE3, 17th of March 2022) and is further be discussed in the next section.

Niche level

As the chemical industry saw the potential in chemical technologies to create new plastic from plastic waste one can argue that CR emerged as a niche-lab experiment outside the current socio-technical regime. CR can thus be conceptualized as a niche-innovation as the technologies are in its early phases and aims to solve the current bottlenecks within the recycling industry which is a key characteristic of a niche. The identified bottlenecks with current mechanical recycling is that the technology cannot handle multi-layered or coloured plastic waste and turns high quality plastic waste into low quality products. CR can therefore "handle the down cycling issues" (A2, 18th of March 2022) and "increase recycling of plastic" (CRE1, 22nd of March 2022) and handle "recycle plastic waste not suitable for mechanical recycling" (CRE1, 22nd of March 2022; CRE4, 21st of March 2022). As CR can handle the plastic waste streams that current technology cannot handle, it highlights that old and new technologies act in symbiosis rather than in competition. Geels & Schot (2007) mention that the relationship between niche innovations and the current socio-technical regime can both be *competitive* (aiming to replace it) or *symbiotic*. The latter is a similar understanding to Geels (2002) where the niche innovation can be adopted as a competence-enhancing add-on to the existing socio-technical regime to improve performance. Lassesson et al. (2021) concluded that CR and mechanical recycling have the potential to complement each other as mechanical recycling can efficiently handle high quality plastic while CR can less efficiently handle the low value plastic. However, based on my interview data it is clear that the different actors do not agree whether CR can be seen as a complement or a disruptive technology. CRE4 (21st of March 2022) and CRE5 (14th of March 2022) are more opportunistic about the potential of the CR technology where CRE5 argues that "they will not lose their input plastic waste streams to CR" meanwhile IE2 (18th of March 2022), IE3 (30th of March) and A2 (18th of March 2022) are more skeptical and argue that CR are competing with the same input flows that today goes to mechanical recycling. The results found in Solis et al. (2021) are more in line with the view of CRE4 and CRE5 thus CR cannot be treated as a competitor to mechanical recycling, rather a complement.

Landscape level

Looking at the landscape level, it is clear that Sweden's recycling targets of recycling 55% of all collected plastic packaging by 2030 and the long-term goal of having zero net GHG emissions by 2045 put pressure on the current plastic recycling industry (Ministry of the Environment and Energy, 2017). Especially as the majority of waste goes to incineration with negative externalities of CO_2 emissions. As argued by A1, the global forces from the EU put further pressure on Sweden's roadmap towards a circular economy, especially as the EU environmental action plan covers the European strategy for plastics in the circular economy, The EU's Single Use Plastics Directive and the Green Deal. Further, CRE3 (17th of March 2022) argues that "the EU is a huge driving force…especially as they banned single-use plastic recently". The clear external pressure on Sweden's current regime shows that we are all part of the wider transition work towards a circular economy within the European Union (European Commission, 2019a).

Another external factor that can be identified that influences the development of CR and the transition to a circular economy is the oil prices. The low oil prices makes it cheap to produce virgin plastic hence it is hard for recycled plastic to compete with virgin plastic. This is both confirmed by the participants (A2; CRE3; IE3; IE4) and stated in the project reports Lassesson et al. 2021 and Bjerkesjö et al. 2021.

6.2 Identified challenges

Following the above characteristics of the Swedish recycling industry and the transcribed data from the 11 interviews, the identified challenges can be clustered into five different themes, these are; 1) economic aspects, 2) regulatory framework, 3) competition with virgin plastic, 4) environment and 5) “other” aspects only mentioned by a few participants (see Table C.2, Appendix C).

1. Cost, process efficiency and input considerations

CR experts from the niche both highlight that CR required “huge investment cost and sunk cost” (CRE3, 17 March 2022) and that CR is an “expensive technology and the end product will be of high cost” (CRE1, 22 March 2022). This is also confirmed by Lassesson et al. (2021) as CR facilities require huge investment costs and that it will be crucial to ensure a constant inflow of raw material i.e plastic waste flow (Lassesson et al. 2021). In contrast, CRE5 (14th of March 2022) argues that it is economically possible. The difference between building a waste-to-energy plant vs a CR facility (e.g pyrolys) is not so big, hence we can then also keep the coal atoms in a circular loop with CR. Thunman et al. (2019a) have a technical focus and present a possible solution showing that it is both technically and economically feasible for a full scale implementation of CR by using the existing infrastructure of the petrochemical cluster in Stenungsund. However, the economic considerations will highly depend on the logistics and “how to ensure big enough waste streams”(IE2, 18th of March 2022). This substance of concern related to securing big enough waste streams is confirmed by the majority of the participants and by the previous project reports by Solis et al. (2021), Lassesson et al. (2021) and Bjerkesjö et al. (2021). However, the results found in this study showcase also that it is unclear who is going to pay the additional costs covering additional transportation, collection and sorting infrastructure. IE4 (30th of March 2022) argues that “no one wants to pay for the additional cost” and “the economic perspectives need to be taken into account”. From a recycling company viewpoint IE3 (30th of March 2022) argues further that they are happy to increase sorting of different plastic waste streams as long as someone is ready to pay extra for it.

Solis et al. (2021) is the only report discussing new possibilities related to the logistics. They identified three new actors as a result of implementing CR in Sweden, suppliers of the technology, owners of the CR facilities and additional transport companies responsible for bringing plastic waste to these facilities. Solis et al. (2021) further highlighted that chemical companies and oil companies need to cooperate with waste management companies to have a better control over the raw material and recycling process. According to IE3 (30th of March 2022) this could be hard as they have different interests, “oil companies often own plastic producing companies and want to increase the plastic production”.

2. Regulations, lacking political and public acceptance

Another obstacle that was frequently mentioned by all different stakeholders from both the regime-, niche- and landscape level is the lack of a clear political framework for CR. Both CR experts from the niches and the participants from the landscape level clearly argue that there is “no policy instrument for CR” and “lack of regulatory framework, hence no incentives to invest” (CRE3, 17th of March 2022) and “lack of long term vision”(A1, 23rd of March 2022). These arguments are found in the previous project reports Lassesson et al. (2021) and Bjerkesjö et al. (2021) where one of the main obstacles that hinders investments within the CR sector is lack of a long term and clear policy framework that can steer plastic waste streams away from incineration. Also the study from BASF (2020) at European level highlights these issues. This is highly related to how Sweden can ensure long term plastic waste streams to CR facilities (Lassesson et al. 2021). As the regulatory framework is developed based on current practices, it mainly focuses on collecting and sorting processes and less focus on how to stimulate the demand for recycled plastic and how to increase recycling rates. This argument is in line with the majority of the participants (A1; CRE2; CRE3; IE1).

Another obstacle that is mentioned frequently is the unclear definition of CR and public acceptance of the technology (A1, 23rd of March 2022; IE1, 23rd of March 2022). The policy framework "must admit that CR is material recycling"(CRE3, 17th of March 2022; CRE5, 14th of March 2022). A1 argues that there is a "unclear definition of CR and what technologies should be included". Both Manžuch et al. (2021) and Krause et al. (2020) also state that the definition of CR is unclear and that there is a lack of consistency within the regulatory framework. Similar results found in the project report by Bjerkesjö et al. (2021) shows that there is a substance of concern related to the absences of standardized definition of CR and how the technology should be related to material recycling and the waste hierarchy. They argue that by admitting that CR is considered as material recycling it will affect actors in the entire plastic value chain as it will increase trust and cooperation. The majority of the participants in Bjerksjö et al. (2021) argue in line with the findings in this study, thus having a standardized definition of CR and admitting that the method is considered as material recycling will be a crucial condition to enable investments in CR.

<u>3. Competition with conventional processes and feedstock</u>

One of the biggest obstacles from the interviews according to both the regime, niche and landscape participants is the competitive environment with virgin plastic as it is cheap to produce. The competition with the price of virgin plastic is further highlighted as one of the biggest challenges according to Bjerkesjö et al. (2021). The price of chemically recycled plastic is therefore a crucial issue in order to make chemically recycled plastic competitive on a large scale. The final quality of the recycled plastic must be comparable to the quality of virgin plastic (Bjerkesjö et al. 2021). How the market for CR will develop will therefore depend on the demand for recycled plastic. The majority of the participants in Bjerkeskö et al. (2021) argue that the demand for recycled plastic is too low hence the incentives for waste management companies to increase recycling is low. This is also highlighted by Lassesson et al. (2021) as the flows of recycled plastic are too small to provide a sufficiently stable situation for many major potential users (" a moment 22").

However, the majority agree that we need to stimulate the demand for recycled plastic with new regulations, e.g implement a "recycled plastic quota or make production of virgin plastic more expensive", "..recycled plastic quota, in special plastic products e.g. 20% is recycled plastic"(A1, 23rd of March 2022). This recommendation is further highlighted in Bjerkesjö et al. (2021) as having great potential to stimulate the demand for recycled plastic and thereby improving the conditions for developing CR in Sweden. The effect of implementing recycled plastic is further analyzed in Bjerkesjö et al. (2021) who argue that by implementing a minimum requirement of having 30% recycled plastic in plastic packages, the demand for recycled plastic will increase with 9% (or with 11 500 tonne) compared to the total amount recycled plastic in 2016. However, the downsides with implementing a recycled plastic quota is further highlighted in this report as the risk for green washing[3] will increase, and the extensive administration and supervision of authorities to ensure compliance (Bjerkesjö et al. 2021).

<u>4. Environmental impacts</u>

Looking into the identified obstacles related to the environmental aspects, the majority mentioned that the CR technology is "an energy dependent process"(CRE3, 17th of March 2022) as it depends on the technology and energy source. This result is supported by Bjerkesjö et al., (2021) especially the CR technology gasification. However CRE5 (14th of March 2022) argues that the environmental aspects are not a big obstacle for developing CR as incineration is an even worse solution and the production process of paper needs even more energy than CR,"it is all about how we look at energy" (CRE5, 14th of March 2022).

<u>5. Other</u>

Another identified obstacles not so frequently mentioned is that "more R&D is needed" (CRE3, 17th of March 2022) ,"current infrastructure is not developed for CR" (IE2, 18th of March 2022), "lack of transparency"(CRE2, 18th of March 2022) and that CR is a "new technology for the industry" (CRE1, 22nd of March 2022). These are all of relevance when discussing the future aspects of CR developments in Sweden.

6.3 Transition to a circular economy for plastic

How the transition will look like will highly depend on whether Sweden's recycling industry can overcome the identified challenges within the current socio-technical regime to create windows of opportunity for the niche innovation of CR. To solve current bottlenecks within the current recycling industry, CRE5 (14th of March 2022) argues that CR is "the only type of technology in quantity that can make a circular economy a reality" which is also supported by CRE4 that argues "we need CR to get a full circularity of plastic".

Based on the interview data, the majority of the participants argued that the current infrastructure needs to be developed to enable a redirection of plastic waste streams away from incineration and to CR and mechanical recycling (A2; CRE1; CRE3; IE2). Whether big enough waste streams can be collected and stored for CR puts pressure on both society and the recycling industry. Lassesson et al. (2021) concluded that investments within current recycling infrastructure are needed to be able to redirect plastic waste streams to CR. These are also results from the interviews as both IE2, CRE1 (22nd of March 2022) and CRE4 (21st of March 2022) argue that investments are necessary to be able to steer plastic waste streams to CR facilities. Solis et al. (2021) argue further as Sweden produces relatively low amounts of plastic waste compared to other countries, the economics of scale will be an important topic, especially in relation to profit related questions (Solis et al. 2021). Maybe an increase of imported plastic waste can be a solution to secure big enough waste streams going to CR.

Whether we can overcome the identified obstacles, CR can "focus on plastic waste streams that include many different polymers"(CRE3, 17th of March 2022) and" handle a broader range of plastic waste streams" (CRE2, 18th of March 2022). Further, CR can "take care of plastic that goes to incineration" (IE1, 23rd of March 2022) and therefore increase recycling rates, hence contributing to a circular economy of plastic. The result from Solis et al. (2021) shows that CR will have a positive

[3] a way "to make people believe that your company is doing more to protect the environment than it really is" (Cambridge Dictionary, 2022).

effect on the circularity of plastic and by developing the CR technology pyrolys in Stenungsund, the circularity of plastic will increase by 40% by 2025. However, the households, norms and culture will also have a big impact if Sweden can reach their recycling targets as they are the first one responsible to sort the household waste and facilitate the sorting and recycling processes.

Which of the transition pathways (Geels & Shot, 2007) the case of Sweden will take will highly depend on how the interaction evolves between the landscape, the regime and the niches and how the "windows of opportunity" will emerge. As CR is not fully developed and mature one can argue that a potential *Technological substitution pathway* is not possible hence, the majority of the participants argued that mechanical recycling is still the cheaper and that CR can act as a complement to the already existing recycling technology. "A radical niche innovation exists and replaces current technology" (Geels & Schot, 2007) is therefore not likely to be a pathway towards a circular economy of plastic. One can argue that a *Reconfiguration pathway* according to Geels & Schot (2007) is more likely as CR would potentially act symbiotically to the current technology if the niche innovation can solve current obstacles. However, a transition pathway is not a linear process (Geels, 2019) and worth mentioning is that the author analyzes only one socio-technical regime based on Geels (2002). Taking Raven (2012) and Genus & Coles (2008) main critique of the MLP into consideration, further studies may analyze multiple regimes as the recycling industry depends on other industries and external actors as well. The complexity behind analyzing sustainability transitions shows that multiple angles need to be tackled and that it consists of many actors and industries that are connected.

7. Conclusions

The case of the Swedish recycling industry analyzed using the MLP shows that the current industry is facing multiple obstacles hence developing chemical recycling (CR) for a circular economy is hard. The biggest obstacles found in this study are related to 1) economic aspects, 2) regulatory framework, 3) competition with virgin plastic, 4) environment and 5) “other” aspects covering the need for more investment and R&D. As the current recycling industry in Sweden is characterized by having an overcapacity of incineration, a malfunctioned market for recycled plastic, a resistance to change from key actors and a current infrastructure and policy framework that does not facilitate the development of CR, make a potential transition slow. These findings are in line with the previous project reports and studies analyzed (Bjerkesjö et al. 2021; Lassesson et al. 2021; Solis et al. 2021). However, some of the results found in this study also showcase that there is a growing concern related to the economic aspects and who is going to pay the additional costs (IE3; IE4). From a recycling company’s viewpoint this study also found that they are happy to increase sorting of different plastic waste streams as long as someone is ready to pay extra for it.

CR is conceptualized as a niche innovation in this study as it aims to solve current bottlenecks with mechanical recycling. As a large fraction of already collected and sorted waste streams is being burned (waste-to-energy) and multiple waste streams are being rejected for mechanical recycling showcase the bottlenecks of current recycling technology. However, the findings from this study also show that the different actors do not agree on whether CR can be seen as a complement or a disruptive technology. Participants from the niche level, CRE4 and CRE5 argue in line with Geels (2002) that the technology will act in symbiosis with current practices, solve current bottlenecks with mechanical recycling and therefore increase recycling rates. IE3 and A2 are more skeptical and argue in line with Geels & Schot (2007) that CR are competing with the same input flows that today goes to mechanical recycling. From the landscape level and the case of Sweden, it is clear from the results that the EU roadmap to a circular economy together with Sweden's national recycling targets put a lot of pressure on the current recycling industry. Whether this pressure is enough to create a system change will thus depend on how mature and developed the CR technologies are.

To facilitate and speed up the transition to a circular economy of plastic it is therefore of high importance of collaboration between actors in the entire value chain and work towards the same goal of a circular economy. Further policy recommendations based on the results found in this study is to develop a supportive regulatory framework to stimulate the demand for recycled plastic and close the gap between innovations and regulations. The majority of the participants argue that a recycled plastic quota is of high relevance to spur the demand for recycled plastic, also confirmed by Bjerkesjö et al. (2021). To further make sure that the CR sector gets sizable, long-term investments, the policy framework needs to have a long term vision, admit that CR is material recycling and develop policy instruments that can steer plastic waste streams away from incineration. The reliance on incineration and waste-to-energy facilities may also lower the motivation to increase recycling and reuse materials. The case of Sweden showcases therefore the importance of developing CR and with the right conditions in place, CR can increase recycling rates and take care of all the plastic waste streams that today are being burned or rejected with current technology. Plastic is thus fantastic, as long as we keep it in a “closed loop”.

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Appendix A

Figure A1 - The Waste hierarchy (EU, Directive 2008/98/EC)

Appendix B

Interview Guide

Time of interview:
Date:
Place:
Interviewer:
Interviewee:
Position of the interviewee:

Opening question: ”Tell me a bit about yourself and your role in the company?”

- What are the current obstacles within the Swedish recycling system that prevent us from increasing the recycling rates?
- How would you define chemical recycling?
- What are the benefits of chemical recycling?
- What are the main challenges these technologies face?
- How sustainable is the process itself?
- What is needed to make it complementary to mechanical recycling?
- What are the costs of chemical recycling?
- What is needed to scale it up CR?
- How do you see the Swedish plastic recycling industry develop in the next three-to five years?

Thank the individual for participating in the study and assure him/her of confidentiality of responses.

Appendix C

Table C.1 - Sample Description

Name	**Role**	**Company**	**Description of company/network**	**Date of interview**	**Time**
IE1	Production engineer	Borealis Sverige	The only plastic producer of polyethene (PE) in Sweden. Their facilities in Stenungsund use input raw materials (nafta, etan, propane & butane) to produce HDPE & LDPE (Borealis, 2020).	23rd of March	30 min
IE2	Development engineer	Swedish Plastic Recycling	The biggest collecting company in Sweden who offers a nationwide system for collecting and recycling of plastic packaging into companies with extended producer responsibility (Swedish Plastic Recycling, 2020).	18th of March 2022	25 min
IE3	Technical Advisor waste to energy	The Swedish Waste Management Association	The Swedish Waste Mgmt & Recycling association has 400 members (both private and public waste mgmt and recycling sectors) (The Swedish Waste Management and Recycling Association, 2021b).	30th of March 2022	35 min
IE4	Development Strategist	Renova	A waste management company based in the West of Sweden offering a wide range of services for business and municipalities (Renova, 2022).	30th of March 2022	30 min
CRE1	CEO at Josefsson Sustainable Chemistry AB	Josefsson Sustainable Chemistry AB		22nd of March 2022	30 min
CRE2	Senior researcher	KTH		18th of March 2022	25 min
CRE3	Senior researcher & project	RISE	Independent, state-owned research institute.	17th of March 2022	40 min

	manager				
CRE4	Head of Plastic Converting	IKEM	Innovation and Chemical Industries in Sweden represents 1,400 Swedish and foreign-owned companies with the vision to find industrial solutions to the global social challenges (IKEM, 2020).	21st of March 2022	30 min
CRE5	Professor at Department of Energy and Environment	Chalmers		14th of March 2022	35 min
A1	Climate Analyst	SEPA	The Swedish Environmental Protection Agency conducts and coordinates Sweden's environmental work	23rd of March 2022	30 min
A2	Project manager	IVL	Swedish Environmental Research Institute, state-owned and combines applied research and development with collaboration between the public sphere and industry (IVL, 2021).	18th of March 2022	30 min

Note: Industry expert = IE; Chemical recycling expert = CRE; Agency = A

Table C.2 - Overview of thematic coding scheme

Themes	Sub themes
Definition of CR	Break down into molecules
	Hard to define
	Specific CR processes
	"Building blocks"
Advantages	Input flexibility & treatment of problematic waste not suitable for mechanical recycling
	Resources conservation & reduction of environmental impacts
	Product flexibility & value-added high-quality products
	Increase recycling rates
	Other
Obstacles	Cost, process efficiency & input considerations
	Regulations, lacking political & public acceptance
	Competition with conventional processes & feedstock
	Environmental impacts
	Other
Suggestions for CR Implementation	Infrastructure, cooperation & communication
	R&D and reference projects
	Supporting regulatory framework, new legislation