Transaction costs in WEEE recycling value chains

An analysis of WEEE recycling under collective and individual producer responsibility

Wan-Chun Hsieh

Supervisor

Jessika Luth Richter

Thesis for the fulfilment of the
Master of Science in Environmental Management and Policy
Lund, Sweden, May 2021

LUND UNIVERSITY
THE INTERNATIONAL INSTITUTE FOR INDUSTRIAL ENVIRONMENTAL ECONOMICS

Published in 2015 by IIIEE, Lund University, P.O. Box 196, S-221 00 LUND, Sweden,
Tel: +46 – 46 222 02 00, Fax: +46 – 46 222 02 10, e-mail: iiiee@iiiee.lu.se.

ISSN 1401-9191

Acknowledgements

I want to thank my supervisor, Jessika, to guide me through thesis writing and generously share sharp insights. In addition to your valuable input and in-time feedback, I especially appreciate your guidance in the beginning stage, which helped me identify what I am interested in. I would also like to thank Luis for giving ideas on theories, and Carl for the input and wise words in peer-group feedback sessions. Thank you to all the interviewees who kindly took the time to share their experiences with a student. Without your support, it would be impossible for me to complete this thesis.

Thank you to my family to support me no matter what; talking with you always can remind me why I am here. I am also thankful for friends back home and all the trash-talk. It is so good to know some people always have your back regardless of the distance. Thank you to my flatmate for being there with me and, most importantly, feeding me. Special thanks also go to Vincent to always show up when I needed it and calm my mind in stressful times.

Of course, deepest appreciation to my dearest batchmates and the insti. Thank you all for making the past two years so unforgettable. Even though we only got to see everyone in person for the first six months, I truly cherish each one of you and all the chat, trips, walkies, foods, fikas, drinks and great vibes we shared. Without you lovely people, Lund would never be this special. It would be odd only to mention some of you. So as the Taiwanese proverb says: there are too many people I am thankful for, so let's thank the universe. Thank you, the universe, for bringing us together. If we must experience a pandemic, you are the best company I can imagine.

Abstract

Increasing waste electrical and electronic equipment (WEEE) has become a global issue that raises social and environmental impact concerns, and recycling and using recycled materials is proposed by policymakers and academics as a solution. Nevertheless, barriers still exist and result in low collection and recycling rates and underdeveloped recycling markets. This paper aims to first understand how WEEE recycling value chains are structured, from WEEE collection, pre-treatment, recycling to using recycled materials in new products. To give a more holistic view, two types of waste management approaches are examined: Sweden for collective producer responsibility (CPR), and Dell Technologies for individual producer responsibility (IPR). Then, this paper seeks to analyse how transaction costs associate with the use of recycled materials and how they influence the upscale of WEEE recycling.

Qualitative research is adopted in this research, and data is collected via literature review and fifteen interviews with practitioners. The results show that the WEEE recycling value chain is fragmented and dispersed with multiple stakeholders involved. WEEE is transported between regions before converting into recycled materials. In the phase of using recycled materials, transaction costs are associated with due diligence (searching for and assessing buyers and sellers), negotiation on quality and prices and lastly, monitoring and verification of environmental benefits. Both actors under CPR and IPR have to overcome transaction costs when adopting recycled materials.

Even though transaction costs of WEEE recycling are unavoidable, stakeholders driven by solid incentives proven that transaction costs can be overcome and closed-loop recycling is possible. Nevertheless, transaction costs still hinder WEEE recycling and outweigh the benefits of recycling. In light of this, policymakers should initiate more stringent regulations to nudge the transitions, and two strategies are proposed based on findings: optimise recycling outcomes so the benefits outweigh transaction costs, or eliminate transaction costs with policy instruments.

Keywords: waste electrical and electronic equipment (WEEE), recycling, global value chain, transaction costs, collective responsibility system (CPR), individual responsibility system (IPR)

Executive Summary

Problem definition

As one of the most resource-intensive industries, the electronics industry faces the pressure of transition to a circular economy. Increasing waste electrical and electronic equipment (WEEE) has become a global issue that raises social and environmental impact concerns. In addition, mining virgin raw materials result in significant environmental and social impact. Recycling and using recycled materials is thereby proposed to better manage the waste while eliminating the extraction of raw materials. From a strategic perspective, retrieving and reuse materials can also reduce dependence on imported resources.

Policymakers have widely recognised the importance of recycling, and various studies have been conducted. In particular, the concept of Extended Producer Responsibility (EPR) is an environmental policy instrument that has been broadly adopted to encourage producers to take life-cycle thinking. Even though the importance and benefits of WEEE recycling are well accepted, barriers still exist and result in low collection and recycling rates. This paper aims to research the difficulties of WEEE recycling from the lens of transaction costs, which can be defined as indirect and unavoidable costs during the transaction. As indirect costs, transaction costs mean additional time and effort requires to make the transaction happen. Understanding the nature and influence of transaction costs can be helpful to facilitate WEEE recycling.

Research questions and methodology

Two research questions are used to guide the research:

Research Question 1:
> How are WEEE recycling value chains structured under Extended Producer Responsibility (EPR)?

Research Question 2:
> What kinds of transaction costs are identified in the WEEE recycling value chain?

Qualitative research is adopted in this research, and data is collected via literature review and fifteen interviews with practitioners from electronic industries, including producers, waste collectors, recyclers and NGOs. Content analysis is then conducted to analyse collected data. Two theories are used as an analytical framework: global value chain theory and transaction costs. The former is used to map the WEEE recycling value chain to build a fundamental understanding. The latter is used to analyse additional costs that make the use of recycled materials less attractive.

In RQ1, this paper first examines how the WEEE recycling value chain is structured due to the complexity of WEEE recycling. WEEE recycling value chain can be generally divided into four stages: from WEEE collection, pre-treatment, recycling to using recycled materials in new products. As there are multiple waste management approaches, this paper focuses on WEEE recycling under the concept of EPR, which can be further divided into collective producer responsibility (CPR) and individual producer responsibility (IPR). Both CPR and IPR are examined to provide a more comprehensive view of WEEE recycling, and Sweden is used as an example of CPR while Dell Technologies is used as an example of IPR. For RQ2, a taxonomy of transaction costs from literature is utilised as a baseline to analyse the case of WEEE recycling, including costs of due diligence, negotiating and monitoring and

verification. Transaction costs associated with the use of recycled materials are first identified, and their nature and influence are analysed.

Key findings

The results show that the WEEE recycling value chain is fragmented and dispersed with multiple stakeholders involved. Due to centralised recycling activities, WEEE is transported between regions before converting into recycled materials. Additionally, high quality recycled materials are not applicable in every region, which causes extra difficulties for producers to seek recyclers since modern manufacturing networks are also dispersed.

In the phase of using recycled materials, transaction costs influence both CPR and IPR. Identified transaction costs can be divided into three categories:

- Due diligence costs:
  searching for buyers (electrical and electronic equipment producers) and assessing available sellers (recyclers or smelters)
- Negotiating costs:
  negotiating over the quality of recycled materials (function, colour and hazardous substance) and prices
- Monitoring and verification costs:
  monitoring performance of products using recycled materials and verify benefits of using recycled materials, such as lower environmental impact

Recommendations

Although transaction costs are unavoidable, pioneers in the field have showed it is possible to overcome transaction costs. Nevertheless, as not all stakeholders are capable of handling high transaction costs, policy instruments should be taken to either minimise the impact of transaction costs or maximise the benefits of recycling to outweigh transaction costs.

The first strategy is to eliminate transaction costs via policy instruments. For example, building third-party certification to verify the quality of recycled materials can reduce negotiation costs, which can ease the pressure for producers to conduct research themselves. Raising awareness of the benefits of recycling or setting minimum use of recycled materials in new products can also stimulate more interested buyers, thereby save the transaction costs of searching for and persuading buyers. The second strategy is to maximise the benefits of recycling to outweigh transaction costs. For instance, optimising the WEEE collection process can ensure a stable input for recycling. Encouraging the public to sort out waste correctly can help improve the quality of recycled materials. Adopting new recycling technologies can enhance recycling efficiency while reducing the environmental impact arising from recycling activities.

Conclusion

In conclusion, transaction costs have hampered the further development of WEEE recycling. Even though transaction costs are unavoidable, stakeholders driven by solid incentives have proven that transaction costs can be overcome, and closed-loop recycling is possible. Nevertheless, not all stakeholders can deal with high transaction costs, and policy approaches should be initiated to promote WEEE recycling.

Table of Contents

List of Figures

List of Tables

Abbreviations

CPR - Collective Producer Responsibility

CRMs - Critical Raw Materials

EEE - Electrical and Electronic Equipment

EoL - End-of-life

EPR - Extended Producer Responsibility

EU - European Union

GVC - Global Value Chain

IPR - Individual Producer Responsibility

OECD - Organisation for Economic Co-operation and Development

PRO - Producer Responsibility Organisation

PCBs - Printed Circuit Board

REEs - Rare Earth Elements

SDGs - Sustainable Development Goals

TC - Transaction costs

UN - United Nation

WEEE - Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background

1.1.1 Circular economy and recycling

The traditional linear economy has been criticised for highly depending on the extraction of virgin raw materials, causing environmental and social impact and resulting in growing waste streams. The circular economy has been proposed to replace the linear economy and ease accompanying effects (Ayuk et al., 2020). In the EU Regulation, the definition of circular economy is *"an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, minimising waste and the release of hazardous substances at all stages of their life cycle, including through the application of the waste hierarchy"* (Regulation (EU) 2020/852 of the European Parliament, 2020).

At the global level, A Green Economy has been promoted by the United Nations Environment Programme (UNEP) as a way to "*improve human well-being and social equity, while significantly reducing environmental risks and ecological scarcities*" (UNEP, 2011). The 2030 Agenda for Sustainable Development with 17 Sustainable Development Goals (SDGs) has been adopted by the United Nations (UN) to transit towards a more resilient future (UN, n.d.). In light of impacts arising from modern production and consumption patterns, SDG 12 focuses on sustainable consumption and production by improving the efficient use of natural resources, reducing waste generation and minimising chemical and waste pollution with better life cycle management (UN, 2015). In addition, the European Green Deal is proposed to nudge the transition towards a sustainable economy by reducing Greenhouse Gas (GHG) emissions and decoupling economic growth with resource use (European Commission, n.d.-a). Under European Green Deal, a Circular Economy Action Plan was adopted in 2015 and updated in 2020 (European Commission, n.d.-b).

In general, the EU suggested a waste management hierarchy to promote the proper use of resources and reduce waste generations (see figure 1-1). This concept is also expanded to improve the design, manufacturing, recycling and reuse of electronics. Firstly, waste prevention is a preferable option to tackle the problem from the source, which ensures products are designed in an eco-friendly way and not overproducing commodities. Thereby, eliminating excessive production can reduce the generation of waste. Next, once products are discarded and become waste, it is essential to check the condition and evaluate whether we can repair them by replacing broken components to be reused. If discarded products cannot be refurbished and reused, recycling systems play a critical role to ensure waste is properly collected, sorted and fed into waste streams. Then, with the help of technology, valuable materials can be recovered from the trash. Lastly, the remaining waste is disposed of in landfills or sent to incineration plants (European Commission, 2018).

As the third tier of the waste hierarchy, recycling plays a critical role to collect discarded products and transform waste streams into a resource stream. Even though reuse is prioritised over recycling to prolong product lifespans, recycling is still necessary to take care of end-of-life products that can not be repaired or refurbished. As the current constitutional structure of waste management is not fully aligned with the concept of reuse, this situation further emphasises the importance of recycling to capture obsolete products (Zacho et al., 2018). Therefore, recycling is a crucial point of a long-term strategy to tackle increasing e-waste generation and enhance resource efficiency (European Commission, 2020a; Watari et al., 2020).

Figure 1-1. Waste Hierarchy

Source: European Commission (2018)

1.1.2 Extended Producer Responsibility

Regarding waste management, the role of producers in waste management has been particularly highlighted by policy frameworks, such as the EU Circular Economy Action Plan and OECD (European Commission, 2019; OECD, 2016). Extended Producer Responsibility (EPR) is an environmental policy approach introduced in 1990 and globally adopted by several legislations (Walls, 2006). Before, managing end-of-life products tended to be consumers or municipalities' responsibility. However, the increasing waste volume gradually exceeded the municipality's capacity to properly handle waste and raised the question of whether it is the private or public sector's responsibility to treat end-of-life products (OECD, 2016).

In light of this situation, EPR suggests that the responsibilities of waste management should be reallocated, and producers should financially and physically support waste disposal and treatment (OECD, 2016). The definition of EPR proposed by Lindhqvist (2000) is "*Extended Producer Responsibility (EPR) is a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product.*" Here, both physical and financial responsibility are included. While the prior means taking physical management of products, the latter means financially supporting the costs for waste collection, recycling and disposal (Lindhqvist, 2000). In theory, EPR can incentivise producers to adopt a more environmentally friendly approach in product design to prevent waste generations (OECD, 2001). Until now, the EPR concept had been implemented and integrated into waste management policy by most OECD countries, such as EU Member States, Japan and the United States (OECD, 2001).

The concept of EPR has been utilised in many industries, including electronics, packing and batteries (OECD, 2016). Various instruments are utilised to promote better waste management, including setting take-back and recycling targets, charging waste disposal fee and requiring minimum use of recycled contents in products (OECD, 2001; Walls, 2006). Take-back requirements have been most widely used to require producers to collect their products once they reach the post-consumer phase (OECD, 2016). In general, there are two kinds of EPR: collective or individual producer responsibility (Walls, 2006). The former implies multiple producers jointly arrange an industry-wide waste collection system, usually via collective "Producer Responsibility Organisations" (PROs), while the latter means individual producers are only responsible for their own products. Both approaches have their advantages and disadvantages, and there is no conclusion on which one can achieve better waste management. A more detailed comparison of collective and individual systems is given in Chapter 2: literature review.

1.1.3 Waste electrical and electronic equipment (WEEE) and recycling

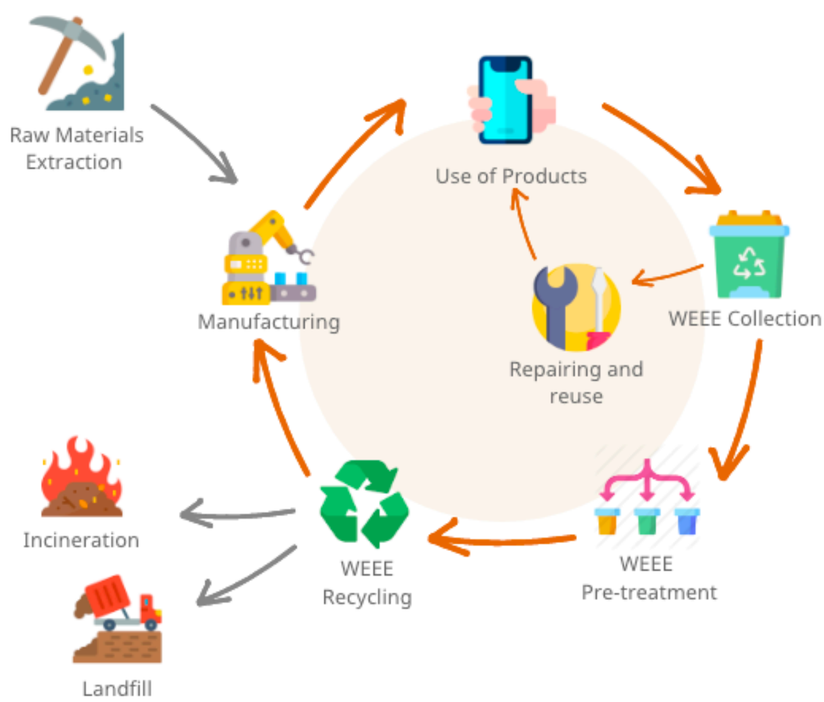
As one of the most resource-intensive industries, the electronics industry is inevitably facing the challenge of transition to a circular business model. From computers to smartphones, the global consumption of electronic devices is predicted to increase annually by 2.5 million metric tons. The global amount of e-waste is expected to double from 2014 to 2030 due to the high consumption rates of electronics, short life cycles and difficulties to repair and reuse (Crafoord et al., 2018; Forti et al., 2020; Lukowiak et al., 2020). Apart from waste generation, concerns over environmental impact due to the production process and improper waste treatment also occur, such as the toxicity of e-waste in landfills damaging the soil and nearby ecosystems (Ayuk et al., 2020; Werner et al., 2015). While the mining of virgin metals links to human rights issues, such as conflict minerals in Africa, the improper treatment process of e-waste could also put workers' health in danger (Hofmann et al., 2018; Terada, 2011). From the global to the national level, policymakers have recognised the importance of this issue. A Circular Electronics Initiative is currently under development by the EU to promote energy efficiency, durability, reuse and recycling, and improve proper collection and treatment of e-waste (European Commission, 2020a). Electrical and electronic products are one of the product groups that is often mandated to have appropriate collection and recycling with specific targets (OECD, 2001).

Regarding electronics, recycling can serve as an alternative resource source as materials can be recovered from the waste (Lukowiak et al., 2020). Turning discarded end-of-life products into urban mines can be potentially valuable as a significant amount of precious materials is hidden in e-waste. Take gold, for example. While the concentration of gold in ores is around 5 grams/ton, gold content in e-waste, such as mobile phones and PCs, can be 100-150 grams/ton (European Chemical Society, 2020). Decreasing the extraction of virgin raw materials can substantially lower the carbon footprint arising from the production phase. Since the mining of raw materials accounts for a significant environmental impact, using recycled materials can help reduce carbon footprints (El-Kretsen, n.d.).

Additionally, recycling is essential for countries that do not produce virgin raw materials but highly rely on them for long term economic development. For example, Critical Raw Materials (CRMs) increasingly play vital roles as the EU has recognised the criticality of these materials essential for the production of electronics and emerging clean technologies in renewable energy (European Commission, 2020c). In addition to the economic importance of CRMs, supply constraint is one of the concerns since they are over-concentrated in one or two countries (Andersson et al., 2019). For example, the United States produces more than 90% of beryllium for the global market. South Africa accounts for more than 90% of iridium and ruthenium, and China accounts for nearly 70% of tungsten production (European Commission, 2020b). Due to increasing sustainable awareness in developed countries, some metals are only mined in developing countries where environmental legislation or enforcement is not yet (El-Kretsen, n.d.). Therefore, the EU has identified critical raw materials as one of the priority concerns in the EU action plan for the Circular Economy, and 30 materials fall under this category in 2020, such as cobalt, indium and lithium (European Commission, 2020c).

In general, EEE falling under the scope of regulations include large and small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment (Directive 2002/96/EC, 2003). WEEE recycling value chain starts from WEEE collection, then WEEE goes through processes of pre-treatment and recycling, and finally turns into different streams of recycled materials that are ready to be put into new products (see figure 1-2). In addition to WEEE collection and recycling, using recycled materials in electronic products is equally important as the demand for recycled materials can stimulate developments of whole value chains, thereby building a closed-loop production system. However, research regarding recycled markets pointed out that one of the significant barriers to recyclable materials is "search and transaction costs", such as difficulties in matching buyers and sellers of waste and products (recycled materials) (OECD, 2006). Although similar transaction costs appear in other markets, they are particularly significant for the recycled market since it is relatively new and immature. Buyers need to spend extra time and effort to find suppliers and agree upon the quality and price of recycled material to make transactions happen (OECD, 2006). Even though the benefits of using recycled materials are significant, transaction costs higher than benefits make recycled materials less attractive, therefore adding more uncertainties in WEEE recycling.

Figure 1-2. Life cycle of electronics



Source: created by author based on US EPA (2015)

1.2 Problem definition

Although the importance of WEEE recycling is well recognised worldwide, the upscale of recycling practice is still challenging. Current recycling activities are not keeping pace with the global growth of e-waste, as only 17.4% of e-waste is formally collected and recycled (Forti et al., 2020). If we look into more details, 42.5% of total e-waste is collected and recycled in Europe, followed by Asia with 11.7%, Americas with 9.4%, Oceania with 8.8%, and Africa with 0.9% (Forti et al., 2020). Even though waste is collected, there is no promise of being adequately treated, and recyclable materials are all recovered before sending to landfill or incineration plants (Hageluken, 2006). For regions with relatively well-structured waste collection systems, such as Europe, difficulties still limit their ability to recover materials from e-waste fully. Even in countries with a high collection and recycling rate, further enhancing the collection and recovery rate is a problem. Inefficient WEEE recycling results in increasing amounts of e-waste that need to be handled, and valuable materials with high potential to be recovered and reused are lost. The loss of critical raw materials also means that efforts have to be made to mine new materials or purchase from other countries and causing unnecessary environmental and social impact to local communities. Based on the concept of circular economy, such value can be, and should, be retained. Thereby, improving WEEE recycling remains an unsolved issue for both countries with high and low collection rates.

So far, various studies have been conducted to identify barriers to WEEE recycling, such as from the perspective of improving recycling and recovering technologies (see Dalrymple et al., 2007; He et al., 2006), product design (see Gottberg et al., 2006; Hagelüken & Corti, 2010) and business models (see Levänen et al., 2018; Tong et al., 2018). Some studies also analysed WEEE recycling from a market perspective, such as acceptance of recyclable materials and functions of recycling markets. For instance, a study conducted by Organisation for Economic Co-operation and Development (OECD) identified barriers in markets for recyclable materials, including information failures, consumer perceptions, and search and transaction costs (OECD, 2006). In particular, transactions costs are brought up by other literature to evaluate its impact throughout the life cycle of electronics, such as end-of-life products collection (Morana & Seuring, 2011), and levels of impact based on different collection methods (Calcott & Walls, 2005). From an institutional perspective, Nozharov (2018) researched how transaction costs arising from collective waste oil collection schemes and reflecting upon the effectiveness of EPR.

While the literature has indicated several barriers to WEEE recycling, little is known about how inefficient recycling markets affect WEEE recycling, especially how or to what extent do transaction costs affect WEEE recycling. As OECD (2006)'s research focuses on general recycling markets, it is unknown how transaction costs look like in the context of electronics. As transaction costs are significant in recycling markets, in-depth research is needed to understand how they affect WEEE recycling and how can they be reduced. Therefore, this paper seeks to contribute to this field by examining WEEE recycling value chains from the lens of transaction costs.

A better understanding of transaction costs can help mitigate them and make recycling markets more mature. In particular, understanding how transactions of recycled materials happen and what buyer-seller relationships look like can help analyse difficulties that hinder the upscale of recycling and stimulate more transactions. If necessary, policymakers should intervene to promote market development. It is hoped the result can help give an overview of the current status of WEEE recycling, stimulate discussions and contribute to the transition towards a circular economy.

1.3 Research aim and questions

The overarching aim of this research is to better understand to how transaction costs influence WEEE recycling value chains. The objective of this thesis is twofold:

- to map WEEE recycling value chains to find out the process of converting WEEE into recycled materials
- to identify the natures of transaction costs along the WEEE recycling value chain

The following are research questions that guided this study:

RQ 1: How are WEEE recycling value chains structured under Extended Producer Responsibility (EPR)?

- Collective Producer Responsibility (CPR)
- Individual Producer Responsibility (IPR)

RQ 2: What kinds of transaction costs are identified in the WEEE recycling value chain?

- Due diligence costs
- Negotiating costs
- Monitoring costs

This paper first examines the process of WEEE recycling, from consumer to collection centres, recycling plants, and finally to producers in the form of recycled material. Assessing the process from WEEE collection to recycled materials is beneficial to understand how stakeholders along the value chains coordinate with each other and the transaction relationships between them. In addition, as different approaches are initiated under EPR policies, there are two kinds of approaches to organising collection and recycling: collective producer responsibility (CPR) and individual producer responsibility (IPR). To give a more comprehensive understanding, both CPR and IPR are examined to lay the foundation for understanding WEEE recycling processes. It is beneficial to first map the value chain and identify stakeholders involved due to the complex nature of WEEE recycling. After segments and actors in the value chain are identified, Research Question 2 aims to determine how transactions in the value chain are constructed and how transaction costs influence WEEE recycling. Transaction cost (TC) theory is used to analyse the primary sources of extra time and efforts needed to make transactions happen.

1.4 Scope and delimitations

This paper focuses on general electrical and electronic products and is not limited to specific electronic products to give a comprehensive picture. Post-consumer e-waste is the focus of this study, including household waste and business waste. As industrial waste and its by-products are under other regulations and specific requirements to meet environmental standards, it is not included in this thesis's scope. Most of them are treated separately and might not enter municipal recycling systems. Also, regarding recycling, this paper focuses on material recycling, which does not entirely change the structure of materials. Other recycling, such as energy recovery, which combusts waste to generate energy and heat, is not included.

Both collective and individual producer responsibility are examined in this paper, and this study is limited to chosen cases: Sweden for collective producer responsibility and Dell Technologies for individual producer responsibility. How cases are selected is further explained in Chapter 3: Methodology.

1.5 Audience

The intended audience for this thesis is academic researchers who are working in the field of electronics, recycling, or circular economy. The result can also be valuable for policymakers to understand further the current situation of recycling practices in the business and issues that need to be addressed. As transaction costs are essential factors in policy design, understanding the nature of transaction costs can help research appropriate instruments to upscale WEEE recycling. Lastly, stakeholders involved in the electronics industry are the potential audience as they might be interested in the findings. Understanding what kinds of transaction costs other stakeholders have experienced and how they overcome them can be beneficial.

1.6 Disposition

The remainder of this paper is divided into four sections. Chapter 2 provides literature reviews for the background of WEEE recycling, including an overview of collective and individual producer responsibility and identified WEEE recycling barriers. Also, theoretical frameworks applied in this paper are summarised, including global value chain theory and transaction cost theory. Chapter 3 presents the overall research design, including sources of data, data collection methods, and analysis approach. Chapter 4 shows the main findings and results. First, the overview of recycling practices under collective and individual producer responsibility is illustrated, including mapping the value chain and actors involved. Next, transaction costs that occurred in the value chain are identified and their impact is analysed. Chapter 5 provides discussions based on the findings, as well as limitations of this study. Chapter 6 offers the conclusion of this research, including a summary of findings and recommendations for further investigation.

2 Literature review

2.1 Extended Producer Responsibility (EPR)

Although there are no clear definitions, producer responsibility can be further divided into collective producer responsibility (CPR) and individual producer responsibility (IPR) in general. There are ongoing debates over the effectiveness of two systems and which one can better facilitate the implementation of EPR (van Rossem, 2008).

In theory, both CPR and IPR cover financial and physical responsibility (van Rossem, 2008). While CPR refers to producers working together to collect and recycle all products, IPR refers to single producers handling their own end-of-life products. Nevertheless, there is no clear cut between CPR and IPR, and it is possible to implement IPR in parallel with CPR (Kalimo et al., 2012). In some cases, CPR and IPR are operated in parallel to reinforce the collection system (OECD, 2016). In the following sections, features of CPR and IPR are briefly presented.

2.1.1 Collective Producer Responsibility (CPR)

Under collective producer responsibility, multiple producers cooperate to build an industrial-wide compliance scheme and take care of similar products regardless of brands. The cooperation can be built upon financial (e.g. costs of waste management) and physical responsibility (e.g. waste collection and treatment) (van Rossem, 2008). In other words, end-of-life products within the same product groups are collected and not distinguished by brands, and producers share the costs of waste treatment. Usually, third party organisations consisting of industrial associations, such as Producer Responsibility Organisations (PROs), are formulated and assigned to manage the overall planning (van Rossem, 2008). Producers can join PROs with specific fees, and PROs will work on behalf of their members to ensure producer responsibility is fulfilled. Due to different local regulations, the legal status and tasks of PROs vary by regions. While PROs are typically non-profit organisations, they can also be profit organisations or governments in some cases (OECD, 2016). PROs' tasks usually cover the waste collection, logistics from waste collection points to pre-treatment facilities, waste recycling, reporting to authorities and other requirements set by relevant regulations (van Rossem, 2008). Some of the tasks are then outsourced to service providers via tendering. In countries with waste management regulations before the WEEE Directive, such as Sweden, Netherland, and Belgium, such compliance systems are usually run by a single organisation (van Rossem, 2008). In Sweden, even though another competing scheme was established in 2007 to compete with the original system, the latter still holds the dominant role (van Rossem, 2008).

Strengthens of CPR mainly rest upon the benefits of building economies of scale, reducing overall compliance and arranging costs and enhancing the cost-effectiveness of systems (Kalimo et al., 2012; van Rossem, 2008). It is also more convenient from consumers' perspective since they can dispose of all products in one collection point (Khetriwal et al., 2009). However, critics also point out there are several drawbacks. Firstly, a single national organisation handling waste management could result in less competition. PRO's market power in the waste market also limits producers' opportunity to set up individual systems (van Rossem, 2008). Additionally, it is observed that stakeholders in collective schemes mainly focus on facilitating waste collection and market share calculations (van Rossem, 2008). Therefore, fewer incentives are given to producers to modify product design since waste management costs are shared by all producers, and there is no apparent reward for improving their own products (Atasu & Subramanian, 2012).

2.1.2 Individual Producer Responsibility (IPR)

In the early phase, IPR is connected with EPR since the core is to incentivise producers to take their responsibility to re-design products in a way to facilitate waste management, which implies every single producer should properly design and handle their products for the post-consumer phases (Kalimo et al., 2012). Based on Tojo, (2004) 's research, IPR can be further divided into financial and physical responsibility. The former means producers only pay for the waste management of their products. At the same time, the latter implies that waste is collected and separated by brands so producers can have control over their end-of-life products. The significant difference between CPR and IPR is that producers under IPR only finance the waste from their own products and are not required to financially support other waste treatment (van Rossem, 2008). However, IPR is not limited to one form and could be different based on policy design, such as only collecting end-of-life products or also recycling collected products. Therefore, the setting can vary and should be analysed according to contextual factors.

The benefits of IPR is providing more flexibility and control for producers to arrange their waste. Researchers also noticed that IPR is more effective in incentivising producers to alter products designed for recovery to reduce waste treatment costs (Atasu & Subramanian, 2012; OECD, 2016). Some producers also claimed their individual take-back scheme is more cost-effective, such as Hewlett Packard (HP)(Walls, 2006). Compared to CPR operated by PROs, higher welfare can be achieved by IPR (Fleckinger & Glachant, 2010). On the other hand, IPR also comes along with some challenges. For example, the costs of separating waste can be high and make waste collection less convenient for consumers (Kalimo et al., 2012; van Rossem, 2008).

2.2 Barriers to WEEE recycling

In theory, materials with high values should be recovered from the waste due to their remaining value. However, recycling post-consumer waste is challenging because of the difficulty in collecting, sorting, and dismantling e-waste (European Commission et al., 2013). Barriers to e-waste recycling and potential solutions have been discussed by many studies before, and Bakas et al. (2016) and Wahlström et al. (2017)'s findings are summarised as follows.

2.2.1 Difficulties in regulation enforcement

In some countries, WEEE legislation is published to manage electronics waste better. Nevertheless, even in countries with regulations, such as the EU, it is still challenging to improve recycling practices with existing policy frameworks, and instruments fail to be implemented at the national level (Andersson et al., 2019; Ayuk et al., 2020). Take Europe for example. Even though WEEE regulation is in place and sets the requirements of recycling and recovery, incoherent governance standards and lack of monitoring system hamper regulation enforcement (Wahlström et al., 2017). Also, the recycling rate is currently calculated based on the amount of collection, not the amount of waste generated or on the market (Wahlström et al., 2017). Inappropriate governance design prevents policymakers from building an accurate knowledge of recycling, which discourages the development of new solutions (Bohr, 2006). Therefore, how to build a holistic framework to include all relevant countries is tricky and highly relies on the integration of governance and trade agreement on an international level.

2.2.2 Complex design and materials used

First of all, electronics products have a complex design. Most electronic devices feature a wide variety of substances and high metal complexity, increasing the difficulties of recovering all materials. Research shows that, in general, at least 69 elements can be found in electronic products (El-Kretsen, 2021b). Take smartphones for example. Below is an overview of product contents.

Table 2-1. Product contents of smartphones

Components	Contained Materials
Cases	Plastic, aluminium, iron and copper
Printed circuit board	Aluminium, copper, gold, nickel, silver, plastic
Microphone/speaker	Copper, iron, nickel, rare earth elements(neodymium, samarium)
Battery	Cobalt, graphite, lithium, nickel
Screens	Glass, tin, rare earth elements

Source: El-Kretsen (2019); Responsible Minerals Initiative et al. (2018)

For now, attention is mainly given to high-value materials (e.g. gold and silver) or materials accounting for more significant portions (e.g. copper), so recovering practice for these materials are relatively common. However, it is still challenging to upscale using recycled materials further and expand the scope to other materials. Also, there is a lack of transparency in product content, as producers are not required to disclose a detailed material list used in electronic products. This situation increases the difficulties for downstream recyclers to identify what materials they are handling right now and how they should handle them (Holgersson et al., 2018).

2.2.3 Resource-intensive recycling processes

In addition, it is time-consuming and labour-intensive to dismantle e-waste due to the complex design of electronics. Among all materials contained in electronics, some only account for a low concentration and are usually mixed with other components in the waste streams (Bakas et al., 2016; Lukowiak et al., 2020). Therefore, it is more complicated to recover materials with existing recycling technologies. The amount of effort and cost spent collecting, separating, and purifying materials could be significant (El-Kretsen, 2021d). Only a few recycling plants have developed advanced technologies to handle specific materials, but the cost of operation is relatively high (Bakas et al., 2016).

2.2.4 Low cost-effectiveness

Even though technologies have been developed to recover materials from e-waste, the issue of financial viability still affects industries' interests to invest (Lukowiak et al., 2020). As Godoy León et al. (2020) pointed out, downcycling is a current issue as some recycled material extracted from the waste might be not pure enough to be used as raw materials.

Regarding mobile phones, Geyer & Doctori Blass (2010) assessed the recycling values and found that the recovery of materials other than precious metals would not increase profit margins for recyclers, thereby limiting the recovery scale. Transaction cost can also affect the willingness of businesses to engage with focal technologies as the supplier-buyer relationships are delicate, and transaction costs could be high. As Andersson et al. (2019) noted, individual actors are exposed to high costs of e-waste treatment, such as finding trustworthy partners or sources of secondary raw materials. How to distribute risks and rewards equally to stakeholders, including manufacturers, suppliers and consumers, is the key to enhancing the recycling value chain.

2.2.5 Fragmented value chain

Lastly, because of globalisation, the value chain of electronics scatters across several countries and regions. Regarding collection, e-waste spreads out geographically and thereby increases the complication. Issues occur between different areas as there is a trend for developed countries to export e-waste, resulting in electronic scrap ending up in waste streams in other countries (Bohr, 2006). Even within one region, multiple stakeholders, including producers, consumers and recyclers, are involved and increase the difficulties of building conversations and consensus. Assigning clear responsibility for waste treatment can be complicated as some might argue it is recyclers' job to handle e-waste. At the same time, some believe that it is producers' job based on the concept of Extended Producer Responsibility (EPR) (Wahlström et al., 2017).

2.3 Global value chain theory

GVC theory was first developed and used in the field of economics to understand how economic globalisation is constructed and what strategies are used to coordinate stakeholders (Gibbon et al., 2008). Initially, issues like how leading firms assert their influence over the value chain to organise manufacturing were discussed. For example, how does power relationships between buyers and sellers determine resource allocation (Gereffi, 1994) and how firms choose to specialise in some functions and outsource others (Barrientos et al., 2010). Later, modern GVC has focused on analysing constitutional frameworks (Kaplinsky & Kaplinsky, 2013). The influence of embeddedness is underscored and elaborated to include contextual factors since the social context has affected economic action and shaped both the form and outcomes (Bair, 2008).

Apart from economic development, the GVC framework can also provide an insightful perspective to understand sustainability and environmental issues due to its speciality in integrating fragmented parts of one process (Coe et al., 2008). For instance, GVC was used by Lepawsky & Billah (2011) to trace and map e-waste flows into Bangladesh. Crang et al. (2013)'s research further pointed out why GVC should be included in recycling. Firstly, recovering secondary materials from waste is not simply influenced by the demand of products but also by other factors like supply and the fluctuations in virgin raw materials. Therefore, the interconnection between stakeholders and markets is more complicated. Also, the recycling process is a chain of value extraction, which is highly associated with material content and how value is captured through each tier of the supply chain. Lastly, intermediary agents who coordinate and connect waste flow have a significant role in the value chain and should be analysed how their role affects transactions in the global networks.

Under the global context, recycling activities are highly complex since multiple stakeholders are involved, and commodities are transported between regions. Coordination between stakeholders is thereby essential to form the value chain in the first place. Questions like how WEEE is converted to recycled materials should be better researched. Moreover, GVC theory would be suitable for mapping the geography of WEEE recycling activities and analysing how the value chain is constructed. The exchange of WEEE is under the global networks. Thereby there is a need to explore this issue from the GVC approach since the cross-regional mobility of waste highlights the need to rethink post-consumption practices (Lepawsky & Billah, 2011).

2.4 Transaction cost theory

While GVC highlights the coordinations of segments to nudge WEEE recycling, Transaction costs (TC) theory aims to explain how decisions are made under bounded rationality and asymmetric information. Since the value chain is fragmented, it requires a high level of knowledge and coordination to make transactions along a chain happen (Gibbon et al., 2008).

2.4.1 Definitions of transaction cost

As part of fundamental components of New Institutional Economics, transaction cost analysis is widely used to understand how market agents make economic decisions under specific institutional frameworks (Kiss & Mundaca, 2013; Mundaca et al., 2013). New Institutional Economics is based on two critical assumptions of human behaviour: imperfect information and bounded rationality. Although individuals or organisations seek to act rationally based on their knowledge, entirely rational behaviours do not exist due to natural limits of abilities to collect and process information. Under this circumstance, bounded rationality limits the ability to identify and manage the necessary information to make informed decisions, making it difficult to grasp a comprehensive understanding of one issue, thereby causing imperfect markets. Transaction costs are needed to analyse how humans make decisions under these circumstances and also provide a way to research how to decrease transaction costs (Kiss & Mundaca, 2014).

TC theory was first used to explain how firms make decisions to maximise their profits, focusing on pre-contractual activities, such as searching for information. TC was then promoted to understand how businesses decide to produce products internally or outsource tasks to third parties. By this time, post-contractual activities were included into consideration, such as execution, control and enforcement (Riordan & Williamson, 1985). The broad configuration of transaction cost theory was established, including pre-and post-contracting activities (Furubotn & Richter, 2010). The critical premise of transaction cost theory is that the cost of doing transactions could be so high that they hinder the progress of commerce or even block transactions. As transaction costs are too high for individuals, organising transaction costs from a firm or hierarchy structure would be ideal (Grover & Malhotra, 2003). Nevertheless, transaction costs might still be high for organisations when making decisions to involve business activities. For now, there is no one universally accepted definition of transaction costs. Below is an overview of definitions of transaction costs proposed by different researchers:

Table 2-2. Different definitions of transaction costs

Researchers	Definitions of transaction costs
Coase (1960)	*"the cost of carrying out market transactions"*
Matthews (1986)	*"costs of arranging a contract ex-ante and monitoring and enforcing it ex-post, as opposed to production costs"*
Vatn (2001)	*"costs of gathering information, making decisions/contracting, and controlling/policing to ensure that the results are what was intended"*
Connelly et al. (2011)	*"search and information costs incurred in finding the best goods or services in the market, monitoring and control costs incurred to ensure proper behaviour from the external source, and mediation or legal costs incurred should the external source act inappropriately."*
Kiss & Mundaca (2014)	*"costs related to financial operations, but not directly involved in the production of goods or services, unavoidable and often unforeseeable costs emerging from contracting activities."*

Traditionally, transaction cost theory is used to explain economic behaviour or activities. For instance, Grover & Malhotra (2003) utilised transaction cost theory to examine operation and supply chain management in the electronics industry. Later, the use of TC is expanded to the field of sustainable development. It could be the case that when organisations evaluate the possibilities of adopting new recycling technologies, they need to identify potential suppliers and analyse implementation costs and potential benefits (Connelly et al., 2011). Mundaca (2007) examined the nature and scale of transaction costs of an energy efficiency commitment in the UK and found out that TCs can make new technologies seem more expensive and unattractive, even though the overall economic benefits eventually outweigh the cost. Kiss & Mundaca (2014) used TC theory to understand transaction costs arising from energy-efficient projects of passive houses by assessing each phase of the life cycle of building projects.

McCann et al. (2005) argued that transaction cost should be included in evaluations of public environmental policies for ex-ante and ex-post policy analysis. Before formulating a policy, including transaction cost can help evaluate the feasibility of different policy approaches. After a policy is implemented, transaction cost theory can help measure the cost of monitoring the performance (McCann et al., 2005). For policymakers, including transaction costs into policy analysis frameworks can contribute to formulating a better policy design. By identifying sources of transaction costs, policymakers can understand what transaction costs stakeholders are facing now and to what extent they have influenced the market. If transaction costs occur and affect most stakeholders, it is worth discussing how to eliminate transaction costs with policy instruments. Overall, including transaction cost theory into policy design can help understand how to achieve anticipated policy goals with less cost, improving policy design (McCann et al., 2005). Also, TCs can be used to assess the performance of the policy. Decreasing transaction costs with policy instruments can help promote the diffusion of innovative sustainable technologies (Mundaca et al., 2013).

2.4.2 Taxonomies of transaction costs

Though there is no unified framework to apply transaction cost theory, identifying and categorising transaction costs can help compare different studies (McCann et al., 2005). Some researchers attempted to provide a clear framework to understand different categories of transaction costs. Below are examples of different taxonomies of transaction costs identified from literature review.

Table 2-3. Different taxonomies of transaction costs

Researchers	Natures of transaction costs	Notes
Thompson (1999)	• enactment costs • implementation costs • monitoring/enforcement costs	Focus on costs occurring after the transaction is enacted
McCann et al. (2005)	• research and information • enactment or litigation • design and implementation • support and administration • contracting • monitoring/detection • prosecution/enforcement	Take initial costs for research and information into considerations
Mundaca (2007)	• search for information • persuasion of customers • negotiation with business partners • measurement and verification activities	Focus on energy efficiency commitment
Morana & Seuring (2011)	• information costs • planning costs • inventory costs • travel and transportation costs • time costs • psychological costs	Focus on transaction costs for consumers to return waste products
Mundaca et al. (2013)	• searching for information • negotiation • approval and certification • monitoring and verification • trading costs	Focus on low carbon technology
Kiss & Mundaca (2014)	• due diligence costs • negotiating costs in the procurement process • monitoring costs	Focus on energy-efficient projects

McCann et al. (2005) further identified when transaction costs happen. For example, while costs of research and information run through the whole process from policy development to implementation, monitoring/detection and prosecution/enforcement cost only happen after the policy is implemented. Apart from timing, McCann et al. (2005) also discussed which stakeholders or agencies can trigger transaction costs and who eventually bears the costs as the senders, and the receivers could be different. For example, while policymakers are the ones who formulate an inappropriate design of renewable energy development policy, industries participating in the program might be the ones to absorb the cost (McCann et al., 2005).

Since transaction costs theory can be used in different disciplines, nature and categories vary case by case. Therefore, transaction costs should be analysed based on one specific case, industry or region.

2.4.3 Scales of transaction costs

To date, only a few studies have quantified scales of transaction costs associated with sustainable issues. Transaction costs can be measured in absolute value, like monetary terms (e.g. SEK) or units of time (e.g. hours), but most of the time, TC are presented in percentage (%), so it is easier to understand proportion to the total cost.

For example, Kiss & Mundaca (2014)'s analysis found out that transaction costs of passive house renovation in Sweden can be 200% higher than traditional renovations. Fang et al. (2005)'s research of a point–nonpoint source trading program in Minnesota, U.S., found out transaction costs increased the total cost of the projects by at least 35%. Pannell et al. (2013) used one institution under the Australian government to research the public sector. They found out more than 65% of funds are categorised as transaction costs to communicate environmental policies, including building networks, providing information, and building capabilities for regional government bodies. Wang et al. (2018)'s research pointed out transaction costs (monitoring, reporting and verification) represent around 10-16% of the total costs of emissions trading scheme (ETS) in seven regions of China. Krey (2005) focused on the Clean Development Mechanism (CDM) projects in India and found out transaction costs for chosen projects range from 0.07 to 0.47 $US/t CO2. By assessing GHG trading projects in the U.S., Antinori & Sathaye (2007) found out that while transaction costs for large projects are about $0.03 per tonne of carbon dioxide, smaller projects are under the more significant influence ($4.05 per tonne of carbon dioxide).

2.4.4 Limitations of transaction cost theory

Even though the importance of transaction cost is well recognised, there are still several limitations and uncertainties when applying transaction cost theory. To begin with, identification of transaction costs could be an issue. While explicit transaction cost is easier to tell, it is harder to distinguish implicit cost. For example, explicit transaction costs could be cost paying for consulting services to evaluate the cost-effectiveness of recycling technology, which is quite evident for calculation. However, implicit costs like time spent searching available consulting firms and reading information are more difficult to track (Verhaegen & Van Huylenbroeck, 2001). Thereby identifying TC is highly subject to stakeholders' feelings and memories.

Moreover, the accuracy of quantified transaction costs could be controversial as various issues could affect the performance and implementation, accountability might be unclear. Findings also highly rely on tools used to monitor or track performance. Also, data collection could be troublesome as most transaction cost analysis depends on interviewing stakeholders or conducting surveys. Some transaction costs could be complicated to track and rely on stakeholders' memory, such as time investing in researching information or negotiating. Therefore, how rigorous the interview protocol or survey design is can significantly affect findings. As one criticism of qualitative research, like interviews, is that stakeholders' opinion could be biased, researchers need to identify and eliminate subjective statements. Moreover, identified transaction costs are only suitable to explain situations under a specific geographical and temporal scope. Because contextual factors play critical roles in transaction cost analysis, directly applying transfer findings and applying them to other cases is unsuitable. As emphasised by Mundaca et al. (2013), TC analysis can not be generalised due to endogenous determinants (sizes of projects, baseline setting, technologies), exogenous drivers (policy frameworks, regulatory complexity of schemes), and methodological aspects.

2.5 Summary

To conclude this section, the literature identified that EPR can be broken down into two forms: CPR and IPR, and both have their strengths and weaknesses. Even though WEEE recycling is a well-recognised approach to better manage e-waste, obstacles still exist and prevent the promotion of recycling. To tackle this issue, this paper aims to analyse this issue from the angle of transaction costs. Even though TCs is complicated and transaction costs theory has some drawbacks, such as the accuracy of classification and calculation of TCs, it can still be a valuable tool to understand the WEEE recycling value chain. As the electronic supply chain is often across several countries, it increases the difficulties to integrate stakeholders. Therefore, the GVC theory can be used as an important point to develop a general understanding of WEEE recycling value chains. Then, transaction cost theory can serve as a valuable angle to deepen understanding of electronic recycling. From producers, e-waste collectors, recyclers to refiners, each stakeholder might face different sources of transaction costs. By researching segments of value chains essential to make recycling happen, we can summarise the typical transaction costs that occur, identifying appropriate solutions.

3 Methodology

3.1 Research design

A qualitative approach was deployed in this research to obtain in-depth knowledge of transaction cost influencing WEEE recycling in both collective and individual producer responsibilities. Because of the complexity of the issue and multiple stakeholders involved, qualitative methods are suitable to build a thorough understanding of the socio-economic background of recycling practices (Blaikie & Priest, 2019). Also, different perspectives based on various social backgrounds can be examined and considered to grasp the bigger picture of the social framework (Flick, 2006). Given that the application of WEEE recycling is relatively novel and still under development, literature analysing the transaction costs of WEEE recycling value chains is relatively few. Qualitative research can help set the baseline to understand situations of chosen cases and build the cornerstone for further analysis.

An interdisciplinary research approach is utilised to enhance the robustness of this paper. Due to the dynamic nature of electronic value chains, it is clear that solutions for WEEE recycling are beyond the scope of a single discipline and require a broader perspective. In this paper, two concepts are adopted to draw up a bigger picture: global value chain theory and transaction cost theory. GVC theory is adopted to first map WEEE recycling value chains for several reasons. First, WEEE recycling value chains look different in different regions or under different approaches. In addition, the transboundary movement of WEEE is a common practice. Thereby, it is beneficial to first build an understanding of how recycling segments are connected in chosen cases. Next, WEEE recycling is intertwined with EEE supply chains as recycled materials are sent back for manufacturing new products. Therefore, understanding how WEEE recycling value chains are structured from a global perspective is required, such as how WEEE is collected and where does recycling take place. After having a basic understanding of how the WEEE recycling value chain is constructed, TC theory is then used to discover how transaction costs influence WEEE recycling and the market of recycled materials. Apart from identifying the categories of transaction costs, this paper also researches how transaction costs are related to the essence of global value chains. For instance, whether the dispersed value chains increase transaction costs and make WEEE recycling more challenging. Using interdisciplinary research with these two concepts can help better understand the complex nature of WEEE recycling and draw specialized insights into this topic.

3.1.1 Case studies and case selection

This paper is based on case studies research, along with professional experience and academic research. As Yin (2003) suggested, case studies are suitable to analyse situations or phenomena featuring multiple variables within the geographical and temporal context. In this study, case studies were adopted to identify the nature and categories of transaction costs arising from WEEE recycling.

Since this study focuses on WEEE recycling in two chosen cases, it is essential to highlight that findings are built upon the defined scope and cannot be simply generalised or transferred to understand other cases (Blaikie & Priest, 2019). Considering WEEE management and waste systems vary significantly by countries, this study only covers particular cases and can not be generalised or replicated to explain other cases with different waste management mechanisms or diverse contextual backgrounds. The following is an introduction of two cases: Sweden for CPR and Dell for IPR.

Case of collective producer responsibility (CPR)

Sweden is used as a case study to present the electronics recycling value chain under CPR and understand how collective systems are structured via cooperations of producer associations and municipalities.

In Sweden, WEEE management legislation was introduced in 2001, before the Waste Electrical and Electronic Equipment Directive formulated by the EU in 2003. The concept of EPR was adopted in the early stages to encourage producers to treat post-consumer products properly, and electrical and electronic products (EEE) is one of the seven product groups under its influence. Producers of EEE, including companies who manufacture EEE in Sweden and resellers who import EEE from other countries to Sweden, should take the responsibility to manage their products when products reach the end-of-life phase (Naturvårdsverket, 2020b). Under regulations, Producers are required to take back discarded products and cover the financial cost of WEEE management.

In practice, producers in Sweden mainly work together via PROs to set up waste collection and treatment systems. Working on behalf of producers, PROs assist their members in implementing EPR by taking over end-of-life products and prepare them for recycling. Producers have to provide financial support to cover the costs of PROs by paying a membership fee and are charged based on market shares. On the other hand, producers are obligated to cover WEEE collection and treatment costs and provide necessary information on the local collection system to consumers (Naturvårdsverket, 2020b).

In addition, Sweden is chosen for several reasons. First of all, regarding the WEEE generation per capita, Sweden ranked top 3 in Europe in 2018 (Eurostat, 2021). Also, the WEEE collection rate in Sweden is less than 60%, which is still below the EU target of 65% by 2035 (Eurostat, 2020). According to research conducted associated with Sweden's trade organisation for the recycling industry, only 24% of the original value of materials is retained through recycling. Forty-two billion kronor of material value is lost every year due to material loss and down recycling (Material Economics, 2020). Therefore, Sweden must research potential approaches to manage e-waste properly. Below is an overview of the retained and lost value from recycled materials in Sweden.

Table 3-1. Retained and lost value from recycled materials of Sweden

Types		Plastic	Steel	Aluminium
Worth of end-of-use materials (annually)		10	29	3.1
Value retained via recycling (secondary raw materials and energy recovery)		1.3	9*	1.2
Value loss	Improper collection and processing	8.7	7	0.9
	Downcycling		5	1.2

**Note: recycling process of steel requires 9 billion SEK* *(Units: billion SEK)*

Source: Material Economics (2020)

In 2020, the Swedish government published a "Circular Economy Strategy." One of the key targets is to handle materials in a more circular way to reduce loss of value from material flow (Government Offices of Sweden, 2020). Several action plans are also under discussion now, including providing convenient ways for households and business to leave their waste, separating waste at the source, promoting recycling capacity, increasing the supply and demand of secondary raw materials, setting requirements for virgin and recycled materials, and disclose relevant information to facilitate recycling (Government Offices of Sweden, 2020). As retrieving materials from e-waste is highly built on the foundation of a robust waste management system, Sweden can serve as a valuable case to understand what factors hamper the promotion of WEEE recycling even in countries with relatively high WEEE collection rates.

Due to the complexity of the electronics supply chain, it is expected that different sources of transaction costs occur in each stage of the electronic life cycle. Thereby multiple stakeholders were interviewed to obtain their perspectives, including producers, collectors, recyclers, smelters and NGOs. As Sweden is one of the Member States of the EU, EU policies and legislations were also taken into consideration.

Case of individual producer responsibility

In comparison, Dell Technologies (hereafter referred to as Dell) is used as a case study to analyse individual producer responsibility, which means a single producer initiates a closed-loop recycling system to recycle their own products. As a multinational company, Dell operates its take-back schemes worldwide and has successfully built "closed-loop recycling" for several materials.

In the beginning, Dell started setting up their own take-back schemes in some states in the U.S, then expanded to other states and countries by cooperating with local NGOs. Nevertheless, Dell is ambitious to go beyond simply taking back their products and aims to fulfil their responsibilities by taking more control over collected waste. Dell believes a more holistic approach to solve waste generation issues and achieve a circular economy would be recovering materials from waste and sending them back to the production loop, and that is why Dell chooses to build a closed-loop recycling. Under the company-wide sustainable agenda, Dell reviews and renews the sustainable goals regularly, and material innovation is one of their mid-term targets. According to the recent agenda, the company aims to fulfil the following goals by 2030 (Dell Technologies, 2021a):

- More than 50% of products are made from recycled or renewable material
- Reuse and recycle an equivalent product for every product Dell sells

Dell has initiated several pilot projects in different countries to test the possibilities of closed-loop recycling, and plastic was one of Dell's early successes. Apart from plastic, Dell has expanded its research scope to gold and rare earth elements. Therefore, Dell is one of the successful cases that producers individually carry out their responsibility by setting their own take-back scheme, recycling their collected waste and using recycled materials collected from waste to produce new products. In this way, a close-loop of connecting production and recycling is built.

In this paper, the main focus is given to how Dell runs take-back schemes and forms closed-loop recycling stemming from the waste collected in the US. Since Dell's value chain starts from collecting waste in the US to shipping waste to Asia for pre-treatment and recycling, Dell's partners in the US and Asia are included in this paper to understand the complexity of electronic value chains. Dell's general waste management practices in the EU is also analysed to compare and research why Dell takes different approaches.

3.2 Data collection

Both literature reviews and interviews were used as data collection methods, and the purpose is to triangulate the information as different perspectives can be included to examine the social phenomenon (Flick, 2006). Since the electronic value chain is highly complex, collecting insights from other data sources can help construct a more comprehensive situational context by combining or supplementing various opinions, thereby reducing potentially biased statements. For example, producers and recyclers might have different emphases, and stakeholders from other regions might encounter different experiences. It would be valuable to conclude the most significant factors based on materials collected from various sources. While interviews and literature review are used to answer Research Question 1 by mapping the overall situation of WEEE recycling and identifying who is involved in the process, Research Question 2 relies on interviews to categorise transaction costs based on practitioners' experience.

3.2.1 Literature Review

Based on the structure proposed by Flick (2006), three forms of literature reviews were conducted:
(1) Theoretical Literature to build a foundation
First, a preliminary literature review was conducted by reviewing government documents, industry reports, academic articles, and relevant webinars to understand the background on the topic. It can help comprehend what area is already discussed before, if there is any debate or disagreement, and what remains unknown. Thereby, research gaps can be identified. In this research, the use of this step was to verify if WEEE recycling barriers exist, the main issues, and if current regulations are sufficient. Terms like "WEEE," "recycling", "barriers", and "policy" were used to search literature via online searching engines, including Google Scholar and Lund University Library.

(2) Methodological Literature to understand how to research with what methods
Further research was conducted to identify what theories are already in place to explain this issue or what methodological frameworks are usually adopted in this field. Two main theories were identified as most suitable for this study: global value chain (GVC) and transaction cost theory (TC). The analytical framework combined with two theories used to research the topic and a more thorough literature review on both theories was conducted.

(3) Empirical Literature to contextualise findings and answer research questions
Lastly, a detailed literature review was used to answer the research questions. To understand current WEEE regulations and management structure, policy documents, organisations' reports and academic papers were reviewed to collect existing literature to support the arguments. Next, documents from interviewees' organisations, such as company reports and statements, are researched before the interviews to understand better organisations' business model or achievements, which can help construct more specific questions and enable more meaningful discussion.

3.2.2 Semi-structured interviews

To deepen the knowledge on the practice side and gain a better insight, the research centres on an empirical study involving stakeholders in the electronics industry. In-depth interviews were conducted to understand their experience of recycling practice in electronics recycling and their insight on significant transaction costs. The purpose is to identify what transaction costs exist in which stage of the value chain and how they influence recycling. Because of various stakeholders involved in electronics, a sampling method was used to select representatives from key stakeholder groups., including EEE producers, waste collectors, recyclers, smelters, IT infrastructure providers, reverse logistics, industrial associations and NGOs.

The primary criterion for selecting participants was their working experience or knowledge in the electronic value chains. Potential interviewees were first contacted via email or LinkedIn to set up informal talks and identify if they were suitable and interested in this topic. In-depth interviews were then conducted online due to the restriction resulting from COVID-19. A snowball sampling method was also applied to expand the research scope by asking interviewees if they recommend other resources. An interview protocol was formulated and was followed in each interview (see Appendix A). Apart from interview protocol, semi-structured interviews offer flexibility for more discussions if overseen factors are not identified yet (Blaikie & Priest, 2019). A total of fifteen practitioners were interviewed, including EEE producers, WEEE collection, WEEE pretreatment, WEEE recycling and NGOs (see Appendix B). Each interview lasted approximately one to two hours and was audio-recorded and transcribed for later coding and analysis.

3.3 Data analysis

After materials were gathered and interviews were transcribed, qualitative content analysis was performed to identify characteristics of transaction costs by categorising empirical materials, including interviews and business reports obtained from open sources. As one of the classical procedures for analysing qualitative material, content analysis was used to identify patterns or specific characteristics in collected data and categorise them by critical themes. Content analysis can systematically examine data by categorising, which effectively reduces the number of materials to process (Flick, 2006).

In this paper, content analysis was conducted based on the suggested procedure proposed by Mayring (2000). Firstly, collected data is analysed based on the source, approaches to collection and stakeholders involved to understand the contextual factors. Then, GVC literature was utilised to map WEEE value chains under different producer responsibilities. When analysing transaction costs, a coding framework was derived from the taxonomy proposed by Kiss & Mundaca (2014) as a starting point to categorise transaction costs (see table 3-2). Since currently there is no direct literature addressing transaction costs in WEEE recycligng, this paper borrowed the taxonomy from Kiss & Mundaca's research. As the taxonomy proposed by Kiss & Mundaca's focuses on transaction costs in implementing energy efficient technologies, the basic farework shared some similarities with this topic as WEEE recycling is also highly connected to recycling technologies. Next, interview transcripts and other literature were reviewed, organised into the framework. Revisions of the taxonomy were made according to the findings to ensure the taxonomy aligns with WEEE recycling. Lastly, results are analysed and interpreted by integrating initial research questions with findings.

Table 3-2. Taxonomy of transaction costs

Categories of transaction costs	Indicators
Due Diligence Costs	searching for and assessing information on • forms of collaboration • partners technically • economically feasible solution • assessment methods
Negotiating Costs	• preparation for procurement • contracting • assessment • approval
Monitoring Costs	follow-up on • effectiveness • saving

Source: Kiss & Mundaca (2014)

3.4 Ethical consideration

Interactions with stakeholders were planned following the general principles of informed consent. No funds were allocated to this project, eliminating the conflict of interest. All interviews were conducted based on voluntary participation, and interviewees could decide whether they prefer to remain anonymous. A confidentiality statement was highlighted to each interviewee before the meetings, specifying that they had the chance to review the note or transcript of the interview. Permission for audio recording interviews would be brought up in advance. Collected materials would be stored on the author's online drive under the author's account only.

The procedures of collecting and analysing materials and data were disclosed in section 3.2 and 3.3. Apart from thesis supervisors, no one has influenced the author's analysis. Since this thesis aims to understand the current recycling situation in the electronics industry, the finding does not potentially harm interviewees' reputations or privacy. While only significant findings are included, sensitive information was avoided by using codes instead of specifying interviewees' names. This research design has been reviewed against the criteria for research requiring an ethics board review at Lund University. It has been found not to require a statement from the ethics committee.

3.5 Limitations

One main limitation of qualitative tools is that findings might be subjective because qualitative research relies on people's observations. Also, not all relevant practitioner groups were included in the study due to a lack of access to them and time constraints. This limitation was minimised by disclosing data collection and analysis procedures, so readers can clearly understand the defined scope of this study. The interviewees' basic information was provided to build institutional contexts of that case and how interviewees' viewpoint might be affected by their positions or organisations' philosophy (Flick, 2006). Additionally, collecting data from multiple sources can help triangulate findings, including interviews and literature. Another limitation is that this paper only focuses on identifying the nature of transaction costs emerging from WEEE recycling chains instead of also measuring the scale of transaction costs. Although quantifying transaction costs could be valuable to understand the actual impact, it is challenging to conduct since there is no clear definition of transaction costs concerning WEEE recycling.

4 Findings and analysis

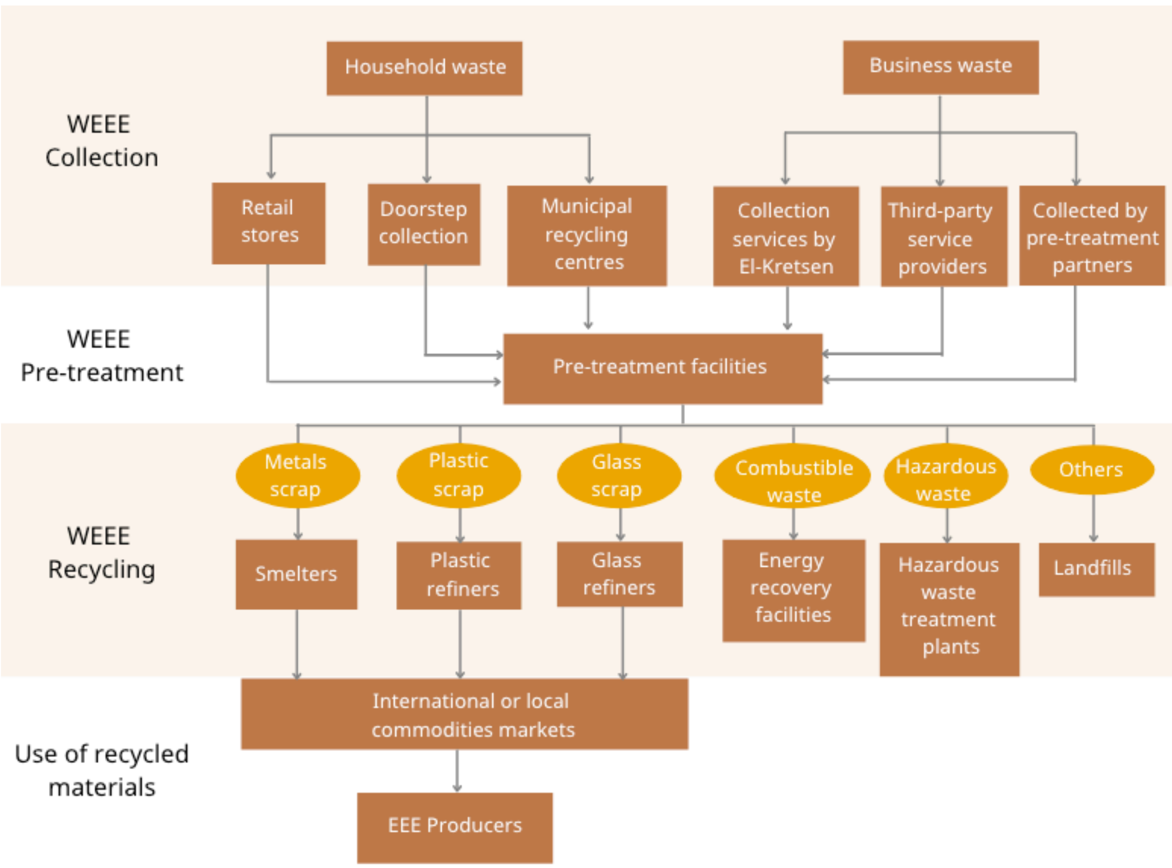
In this section, WEEE recycling under CPR is first presented by using Sweden as a case study. While most EEE producers in Sweden join the collective waste collection scheme, most WEEE products groups are collected and recycled together. Next, recycling under IPR is examined by using Dell as an example. As a multinational company, Dell has initiated their own take-back schemes worldwide and built closed-loop recycling for plastic and gold. Lastly, by combining CPR and IPR, transaction costs appearing in value chains are identified and connected. The nature of transaction costs is analysed to specify how they influence the transaction.

4.1 Value chains of WEEE recycling

4.1.1 Collective producer responsibility (CPR)

The following section describes WEEE recycling value chains in Sweden, focusing on WEEE collection, pre-treatment, recycling and finally, the use of recycled materials. The overview of the recycling value chain is summarised in figure 4-1 and divided into four stages of value chains. These four stages are separately explained as follows.

Figure 4-1. Overview of WEEE recycling value chains in Sweden



Source: created by author based on Ylä-Mella et al. (2014)

WEEE collection

In Sweden, multiple approaches have been adopted to facilitate collections, and most of the collection is accomplished based on non-profit Producer Responsibility Organisations (PROs). Currently, there are two approved PROs in Sweden: El-Kretsen and Recipo (Avfall Sverige, 2020). The former collects WEEE via municipal collection centres, and the latter collect WEEE via retail stores (Naturvårdsverket, 2020a). As the first PRO in Sweden, El-Kretsen was established in 2001 when WEEE management legislation came into force in Sweden and currently consists of 19 EEE industrial associations (Naturvårdsverket, 2020a). By cooperating with local municipalities, El-Kretsen accounts for around 99% of WEEE collection. On the other hand, Recipo was later found in 2007 with 14 members and mainly focuses on collection via retail stores, which account for around 1% of WEEE collection(Naturvårdsverket, 2020a). Apart from collective systems, it is also possible for producers to collect and treat WEEE independently, such as setting individual take-back schemes or through waste management service providers. The following section focuses on El-Kretsen's practice due to its significant role in the collection.

As the largest PRO in Sweden, El-Kretsen cooperates with the Swedish Waste Management and Recycling Association, Avfall Sverige, to collect WEEE. The cooperation mechanism between El-Kretsen and Avfall Sverige is called El-retur (Avfall Sverige, 2020). El-Kretsen has agreements with local municipalities to organise and collect WEEE at 583 municipal recycling centres in Sweden (Avfall Sverige, 2020; Naturvårdsverket, 2020c). It is the municipalities' responsibility to set up collections points for consumers to leave waste electronics products and also inform the public about correct waste disposal and sorting practices (Naturvårdsverket, 2020a). El-Kretsen is responsible for arranging WEEE collection, including procuring collection, transporting and recycling services (Respondent 1). In addition, El-Kretsen communicates with authorities and reports collected and recycled information (Naturvårdsverket, 2020a).

Product fees and materials revenues finance El-Kretsen. Product fees are charged based on the product's material content and size and account for one-third of El-Kretsens' operating expenses (Naturvårdsverket, 2020a). El-Kretsen then subcontract services to around 500 sub-contractors to facilitate the collection process (Naturvårdsverket, 2020a). When selecting suppliers, El-Kretsen' partners must be certified by one of the European collection standards organisations, including the European Committee for Electrotechnical Standardisation (CENELEC) or the WEEE label of Excellence (WEEELabex) (Respondent 1). CENELEC is the European Standardisation Organisation which formulates standards to collect properly, transport (TS 50625-4) and treat end-of-life products (TS 50625-3-1) (CENELEC, 2017).

For household waste, consumers can either send discarded electronic products to municipal collection centres or electronic shops as they are responsible for taking over the waste no matter if these are their products or not (Respondent 1). For business waste, companies can work with private waste management companies, which offer services to collect waste and take care of the rest of the process, such as assessing products' status and see whether they can be repaired or sent to pre-treatment (Respondent 8). Also, for large amounts of e-waste, businesses can directly order containers from El-Kretsen to collect their waste (Respondent 1). In some cases, businesses also have agreements with pre-treatment partners to directly send the waste to pre-treatment facilities (Respondent 3).

At collection points, EEE is collected based on six fractions: small appliances, refrigerators and freezers, white goods, batteries, fluorescent lamps, LED and incandescent light bulbs (Respondent 1). Guidance workers can be found in collection centres to guide customers on putting obsolete products in the correct recycling bins (Respondent 2). For hazardous waste, such as batteries, it should be pulled out and collected separately and then sent to corresponding pre-treatment and recycling facilities (Respondent 2). Pre-sorting is conducted in collection points to identify whether electronic products can be refurbished (Respondent 2). If yes, they will be sent to repair shops; if not, they will be sent to pre-treatment partners to dismantle and recycle. To protect the collected waste from being directly exposed to rain or sunlight, legislation is in place to ensure proper waste storage and transport of waste. Nevertheless, damages on the site or transporting might still happen and decrease the quality of waste (Respondent 2).

For now, El-Kretsen has 50,000 containers for WEEE (El-Kretsen, 2021a). To better monitor the waste flow, ID tags are placed on containers by El-Kretsen (Respondent 1). Once containers are full, logistics are contacted by El-Kretsen to pick up containers and transport WEEE to pre-treatment facilities. In particular, 2 percent of WEEE is sent to El-Kretsen's analysis facility to identify waste content and aggregate statistics for further research (Respondent 1). From collection points to pre-treatment facilities, El-Kretsen commissions the transportation to 15 transport partners via procurement (Naturvårdsverket, 2020a). How to better plan transport routes and enhance containers' full rate is an issue El-Kretsen keeps working with their partners (Respondent 1).

In 2020, a total of 156,000 tonnes of WEEE was handled by El-Kretsen, which is equivalent to approximately 67 million products (El-Kretsen, 2021a). Below is an overview of WEEE collected in recent years:

Table 4-1. Volumes of collected WEEE by El-Kretsen

Collected WEEE	**2018**	**2019**	**2020**
General electronics	78,730	80,225	84,512
Refrigerators and freezers	25,363	24,662	28,120
White goods	34,114	35,805	36,017
Batteries	3,170	3,383	3,460
Fluorescent lamps	1.734	1,878	1,813
LED and incandescent light bulbs	680	624	616
Other/ professional electronics	2,438	1,030	1,183
Total	146,228	147,627	155,721

(Units: tonnes)

Source: El-Kretsen (2021)

WEEE pretreatment

After WEEE is collected and sorted in different containers, household and business waste are sent to pretreatment facilities where WEEE are prepared for recycling (Respondent 3, 4). Apart from receiving WEEE from PROs, pretreatment facilities also offer customised service to collect, sort and process industrial waste directly (Respondent 3). In that case, waste varies greatly depending on the customer. For example, it could be containers full of PCs and laptops or a mix of everything (Respondent 3).

Stena Recycling is one Swedish company that handles WEEE and prepares them for recycling. At the pretreatment facilities, the primary purpose is to ensure hazardous components are removed to avoid contamination of waste fractions during recycling (Respondent 3). Firstly, WEEE is sent to a sorting belt where waste is manually sorted and examined. Even though automatic systems do exist, manual sorting is still necessary to ensure clean waste streams (Respondent 3, 4). Environmentally harmful components like batteries, oil, lead, asbestos, capacitors containing printed circuit boards (PCBs) and toners are separated and treated differently (Stena Metall, 2015). Monitors containing mercury should also be separated from others. Also, high-value components like circuit boards are dismantled from equipment and put in separate containers. In addition, valuable electronics like laptops and mobile phones are picked out and sent to the reuse department to test if they can be repaired and reused. If not, they will be sent back to the pretreatment processes (Respondent 3, 4).

Once the waste is sorted and decontaminated, it will go through a fragmentation process, where a shredder crushes and ground waste into small pieces (Respondent 3, 4). Small pieces of WEEE then go through an automatic process to further sort waste into categories, including metal, plastic, glass and others (Stena Metall, 2015). Below is an overview of pretreatment processes used to separate materials from each other:

Table 4-2. Different types of pretreatment processes

Process	Purpose
Magnet drum	Separate ferrous metals and copper (copper are separated by hands)
Separation table	Separate precious metals with high copper content and others
Eddy-current separation	Separate non-ferrous metals, such as aluminium, circuit boards
Flotation/ density	Separate recyclable non-brominated plastics from plastic containing brominated flame retardants, which must be incinerated
Optical separators	Scan, recognise and separate based on its colour Circuit boards with precious metals are separated from aluminium

Source: Stena Metall (2015)

After going through the above processes, WEEE is sorted into more than 30 material fractions, including ferrous metals, copper, aluminium, circuit boards, precious metals with copper, recyclable plastics, brominated plastics and others (Stena Metall, 2019). Since the output of pre-treatment facilities are roughly separated into different materials, further refining is required to enhance the quality of recycled materials and ensure they can be used in production (Respondent 3, 4).

As the respondent noted, several factors are essential to facilitate pre-treatment. First, modern technology is a necessary investment to ensure efficient sorting (Respondent 3, 4). Next, sufficient know-how is vital since waste must be processed in the right size and quality to facilitate smelting and increase output (Stena Metall, 2017). Lastly, expertise must understand how to handle different materials without compromising quality (Respondent 3, 4).

WEEE recycling

After pre-treatment processes, different scrap materials are sold and sent to corresponding recycling facilities, such as smelting plants, foundries, plastic producers and other manufactures. In the following sections, the recycling process of several materials is discussed, including copper and aluminium. Since there is increasing discussion over recycling Rare Earth Elements (REEs) and plastic from WEEE, a brief summary is also included.

Copper

In general, scrap metals are sent to smelting plants to be melted and mixed with virgin metals. Boliden is one Swedish metals company that recovers metals from WEEE, including copper, silver, gold and zinc (Boliden, 2020a). Around 120,000 tonnes of electrical materials are recycled via Boliden every year, most of which are sourced from the E.U. Boliden is the first company to offer two separate copper: low-carbon copper and recycled copper. Recycled copper is produced from electronic scrap, resulting in fewer carbon footprints (Boliden, 2020c). According to research conducted by Boliden, recycling copper causes around 1.5 kg CO2 eq/kg, while virgin raw copper causes about 4 kg CO2 eq/kg (Boliden, 2020b).

Once e-scraps enter the facilities of Boliden, scrap is sampled to identify and track general product content (Respondent 5, 6). Then, they are shredded and sent to furnaces. After materials are smelted, the so-called back copper (or slag) then continues through the normal process and is mixed with the virgin material flow for refining (Respondent 5, 6). Lastly, base metals (copper) and precious metals (gold and silver) are extracted (Respondent 5, 6). Molten copper matte is discharged from the furnace, oxidised to 99 percent raw copper. Due to its electrical contact, silver can be found in circuit boards in mobile phones and computers (Boliden, 2020d). Zinc extracted from waste is then used to produce zinc clinker, which contains zinc oxide, iron and lead, and sent to another facility of Boilden for refining. Other materials like iron and aluminium are removed in the process and sent for additional treatment (Respondent 5, 6). The remaining waste is then deposited at a deep rock cavern deposit (Respondent 5, 6). In addition, it is worth noting that plastic in electronics can help the waste melt. Thereby plastic is not wholly removed before sending it to the furnace (Respondent 5, 6).

Aluminium
In Sweden, aluminium is another material that can be recovered from WEEE and used to produce new products. Stena Aluminium is one company that offers recycled aluminium alloys to customers. Stena Aluminium owns its aluminium smelter in Älmhult, where around 70,000 tonnes of recycled aluminium alloy are produced each year (Respondent 4). Long before the enforcement of the WEEE Directive, Stena Aluminium has operated recycling activities since the 1900s and acquired sufficient knowledge in this field (Stena Aluminium, n.d.). It is advantageous for Stena to expand aluminium recycling (Respondent 4). Secondary aluminium from industrial waste, WEEE, cans, or cars is treated and refined. After aluminium is refined, they are sold to customers in northern Europe, primarily foundries or end customers in the automotive sectors (Stena Aluminium, n.d.).

Plastic
In Sweden, valuable plastic from e-waste was usually sold to recycling facilities in Asia and Europe after sorting out (Naturvårdsverket, 2019). For example, China used to take plastic waste from Sweden (El-Kretsen, 2021c). However, since China initiated an import restriction for (unsorted) waste in 2018, it has significantly influenced the waste management and recycling industry worldwide (El-Kretsen, 2021c). Since 2019, Stena Recycling, a Swedish recycling company, has initiated investment in plastic recycling processes to turn wasted plastic from WEEE into recycled plastic pellets.

Since plastics appear in electronic products in different forms, including Polypropylene (P.P.), Polyethene (P.E.) and Acrylonitrile butadiene styrene (ABS) (El-Kretsen, 2021c), the first step of recycling is separating different plastics with a wet process. Plastic is thrown into a water tank, and those containing flame retardants will sink to the bottom. The rest of the plastic is then sent to the refining process and converted into pellets of PP/PE, P.S. and ABS (El-Kretsen, 2021c). After checking the quality and ensuring no containing chemicals based on legislation, such as RoHS, recycled plastic is ready to use and put on the international and local commodities market (Respondent 4). For now, around 50 per cent of the plastic in WEEE can be recycled, and the facility can generate 12,000 tonnes of shredded PS/ABS per year (El-Kretsen, 2021c).

REEs
Currently, REEs recycling is not happening in Europe, and E.U. mainly relies on importing raw materials from China (Stena Metall, 2016). Considering the strategic importance of REEs, one pilot project was funded by the E.U. to recycle neodymium (Nd) magnets from hard disks (Stena Metall, 2016). A discussion over how to dismantle equipment was initiated, and another more significant problem is how to commercialise the implementation. Stena has tested the possibility of using the thermal method or extraction method, or solvent to extract REEs (Stena Metall, 2016). It is challenging to take Nd from hard drives due to the small amount (Respondent 4). For other materials, iron can be taken out by magnets; plastic can be separated by flotation (Respondent 4). Therefore, they are still working on the best approach to recycle REEs efficiently, and new automated dismantling technologies are needed to achieve high recycling rates of REEs. Also, since only one kind of REEs can be found in hard disk drives, it can not provide efficient incentives for recyclers to invest in new technologies (REE4EU, 2015).

Use of recycled materials
After recycled materials are extracted from WEEE and refined, they are usually sold on international or local commodity markets. For metals, since they can be recycled without

compromising the quality, recycled metals are usually melted with virgin metals and used for the same purposes. However, using recycled plastic could be more challenging due to quality, colour and function concerns (Respondent 7).

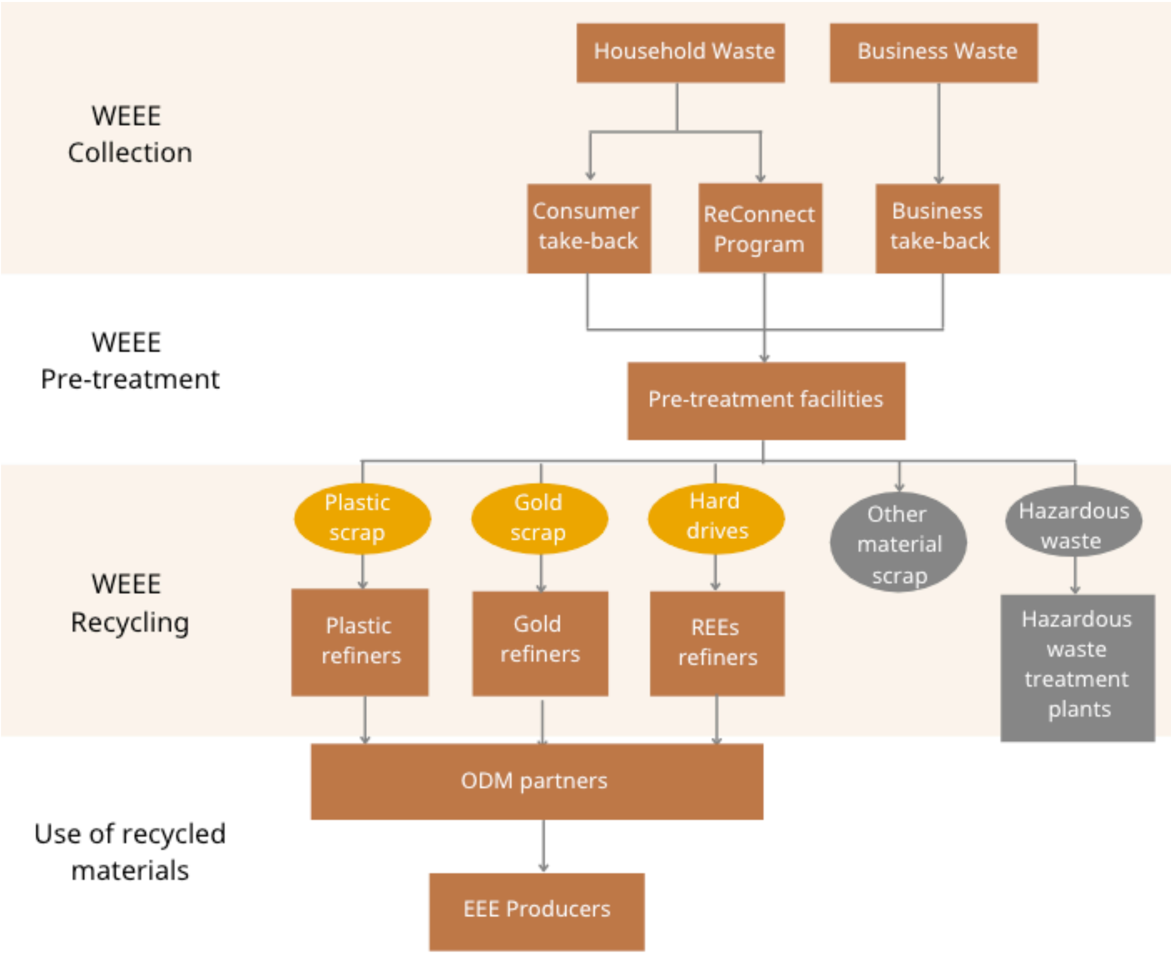
Electrolux is a Swedish EEE producer that has adopted recycled plastic and is used to present how producers use recycled materials. They have made progress in adopting recycled steel and plastic and designing products for better recycling (Electrolux, 2021). Electrolux first started using recycled plastic harvested from oceans to produce vacuum cleaners in 2010 (Electrolux, 2010). Later, the Global Technology Center of Electrolux successfully developed recycled polypropylene, called CarboRec, made by post-consumer products and used to produce electronic appliances (Electrolux, 2016). When adopting recycled plastics, the quality of recycled plastic is tested to ensure chemical composition fulfils both Electrolux's standard and legal requirements (Respondent 7). Also, functions are tested to ensure they can reach the same level of performance as virgin raw plastic (Respondent 7). Lastly, since the colour of recycled materials could be different from virgin raw materials, aesthetics is also considered (Respondent 7). In 2020, a total of 6,800 metric tons of recycled plastic was used (Electrolux, 2021). Electrolux is working on expanding the use of recycled plastic from Europe to other regions. However, one challenge is finding high quality and sufficient local supply outside of Europe (Respondent 7). For now, trials have been conducted in Asia and the U.S. to investigate possibilities (Electrolux, 2021).

In addition, Electrolux and Stena Recycling jointly initiated a circular initiative in 2019 (Electrolux, 2020). One of the pilot projects is to produce vacuum cleaners made of reusable materials and 100 percent recycled plastic (Electrolux, 2020). Recycled plastics are recovered from end-of-life consumer electronics products Stena collects, including hairdryers, computers and vacuum cleaners (Electrolux, 2020). The purpose of this partnership is to learn more about the use of recycled plastics recovered from WEEE and test whether they can reach the same quality and functionality as using virgin materials (Respondent 3, 4). For example, without adding anything, could it be possible to produce reliable vacuum cleaners which meet environmental standards, such as chemical substance content (Respondent 3,4). Even though vacuum cleaners made of recycled materials do not exist in the market yet, this pilot project enables a better understanding of how to close the recycling loop by using recycled materials for manufacturing (Respondent 3, 4, 7).

4.1.2 Individual producer responsibility (IPR)

The following section describes Dell's WEEE recycling value chains, with a focus on WEEE collection, pre-treatment, recycling and finally, the use of recycled materials. The overview of Dell's recycling value chain is summarised in figure 4-2 and can be divided into four stages of value chains. These four stages are separately explained as follows.

Figure 4-2. Overview of Dell's WEEE recycling value chains



Source: made by author based on Respondent 9, 10

WEEE collection

Dell has adopted various approaches to collecting end-of-life products, from setting their own take-back scheme for different types of customers, working with local NGOs, and being a member of PROs (Respondent 9, 10). Strategies are different based on regions of operations to facilitate collection and ensure regulatory compliance. The sections below present how Dell collects waste in different ways.

Setting global take-back schemes

The purpose of Dell's take-back schemes is to offer free and convenient approaches to individual customers (Dell Technologies, 2020). Customers can return unwanted electronics products via Dell's online collection platform, which is operated globally. After filling out online applications, customers can drop used electronics attached with shipping labels at nearby mailing centres. Local waste carriers can also come to the designated place and pick up wastes (Dell Technologies, 2020). This service is not limited to Dell-branded products, as any brand of electronic products is accepted. Customers can also directly visit nearby Dell stores or retail stores and drop off electronic equipment.

For business customers, Dell offers Asset Resale and Recycling services program to manage retired equipment, including pick-up logistics, old equipment resale, and proper recycling (Dell Technologies, 2020). To cater specific needs of commercial customers, Dell also offers data destruction service in light of data security concerns. Clients will also get a detailed report and statistics regarding the process from collection to disposition (Dell Technologies, 2020). The goal of offering this service is to maximise the value of assets and return to customers (Respondent 10).

Below is an overview of post-consumer e-waste collected by Dell take-back schemes in 2016:

Table 4-3. Dell's global take-back collection of WEEE by regions in 2016

Regions	Take-back volume
Global	168 M lbs (76.2 M kg)
America	115.3 M lbs (52.3 M kg)
Europe, Middle East and Africa (EMEA)	37.3 M lbs (16.9 M kg)
Asia Pacific-Japan (APJ)	15.4 M lbs (7 M kg)

Source: Dell Technologies (2016)

Working with NGOs: ReConnect Program in the US

In the United States, Dell especially teams up with local NGO, Goodwill Industries, to set up a recycling program called ReConnect (Dell Technologies, n.d.). With Goodwill's more than two thousand collecting points around the countries, customers can drop off any electronics brand and get a receipt for tax reduction (Dell Technologies, n.d.). After e-waste is collected, Goodwill is responsible for conducting initial sorting and testing the function of the equipment to check whether products can be repaired or refurbished. If not, equipment is identified as an end-of-life product and sent to recycling facilities (Respondent 9).

Participating in local governments' programs

Apart from setting up its take-back systems and working with NGOs in the US, Dell takes a different approach in countries where collective WEEE collection schemes exist (Dell Technologies, 2020). In Sweden, Dell fulfils producer responsibility as local legislation requires by being a member of El-Kretsen (Kollberg, 2003; Respondent 10). Customers can directly return unwanted products to municipal waste management systems, such as collection centres (Respondent 10). In addition, third-party waste management service is provided to business customers as an alternative to cater for their needs (Kollberg, 2003). Eurovironment is one waste management company Dell works within Sweden. They provide a series of used I.T. product management services from collection, logistics, recycling to reporting for I.T. companies (Kollberg, 2003).

WEEE pretreatment

After identifying different approaches Dell has taken, the scope of the following section is narrowed down to Dell's ReConnect program in the US for one reason. Since Dell's products collected under CPR are mixed with other brands and sent to local recycling facilities, Dell has less control over how waste is treated and recycled. Instead, this kind of decisions is made by PROs. Therefore, the following section focuses on Dell's waste collection under IPR, especially the cooperation with Goodwill.

After e-waste is collected via Goodwill's collection points throughout the US, end-of-life products are sent to Dell's pre-treatment partner in Texas, the US (Respondent 9). WEEE is first sorted into categories in the pre-treatment plant, dismantled and hazardous substances are removed (Respondent 9). Then, WEEE is broken down into small pieces and divided by components, including metals and plastics (City of McKinney, 2015). In 2019, around 11,000 metric tons of electronic wastes were handled in the recycling plant, including cell phones, laptops, and computers. Next, different material streams are treated separately (Wistron Corporation, 2020). Next, different material scraps are sent to specific recycling plants for further treatment (Respondent 9).

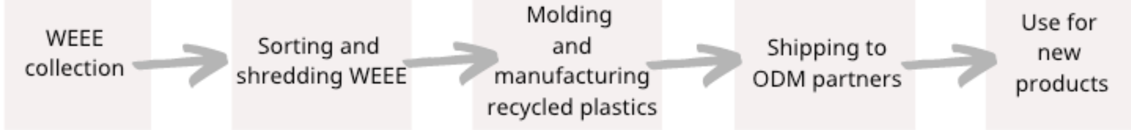
WEEE recycling

In the following section, WEEE recycling processes are presented based on different materials. Since Dell has built closed-loop recycling for plastic, gold and rare earth elements, the following sections focus on these materials.

Plastic

After plastics are extracted from WEEE, plastic scraps are shipped to Dell's recycling partner in Kunshan, China, for recycling and refining (Respondent 9). Plastics are first sorted and shredded into small pieces. Then small pieces of plastic are melted, purified and mixed with virgin plastic (Dell Technologies, 2021b). Finally, mixed plastics are converted into resin pellets and sent to Dell's downstream original design manufacturer (ODM) partners in China for production (Respondent 9). Below is an overview of the plastic recycling process.

Figure 4-3. Dell's plastic recycling process



Source: Dell Technologies (2021b)

Gold

Apart from plastic, Dell and recycling partners tried to expand closed-loop recycling programs to precious metals in WEEE, such as gold, silver, copper, platinum and palladium (Dell Technologies, 2021b). The pilot project built in 2018 focuses on recovering gold from waste circuit boards from notebooks (Dell Technologies, 2021; Respondent 9). After PCBs are separated from WEEE, Dell's recycling partner uses a gold stripping process to leach, strip and extract precious metals from PCBs (Respondent 9). The adopted gold stripping technology is an environmentally friendly approach to recover gold, enhancing recycling efficiency and decreasing air and wastewater pollution (Uwin Nanotech, 2015; UWin Nanotech, 2016). Below is an overview of the gold recycling process.

Figure 4-4. Dell's Gold recycling process

Source: Joshi et al. (2017); UWin Nanotech (2016)

REEs

Regarding REEs, Dell collaborated with hard drive producers to test the possibility of recovering REEs. In the pilot project, Dell worked with hard drive supplier Seagate and IT asset disposition company Teleplan to recover neodymium (Nd) from magnets (Dell Technologies, 2021b).

After used hard drives are collected and sorted in the US, they are sent to Seagate's suppliers in Southeast Asia for further pre-treatment (Respondent 9). Since Seagate's suppliers are responsible for assembling components in the first place, they have sufficient knowledge in how to dismantle magnets from hard drives (Respondent 9). Therefore, sending equipment back to manufacturing partners for dismantling can ensure components are taken out carefully without causing pollution (Respondent 9). After hard drivers are dismantled and ground down into small pieces, scraps containing REEs are sent to the refining partners in Japan (Respondent 9). As Japan is the pioneer of recycling hard disk drives, refining partners there are equipped with the necessary knowledge and technology to recover Nd (REE4EU, 2015; Respondent 9). After Nd is recovered, they will be used in producing magnets for new hard drives. Below is an overview of the gold recycling process.

Figure 4-5. Dell's REEs recycling process

Source: Respondet 9

Use of recycled materials

Plastic

For now, around 30% of plastic used in Dell's 130 kinds of products is recovering from their take-back schemes (Respondent 9). Dell's recycling partner in Kunshan, China, produced around 13,000 metric tons of post-consumer recycled (PCR) plastics in 2019 (Wistron Corporation, 2020). The output of recycled plastic includes ABS HB plastic (for monitor, printer, keyboard), HIPS HB plastic (for the printer, TV, monitor and keyboard) and PC/ABS + GF (for notebook, monitor and TV) (Wistron GreenTech Texas, 2014)). Regarding the benefits of recycled plastic, Dell received the first closed-loop Environmental Claim Validation from UL Environment, proving computers containing around 10% closed-loop recycled plastics can save 11% carbon emission compared with virgin materials (UL, 2014).

Gold

For gold, recycled gold is sent to Dell's suppliers in Taiwan to produce new circuit boards. Apart from circuit boards, Dell also cooperates with jewellery makers in Los Vegas, U.S., to produce jewellery made by recycled gold (Joshi et al., 2017; Respondent 9). According to the research done by Trucost and Dell, closed-loop recycling gold can lower 99% of the environmental impact compared to mining virgin gold (Joshi et al., 2017).

REEs

Regarding REEs, the pilot project has successfully created 25,000 hard drives with 660 pounds of recycled rare earth elements and was recognised by the U.S. Environmental Protection Agency in 2019 (US EPA, 2019). Recovered REEs are used to produce hard drives for Dell's laptop. Since it was a pilot project, the purpose of this project was to test the possibility of recovering REEs. Therefore, RREs recycling has not been scaled up yet (Respondent 9).

4.1.3 Summary

In both cases of CPR and IPR, recycling activities can be roughly broken down into four stages: WEEE collection, pre-treatment, recycling and use of recycled materials. Additionally, recycling networks are carried out in more than one region. In the case of Sweden, while WEEE is collected and pre-treated on the local level, different materials streams end up in different destinations. For example, while metals can be recycled by local smelters, plastics tend to be sent to other regions for recycling, such as China. In the case of Dell, recycling activities also rely on the support of stakeholders from different geographical scopes. In the US, Dell collects waste across the country and WEEE are sent to one pre-treatment facility in Texas for sorting into different waste streams. While plastics are shipped from the US to China, gold is shipped from the US to Taiwan. For the case of REEs, it is particularly complicated as hard drives are collected in the US, dismantled in southeast Asia and finally recycled in northeast Aisa. From these facts one can conclude that WEEE recycling activities are commonly operated across different countries. The reasons for international dispersion of the recycling value chain can result from cost-effectiveness, optimising recycling processes or limited numbers of available and interested recyclers.

4.2 Transaction costs of WEEE recycling

Building upon the taxonomy suggested by Kiss & Mundaca (2014), transaction costs associated with WEEE recycling value chains are identified in the phase of using recycled materials, and it can be divided into

- Due diligence costs:
  searching, gathering and evaluating information and potential partners
- Negotiating costs:
  discussing and bargaining forms of procurement during trading
- Monitoring and verification costs:
  monitoring the performance of recycled materials and provide verifications made by third parties

Following is an overview of what kinds of transaction costs are identified (see table 4-4), and detailed descriptions of transaction costs are presented based on categories.

Table 4-4. Overview of transaction costs in WEEE recycling value chains

Stages of WEEE recycling value chains/ Categories of transaction costs	Due diligence costs	Negotiating costs	Monitoring and verification costs
Use of recycled materials	Searching for buyers (EEE producers) Searching for sellers (recyclers)	Negotiating on quality Negotiating on prices	Monitoring performance and verifying benefits of recycled materials

Source: author

4.2.1 Due diligence costs

In the phase of using recycled materials, both buyers (EEE producers) and sellers (recyclers) have to bear with transaction costs of due diligence. Since there is no formal trading platform for recycled materials, finding potential buyers and sellers needs additional time and effort.

From buyers' perspective, the recycling market is a niche market that they are not familiar with (Respondent 9). It requires extra effort for buyers to obtain all the information and evaluate available sellers. Transaction costs of due diligence vary with materials. Metals retrieved from e-waste are usually purchased and refined by original producers, which are smelters. Then, recycled metals are mixed with other raw metals and sold to commodities. Therefore, recycled metals are fed into the same market stream of virgin raw materials, and it is easier for buyers to find sellers (Respondent 5, 6). However, the transaction cost for searching suppliers is more significant for recycled plastic (Respondent 7, 9). Since plastic recyclers are not the original suppliers of plastics, EEE producers interested in recycled plastic have to spend time and effort to look for new suppliers. For some materials, like REEs, applicable recyclers barely exist. Producers interested in recycled REEs have to reach out to raw material suppliers and refiners to make recycling happen (Respondent 9).

From the sellers' perspective, the transaction cost is linked to searching for potential buyers. Even though two producers this paper interviewed show their strong interest in recycling, generally, not all producers are interested in or have concerns over recycled materials. The reason behind low interests could be a lack of incentives and awareness of the benefits of recycled materials, such as less carbon footprint compared to virgin raw materials (OECD, 2006). The reason behind concerns is high transaction costs from negotiating on recycled materials and forms of procurement. Concerns over the quality is a common perception that producers with less market experience in recycled materials generally have (OECD, 2006). Transaction costs related to quality will be explained in the next section.

4.2.2 Negotiating costs

After buyers and sellers overcome the transaction costs of due diligence and find each other, extra time and effort are required when they try to settle the details of procurements. Negotiation over the quality of recycled materials and prices can be incredibly time-consuming. If buyers and sellers can not reach an agreement, procurement will not happen.

Quality

From the producers' perspective, an overarching principle of recycled materials is that product quality can not be compromised (Respondent 7, 9). Regarding the quality of recycled materials, transaction costs vary with materials due to material properties. For metals, they can be recycled repeatedly without degrading their properties. For plastic, it is more problematic since the quality of plastic degrades during the recycling process as impurities are absorbed and weaken the structure. Therefore, recycled plastic can not fully return to the original state.

Quality related to recycled plastic can be further divided into three categories: safety, function and aesthetics (Respondent 7).

One thing stressed by producers is the potential risk associated with hazardous substances contained in recycled plastic (Respondent 7). Without proper sorting, hazardous substances and heavy metals from old products can be found in WEEE, such as Brominated flame retardants (BFRs), cadmium and chromium (Stenmarck et al., 2017). According to the WEEE Directive, hazardous substances should be removed from the waste before recycling. Nevertheless, it is challenging to separate all harmful content, and sometimes they can still be found in the recycled plastic fractions (Singh et al., 2020). In light of this, producers adopting recycled plastic have to ensure that restricted chemical content meets environmental regulations, which is especially tricky as the quality of recycled plastic is highly related to the source, such as whether the waste stream is well-sorted and clean. Therefore, the content of hazardous components in recycled plastic could fluctuate and should be monitored from time to time.

Apart from safety concerns, the function is another quality issue that needs to be considered for recycled plastic. Engineering departments test the performance and strength of recycled plastic to assess whether the durability of recycled materials is equivalent to virgin plastic (Respondent 7, 9). For plastic used to produce laptop cases, it is crucial to ensure the mechanical properties of recycled plastic meet producers' standards of performance and efficiency (Tostar, 2016; Respondent 9). Lastly, the colour of recycled plastic is a concern arising from the design team. Waste plastics are separated by colour when recycling, and better sorting can help obtain pure or single-colour output. Nevertheless, impurities found in the plastic stream can decrease the properties of recycled plastic, and it is challenging to produce transparent recycled plastic (Riise et al., 2001).

In light of this, strategies are taken to mitigate the impact. For instance, mixing recycled plastic with virgin plastic is one approach. In Dell's closed-loop recycling product, around 30-35% of recycled plastics are used and blended. Producers can also consider re-design or adjust the features of their products, for example, using a single colour of plastic in the beginning to facilitate sorting and recycling (Respondent 7). As coloured and black plastics are generally more difficult to recycle and reuse, using more transparent plastic in the beginning can increase recycling and reuse value. In addition, producers can instead design product in black to mitigate the concerns (Respondent 7).

Since WEEE recycling remains an innovative business, there is no clear standard to ensure the quality of recycled materials. In other words, both sellers and buyers have to invest additional time and efforts to adopt recycled materials. Close discussion between sellers and buyers and quality tests are conducted to determine if recycled material can reach the same quality as virgin raw materials. Some producers choose to rethink product design to ensure recycled materials can fit in their products. In the case of Dell, they and recycling partners spent nearly two years to finally build a process to use recycled materials in products.

Prices

Once technical issues are solved, negotiation over price is another source of transaction costs. Compared to virgin raw materials, a premium is often charged for recycled materials to reflect high investment in recycling technologies and high costs of the recycling process. Due to the lack of official trading platforms, transaction costs of negotiating are associated with time and effort to bargain over the prices. Producers need to gather information and assess whether the premium is worthwhile.

For metals, the prices are mainly aligned with the London Metal Exchange (LME), an international trading platform for industrial metals. It is possible to have premium prices based on the supply and demand, smelting capacity and customised alloys (Boliden, 2020a). Due to high investment in equipment and facilities, and know-how, the cost of recycled plastic is higher in the early stages (Respondent 9). Even though producers are interested in recycled materials and their benefits, the premium is one source of transaction costs due to cost-effectiveness considerations.

In addition, the purchase of recycled materials is affected by the virgin material market and results in competition between virgin raw material and recycled material (Respondent 7). For example, the price of virgin plastics is highly related to the oil market, which fluctuates significantly. When virgin raw materials are cheaper, producers need to weigh between cost and environmental impact. Also, Electrolux pointed out they reduce the use of recycled steel recently due to price considerations. Because of the trade conflicts between the US and China, the price of virgin steel has fluctuated significantly and influenced producers' interests to use recycled steel since virgin steel is cheaper (Electrolux, 2021). Based on the respondent's observation, the price of recycled rare earth elements might not be too much higher as the recycling process is in place already (Respondent 9). What could affect the price is the required quantity. Since rare earth elements are in small amounts, the scale of recycling operation might be small. Then the price might not be lowered by scaling up.

However, an unstable virgin materials market could also drive producers to use more recycled materials to build and secure a stable recycling source. What has been observed from Dell is that the cost of recycled plastic is higher in the early stage. Nevertheless, once the recycling program is scaled up, the price decreases, sometimes even cheaper than virgin raw materials. The respondent also believed that prices could be even lower once there is more demand for recycled materials.

4.2.3 Monitoring and verification costs

Lastly, the source of transaction costs is related to verifying the benefits of using recycled materials. This transaction cost is applied to both recyclers and producers.

For recyclers, they need to prove why recycled materials deserve a premium. Communicating with buyers about recycled material benefits is essential to attract customers sharing similar values. From producers' perspective, they might also face internal pressure over the higher cost, and the proven benefits of recycling can be used as a tool to pursue other departments within organisations. In addition, they also need to bear the cost to show customers the benefits of using recycled materials in new products in light of customer acceptance of products made of recycled material. Analysing and disclosing the benefits of using recycled materials can demonstrate why customers should support the products.

For example, Boliden conducted a carbon footprint report and compared the level of GHG emission between virgin copper and recycled copper. The result showed that recycled copper results in around 400-1300 kg/ CO2eq/tonne, while virgin raw copper causes 3200-4200 kg/ CO2eq/tonne (Boliden Mineral, 2020). Dell also conducted their own research showing recycled materials can effectively reduce environmental impact compared to virgin raw materials. For plastic, one of Dell's products adopting recycled plastic can contribute to 44% of environmental benefits, especially in improving human health, decreasing toxicity and air and water pollution (Trucost, 2015). For recycled gold, 99% of environmental damages can be avoided compared to using virgin gold, including less carcinogenic and non-carcinogenic, ecotoxicity and eutrophication usually occurring from ore extraction (Joshi et al., 2017).

4.2.4 Summary

By combining the cases of CPR and IPR, transaction costs are identified in the phase of using recycled materials. Compared to using virgin raw materials, a significant amount of additional resources is required to facilitate the adoption of recycled materials. The recycling market is thereby constrained by high transaction costs (OECD, 2006).

Firstly, the transaction cost is associated with matching buyers and sellers since the recycling market is a niche market. After buyers and sellers are mated, making transactions reasonable for both sides also requires additional resources. Common sources of transaction costs in this stage lie in the quality of recycled materials and premium prices. Lastly, extra time and efforts are used to monitor the performance and verify the benefits of recycled materials.

Based on the findings, transaction costs are inevitable but can be overcome by strong interest and motivations. Once recycling activities are formalised or scaled up, transaction costs could diminish. The respondent from Dell pointed out they encountered more challenges in recycling plastic, and close communication with recyclers in the early phase is the primary source of the transaction cost. Nevertheless, transaction cost arising from recycled plastic only happens initially; once they overcome the quality issue and build up know-how, it is no longer an issue. For recyclers newly entering the market, know-how has to be built via practical experience, and techniques must be improved to enhance quality. After obtaining experience, refiners gradually grow technical capacities and improve their production process to reach standards set by producers. However, transaction costs still create a barrier for general participants in the market. As not all stakeholders are able to bear transaction costs by themselves, it creates a barrier to promoting WEEE recycling.

5 Discussions

5.1 Findings and significance

5.1.1 WEEE recycling value chains in global context

Based on the findings, WEEE recycling value chains are extremely complex, and stakeholders along value chains are usually across different regions. Similar to the supply chain of electronics productions, the reverse chain of recycling is relatively dispersed. The key features of WEEE recycling value chains are drawn as follows

Centralised recycling activities

After WEEE is collected and sorted locally, different material streams are usually sent to complementary treatment and recycling facilities running on the regional level. Due to the high investment costs of recycling equipment, recycling businesses tend to run on a broader scope to take as much waste as possible to maximise its values. WEEE pre-treatment and recycling facilities in Sweden have attracted nearby countries to transport their waste to Sweden, which also ensures a more stable and large volume of recycling input. Similarly, Dell's application in the US is WEEE collected via the national program are all sent to Dell's recycling partners in Texas.

In practice, recyclers in different regions tend to have their speciality in particular recycling technology or materials, and the development of the recycling industry is highly related to contextual factors. Take Sweden for example, recycling metals is relatively more straightforward to achieve due to its historical background of industrial development. With rich natural resources of metals, Sweden has a long history in metal mining and manufacturing, gaining advantages in developing the recycling business. With its existing technology, infrastructure and sufficient know-how, Sweden has started recycling metals a long time ago and accepted WEEE from nearby countries.

Centralising recycling is particularly necessary for rare earth elements as a small number of recycler and refiners have dominating roles worldwide. According to the respondent's experience, recycling rare earth elements is strongly connected with supply bases and production sites as they are the ones with professional knowledge in this field. To make recycling happen, reaching out to original material suppliers or refiners is one strategy taken by practitioner.

Apart from driving by the purpose of better recycling, WEEE flows may move between regions due to a lack of local facilities. In the case of Closing the loop, WEEE is collected in Africa and shipped to recycling plants in the EU. Since recycling capabilities are generally under development in Africa, WEEE can be treated more appropriately in the EU.

Dispersed manufacturing network

After materials are recovered from WEEE, it is also necessary to send them to production sites to put into new products. In the case of gold, gold extracted in the US was sent to Taiwan to produce new circuit boards. The similar concept also applies to REEs because only a few recyclers have sufficient knowledge and technology. WEEE is moved between several countries in Asia before REEs are finally extracted and used for new products.

Even though moving waste around regions seems necessary for the most case, some producers seek to reduce the distance between recycling facilities and production sites. In the case of Dell, waste plastic is sent to China for refining, where Dell's pre-treatment partner operates a plastic recycling facility. One reason for Dell to ship plastic to China is that it is closer to its manufacturing partners. Once recycled plastic is extracted, it can be directly sent to ODM partners to produce new products. In other words, the distance between collected waste and sourcing is eliminated. Another reason also lies in the fact that Dell's pre-treatment in the US and recycling partners in China are owned by the same parent company. Therefore, it is easier for Dell to cooperate with both of them to better coordinate the transition from WEEE to recycled materials.

Illegal transboundary movements of waste

Even though moving WEEE between regions is necessary to facilitate recycling, the illegal transboundary movement of waste needs to be considered. In the case of Sweden, even though El-Kretsen has built a formal supplier selection procedure with Codes of Conduct and on-site checks, sometimes illegal waste treatment still happens, even though it is relatively rare. In 2020, one case is that batteries containing cadmium were exported from Sweden to Poland without informed consent (El-Kretsen, 2020). Once black mass was found out, El-Kretsen took necessary coping mechanisms through an internal investigation and assisting police's investigation. The owner of a battery treatment company that had a contract with El-Kretsen was sentenced to jail in violation of environmental law. Respondents pointed out they tend to work with known treatment partners with long-term cooperation and good reputations, but somehow they cannot entirely ensure suppliers always behave, especially due to long distance. In response of this case, El-Kretsen initiated a series of actions, including more frequent follow-up measures, tightening monitoring systems and closer engagement with local and national stakeholders to supervise materials flows and audit their suppliers.

Under the nature of the global value chain, companies under IPR also need to properly select their collection partners, such as reverse logistic or NGOs. Adopting various collecting approaches is helpful to enhance the recycling rate. However, for multinational EEE producers, finding suitable partners in different regions is also more time-consuming. How to ensure collected waste is handled correctly in every region is an issue that requires continuous monitoring. Dell has participated in one pilot project operated by the Basel Action Network (BAN) to track their WEEE flow in the US (Dell Technologies, 2018). Trackers were placed on discarded electronics to determine whether they are recycled responsibly or illegally transported to developing countries. The result showed that among 46 trackers, seven were illegally exported from the U.S. to Asian countries, including Hong Kong, China, Taiwan and Thailand (Basel Action Network (BAN), 2016). Increasing the transparency of downstream recycling and monitoring recycling partners is then one critical task.

Summary

To summarise, the nature of the global value chain increases the complexity of WEEE recycling. While centralised recycling is necessary to enhance recycling efficiency, the dispersed nature of manufacturing makes it challenging to connect recyclers and producers. Therefore, it is necessary to transport collected waste to other countries for treatment and recycling. While localising recycling activities is ideal for reducing transportation, the geographical difference remains a challenge. As recycling practices are different from regions, it is impossible to expect recyclers in every region to all equipped with the same level of recycling technology and experience.

Nevertheless, as increasing interests in recycling have been given globally, producers seek opportunities to work with local recycling companies. Nevertheless, this only applies to materials like plastics. While few actors specifically own technologies for extracting REEs, it is challenging to promote localised recycling. In this regard, professional and experienced recyclers play a tremendous role and potentially have the power to influence the recycling business. What is also observed by one respondent is that they encountered some troubles when reaching out to potential recyclers (Respondent 11). Some recyclers are less interested in working with small scales of waste, possibly due to cost-effectiveness concern. Based on their market share and professional experience, recyclers sometimes have the power to decide whom they prefer to work with. Nonetheless, while more new recyclers are entering the market, they tend to show strong interest and are willing to communicate. Dell has highlighted that their recycling partners reached out to them initially and actively involved during negotiations of quality, which is vital to facilitate the discussion.

5.1.2 Comparison between CPR and IPR

In general, both producers from CPR and IPR have to deal with transaction costs. One typical transaction cost is negotiating quality to meet technical, economic and aesthetic requirements brought out by producers. Another source of cost is persuading different departments within organisations and customers why they should use recycled materials. Time and efforts must be invested in communication to ensure product performance, especially for recycled plastic.

Nevertheless, there are also slight differences between CPR and IPR. While producers under IPR are the ones who initiated the system and reached out to collectors and recyclers, it is guaranteed that output will be purchased and fed into production. Therefore, the transaction cost of due diligence can be solved in the beginning, and the transaction costs of negotiating can be eliminated by a close connection between producers and recyclers. On the other hand, recycled materials from CPR are more vulnerable to markets. One respondent pointed out when the price of virgin raw materials is lower than recycled materials, they need to consider the price difference and thereby might purchase less recycled materials due to budget concerns (Respondent 7). Apart from price, as environmental benefits of using recycled materials might not be widely known, the cost in explaining and proving the difference between virgin raw materials and recycled materials is also needed. Several respondents have conducted their carbon footprint analysis to compare the impacts of two different materials (Respondent 5,6,9). One thing emphasised by several respondents is that recycling only happens when there are buyers (Respondent 3,4,5,6). After all, recycling is still a business, and recyclers must make profits to sustain their operation. In this sense, recycling in CPR is more leaning towards market-driven, while it could be strategy-driven in IPR.

Nonetheless, IPR has to bear with some trade-offs to avoid transaction costs of due diligence. Regarding WEEE collection, CPR can effectively reduce the overall cost of planning. In Sweden, EEE producers can fulfil producer responsibility by joining PROs and financially supporting waste collection. In return, PROs arrange a waste collection via municipal collection centres, also ensuring waste is collected and sorted correctly. However, for IPR, producers have to initiate their own collection system while evaluating suitable and trustworthy partners. In countries where PROs do not exist, producers can either work with local authorities or outsource collection to reverse logistics or NGOs. Overall, for IPR, more time and efforts are needed in the beginning to search for suppliers, ensure suppliers can meet the requirements, and maximise waste collection by setting diverse approaches for individual and business customers. Next, similar differences are also observed in WEEE recycling. As PROs working under the collective system ensure collected waste is sent to certified recyclers, it can save the overall cost of planning. IPR have to conduct their own research to find qualified suppliers. As not all recycling facilities are interested in cooperation with small organisations with relatively small amounts of waste, it could be challenging to find recycling partners.

In conclusion, both CPR and IPR have their advantages and disadvantages. Under CPR, centralised management ensures high efficiency in the collection as citizens can leave all electronics at one collection point. Collective systems can save overall cost in planning and coordinating logistics and collection points (Tojo et al., 2007). Producers can join PROs which help arrange waste collection, select qualified waste treatment partners and monitor their performance. Apart from financial support, producers do not have to deal with other transaction costs as they are taken care of by PROs. However, on the other hand, producers do not have direct control over collected waste, as they are mainly managed by PROs. CPR aims to maximise value extracted from WEEE and enhance collection efficiency. Thereby catering to producers' unique needs is not the priority. Due to fragmented value chains, it is also more challenging for producers to directly discuss with recyclers if they have concerns over the quality of recycled materials. Without smooth communication channels, it is more difficult to cooperate and work out a better solution.

For IPR, the advantages are that producers have more control over collected waste, including how to collect, send to where work with whom and extract what materials. Since producers have direct connections with recyclers, it can facilitate communications over the quality of recycled materials. For example, one respondent shared that they came back and forth with recyclers before producers finally ensure the function and aesthetic performance meet their requirements (Respondent 9). Since the quality of recycled materials is highly influenced by the way waste is collected, sorted and recycled. Having direct connections with recyclers can help solve problems more efficiently, as one respondent noted (Respondent 9). On the other hand, the disadvantages are costs in finding partners, selecting qualified recyclers, and setting efficient collection approaches. As large multinational companies might have more access to potential partners, small organisations experienced more difficulties looking for partners (Respondent 9, 11).

5.1.3 Potential strategies to mitigate the influence of transaction costs

According to the cases of CPR and IPR, transaction costs are inevitable and make use of recycled materials more challenging and less attractive to buyers. Pioneers in the field have proved it is possible to overcome transaction costs and use recycled materials on a commercial scale. Nevertheless, as not all stakeholders can undertake transaction costs, more active approaches should be initiated to further promote the use of recycled materials in EEE manufacturing and encourage WEEE recycling. As a result, this paper aims to contribute to this field by summarising two mitigation strategies to reduce impacts of transaction costs and make the benefits of recycling outweigh the costs based on findings.

Minimise transaction costs

Transaction costs of WEEE recycling can be minimised via policy instruments from the public sectors. In light of transaction costs of searching for sellers and buyers, raising public awareness on recycling should be the core of public policy to broadcast information and build correct perception (OECD, 2006). In addition, setting minimum requirements for using recycled materials in new products pr public procurements can help stimulate the demand, thereby reducing the transaction costs of searching for buyers (OECD, 2006). Policymakers can facilitate information exchanges by disseminating information of available producers to reduce transaction costs of searching for recyclers (OECD, 2006).

To reduce transaction costs of negotiating, building third-party verification can transfer the transaction costs of negotiating over the quality of recycled materials from producers to others. This is particularly important for recycled plastic as producers and recyclers have to overcome transaction costs of negotiating quality, performance and colour.

Maximise benefits of recycling

The other strategy of mitigating the impact of transaction cost is to maximise the benefits of recycling. For WEEE collection, the process can be optimised by ensuring clear waste streams. For materials like plastics, the quality of output highly depends on the source of waste. Correctly sorting waste at a source can effectively facilitate following procedures and prevent disruption of recycling lines. This is particularly difficult for plastic as there are many different kinds and without proper marks. Raising public awareness and disseminating the correct way to sort waste can enhance recycling efficiency and quality of recycled materials.

In addition, it is crucial to make the collection as convenient as possible to encourage citizens to get rid of their waste, and it requires detailed planning in the beginning. Also, optimising logistics such as transporting full load containers can help avoid unnecessary costs or carbon footprint. Protecting electronics from damage during transportation or exposure to the sun and the rain while collecting centres located outdoors also require better communication.

For WEEE pre-treatment, training should be given to the employee to ensure they have sufficient professional knowledge to identify hazardous waste that needs to be removed. Adopting innovative recycling technologies can help reach a higher recycling rate while eliminating environmental impacts from recycling activities. Once the equipment is in place, how to scale up input, such as importing waste from other countries, is the key to maximise margins.

5.2 Reflections on research design

The finding of this paper indicates transaction costs are identified in the stage of using recycled materials. As previous literature pointed out, various transaction costs can make recycling and use of recycled mateirlas more challenging, thereby reducing stakeholders' interest. In addition, both CPR and IPR are assessed in the paper, the result can also be used as a reference point to evaluate strength and weakness of both systems.

Regaridng research design, GVC theory is suitable to map WEEE value chain. Since WEEE value chains are structured in various forms, utilising GVC theory is helpful to lay the foundations. Transaction cost theory also provide a unique perspective to analyse WEEE recycling. Nevertheless, due to the nature of WEEE recycling, it is challenging to have a comprehensive understanding of tansaction costs. As transaction costs are affected by contextual factors and approaches of data collection, interviewees' background and perceptions can significantly influence their experience. Also, some kinds of costs are more implicit and it is more difficult to be identified by researchers. Therefore, transaction costs analysis mainly focuses on significant explicit costs that are easier to identify. Although this research attempted to overcome this issue by conducting multiple interviews to triangulate findings, it is worth stressed that the finding only presents an overview of transaction costs in defined scope. Because of difference in contextual facto, it can not be generalised to explain different WEEE recycling value chain in different regions.

In regard to research questions, two research questions focus on the broad scope. Both Sweden and Dell have been proved as valuable examples to understand how WEEE recycling value chains are structured and how transaction costs influence recycling. The advantage is to provide an overview, yet it is more challenging to give more specific comparison. Both Sweden and Dell include a wide scope of recycling activities with multiple stakeholders along the value chains, each can be research further. In addition, the scope of this paper is WEEE in general, not limited to specific kind of EEE. When analysing transaction costs of using recycled materials, house appliances are used as a case for CPR and general electronics are used as a case for IPR. However, as different categories of WEEE are treated differently, it would be valuable to focus on one particular group of prodcuts to give a more in-depth research. For instance, as it is easier to have take-back schems for small appliance, collecting large appliance like refrigerators needs different strategies. Similar concept also applies to recycling processes as recycling approaches could be different.

Similarly, since different materials requires different recycling technologies, it would be beneficial to focus on certain materials and conduct detailed assessment across regions. For example, as respondent from the EU pointed out it is difficult to find high quality recycled plastic outside of the EU, respondent from Asia has built a closed-loop recycling for plastic. The geographicl difference of recycling could be an interesting topic for further research.

6 Conclusions

Overall, upscaling WEEE recycling remains extremely complex even though more attention has been given in recent years. Multiple stakeholders involved and dispersed supply chains significantly increase the difficulties of promoting recycling. This paper aimed to obtain an understanding of how transaction costs affect WEEE recycling. To accelerate WEEE recycling, it is necessary to analyse the current status of WEEE recycling value chains and what kind of transaction costs are in place to create barriers to incorporate recycled materials in new EEE products. As the recycling market is relatively underdeveloped, both buyers and sellers of recycled materials face high transaction costs. As the use of recycled materials can be one significant driver to stimulate WEEE recycling, this paper sought to analyse the nature of transaction costs in WEEE recycling and thereby identify mitigations strategies to facilitate recycling markets. Two research questions are used to guide this study:

Research Question 1:
How are WEEE recycling value chains structured under Extended Producer Responsibility (EPR)?

In the case of CPR, WEEE is collected and pre-treated in Sweden, then different materials streams are sent to corresponding recyclers. While copper and aluminium are sent to local smelters, plastic is usually sent to China for recycling. Nevertheless, trend changes are identified as more plastic recycling activities are observed recently. One reason explained is because China has banned the import of waste since 2018, which pushes other countries being more responsible for their own waste. In the case of IPR, WEEE is collected and pre-treated in the US, then plastic is shipped to Dell's recycling partners in China and then directly sent to ODM partners in China. On the other hand, gold is recovered from PCBs and sent to ODM partners in Taiwan to manufacture new PCBs. With regard to the pilot project of recycling REEs, hard drives are first shipped to southeast Asia for dismantling, then components containing REEs are transported to Japan for recycling and recovering.

Under global value chains, centralised recycling activities are observed in both CPR and IPR for strategic reasons or cost-effectiveness considerations. For example, Sweden has a long history of mining and thereby gain experience in handling metals. Therefore, it is relatively advantageous for Sweden to involve in metal recycling. In the case of REEs, centralised recycling is needed because only a few recyclers around the world are specialised in processing REES. In addition, after recycled materials are extracted from WEEE, transboundary movement is needed to ship materials across countries as manufacturing networks are usually scattered around the world. One reason for Dell to cooperate with plastic recyclers in China is because they are closer to Dell's ODM partners in China. After recycled plastic is extracted from WEEE, it can be directly sent to manufacturing plants in China.

Research Question 2:
What kinds of transaction costs are identified in the WEEE recycling value chain?

In the phase of using recycled materials, three categories of transaction costs are identified:

- Due diligence costs:
  Because of immature recycling markets, additional time and efforts are required to match sellers and buyers. As the recycling market is a niche market, EEE producers

have to spend more time to search available recyclers. While recycled materials are put on commodities markets along with virgin raw materials, recyclers also find it difficult to compete with virgin raw materials as recycled materials tend to be more expensive due to high investment costs. Therefore, connecting available recyclers with interested EEE producers require extra efforts.

- Negotiating costs:
  Due to the uncertainty of recycled materials, producers have to test out the quality, function and colours to ensure products can perform at the same level as virgin raw materials. This transaction cost is particularly important as there is no clear standard or third party verification for each recycled material. Producers have to conduct their own research and tests to find out whether using recycled materials might compromise the performance of products. While metals can be recycled without compromising their quality, transaction costs of negotiating the quality of recycled plastic are more significant as colour and hazardous substance are more unpredictable. In response to the functional and colour difference of recycled materials, producers have to spend more time discussing with recyclers to optimise product quality. In some cases, producers even re-design its product to ensure recycled materials can be adopted.
- Monitoring and verification costs:
  Lastly, verifying the benefits of recycling is one source of transaction costs as recyclers need to convince EEE producers of the benefits of using recycled materials and whether it can result in lower environmental impact. Similarly, producers also conduct their own research to show their customers why they choose to adopt recycled materials with an aim to attract customers sharing similar views.

Even though transaction costs are unavoidable in niche markets, some pioneers in the industry have successfully overcome transaction cost and send recycled materials back into the manufacturing loop. However, how to go beyond single cases and further upscale WEEE recycling to the industry needs more discussion. To upscale WEEE recycling, stakeholders can either maximise the benefits of recycling to outweigh transaction costs or minimise transaction costs via policy instruments. Either way will require close cooperation between stakeholders from different regions, and policymakers play an important role in both scenarios.

This study demonstrated that to adopt recycled materials in EEE manufacturing, producers and recyclers are facing high transaction costs. As not all stakeholders can undertake additional costs, recycled materials are less attractive compared to virgin raw materials. As recycled materials demand remains weak, it is more challenging to stimulate the supply of recycled materials and upscale WEEE recycling activities. The main contribution of this thesis is to identify the nature of transaction costs in WEEE recycling and examine how pioneers acted in response to transaction costs. The result of this paper can be utilised as a reference to assess transaction costs in other WEEE recycling value chains under a different context. For future research, it would be valuable to quantify the scale of transaction costs, such as how much additional time and costs are needed to make a transaction happen. While this paper roughly focuses on the case of CPR and IPR, there are more detailed forms of recycling under these two systems. Extensive research is also needed to analyse transaction costs in other forms of WEEE recycling or comparing the advantages and disadvantages of CPR and IPR. In addition, narrowing down product scope can help understand whether transaction costs vary with products. Similarly, further research can be conducted with a focus on specific materials. For instance, as recycling plastic is more troublesome due to the material prosperities, transaction costs might be more significant and thereby requires more in-depth research.

Bibliography

Andersson, M., Ljunggren Söderman, M., & Sandén, B. A. (2019). Challenges of recycling multiple scarce metals: The case of Swedish ELV and WEEE recycling. Resources Policy, 63, 101403. https://doi.org/10.1016/j.resourpol.2019.101403

Antinori, C., & Sathaye, J. (2007). Assessing Transaction Costs of Project-based Greenhouse Gas Emissions Trading. Lawrence Berkeley National Laboratory.

Atasu, A., & Subramanian, R. (2012). Extended Producer Responsibility for E-Waste: Individual or Collective Producer Responsibility? Production and Operations Management, 21(6), 1042–1059. https://doi.org/10.1111/j.1937-5956.2012.01327.x

Avfall Sverige. (2020). Swedish Waste Management 2019. https://www.avfallsverige.se/fileadmin/user_upload/Publikationer/SAH_2019_publ20_eng.pdf

Ayuk, E., Pedro, A., Ekins, P., Gatune, J., Milligan, B., Oberle, B., Christmann, P., Ali, S., Kumar, V., Bringezu, S., Acquatella, J., Bernaudat, L., Bodoroglou, C., Brooks, S., Bonanomi, E., Clement, J., Collins, N., Davis, K., Davy, A., & Sanders, A. (2020). Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development.

Bair, J. (2008). Analysing global economic organization: Embedded networks and global chains compared. Economy and Society - ECON SOC, 37, 339–364. https://doi.org/10.1080/03085140802172664

Bakas, I., Herczeg, M., Fråne, A., Baxter, J., Vea, E., & Youhanan, L. (2016). Critical metals in discarded electronics: Mapping recycling potentials from selected waste electronics in the Nordic region.

Barrientos, S., Gereffi, G., & Rossi, A. (2010). Economic and Social Upgrading in Global Production Networks: Developing a Framework for Analysis. 25.

Basel Action Network (BAN). (2016). Disconnect: Goodwill and Dell, Exporting the Public's E-Waste to Developing Countries (The e-Trash Transparency Project). https://s3.amazonaws.com/ban-reports/Trash+Transparency/Disconnect+-+Goodwill+and+Dell+Exporting+the+Publics+E-waste+to+Developing+Countries+Report+-+Print+Version.pdf

Blaikie, N. W. H., & Priest, J. (2019). Designing social research: The logic of anticipation (V-husets bibliotek LTH 300.72; Third Edition). Polity Press. http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.5366630&site=eds-live&scope=site

Bohr, P. (2006). Policy Tools for Electronics Recycling Characteristics of a specific certificate market design. 2006, 132–137. https://doi.org/10.1109/ISEE.2006.1650049

Boliden. (2020a). Boliden Annual and Sustainability Report 2020. 124.

Boliden. (2020b). Green Copper. https://www.boliden.com/globalassets/operations/products/copper/green-copper/a5-folder-v2.0.pdf

Boliden. (2020c). Launching Boliden Green Copper. https://www.boliden.com/operations/products/copper/green-copper

Boliden. (2020d). Silver—Boliden. https://www.boliden.com/operations/products/silver

Boliden Mineral AB. (2020). Carbon footprint of Boliden main metals: Copper, nickel matte, zinc, lead. https://www.boliden.com/globalassets/operations/products/copper/green-copper/carbon-footprint-of-boliden-main-metals-2020_2021.pdf

Calcott, P., & Walls, M. (2005). Waste, recycling, and "Design for Environment": Roles for markets and policy instruments. Resource and Energy Economics, 27(4), 287–305. https://doi.org/10.1016/j.reseneeco.2005.02.001

CENELEC. (2017). European Standards for Waste Electrical and Electronic Equipment (WEEE). https://www.cencenelec.eu/news/publications/publications/weee-brochure.pdf

City of McKinney. (2015, October 1). Recycled Technology. https://www.youtube.com/watch?v=Fbqo26cFGX4&t=13s

Coe, N. M., Dicken, P., & Hess, M. (2008). Global production networks: Realizing the potential. Journal of Economic Geography, 8(3), 271–295. https://doi.org/10.1093/jeg/lbn002

Connelly, B. L., Ketchen, D. J., & Slater, S. F. (2011). Toward a "theoretical toolbox" for sustainability research in marketing. Journal of the Academy of Marketing Science, 39(1), 86–100. https://doi.org/10.1007/s11747-010-0199-0

Crafoord, K., Dalhammar, C., & Milios, L. (2018). The use of public procurement to incentivize longer lifetime and remanufacturing of computers. Procedia CIRP, 73, 137–141. https://doi.org/10.1016/j.procir.2018.03.316

Crang, M., Hughes, A., Gregson, N., Norris, L., & Ahamed, F. (2013). Rethinking governance and value in commodity chains through global recycling networks. Transactions of the Institute of British Geographers, 38(1), 12–24. https://doi.org/10.1111/j.1475-5661.2012.00515.x

Dalrymple, I., Wright, N., Kellner, R., Bains, N., Geraghty, K., Goosey, M., & Lightfoot, L. (2007). An integrated approach to electronic waste (WEEE) recycling. Circuit World, 33(2), 52–58. https://doi.org/10.1108/03056120710750256

Dell Technologies. (2016). FY16 Corporate Social Responsibility Report. https://i.dell.com/sites/doccontent/corporate/corp-comm/en/Documents/fy16-cr-report.pdf?newtab=true

Dell Technologies. (2018). Dell and Basel Action Network Team up to Track E-Waste. https://www.delltechnologies.com/en-us/blog/dell-basel-action-network-team-track-ewaste/

Dell Technologies. (2020). Working Together to Eliminate E-waste. Dell Technologies. https://www.delltechnologies.com/en-us/blog/working-together-to-eliminate-e-waste/

Dell Technologies. (2021a). 2030 Goals | Dell Technologies. https://corporate.delltechnologies.com/en-us/social-impact/reporting/2030-goals.htm

Dell Technologies. (2021b). Recycled materials | Dell Technologies US. https://corporate.delltechnologies.com/en-us/social-impact/advancing-sustainability/sustainable-products-and-services/materials-use/recycled-materials.htm

Dell Technologies, D. (n.d.). Recycling your Dell. Dell. https://www.dell.com/learn/us/en/id/videos~en/documents~reconnect-motion-graphic.aspx

Electrolux. (2010). Electrolux to create vacuum cleaners from plastic harvested from polluted oceans. Electrolux Group. https://www.electroluxgroup.com/en/electrolux-to-create-vacuum-cleaners-from-plastic-harvested-from-polluted-oceans-2093

Electrolux. (2016). Electrolux Sustainability Report 2016. Electrolux Group. https://www.electroluxgroup.com/en/electrolux-sustainability-report-2016-23415

Electrolux. (2020). Electrolux presents vacuum cleaner made of 100% recycled and reused materials. Electrolux Group. https://www.electroluxgroup.com/en/electrolux-presents-vacuum-cleaner-made-of-100-recycled-and-reused-materials-31759

Electrolux. (2021). Offer circular products and business solutions—Electrolux Sustainability Report 2020. https://www.electroluxgroup.com/sustainabilityreports/2020/key-priorities-and-progress-2020/our-nine-promises/better-solutions/offer-circular-products-and-business-solutions/

El-Kretsen. (n.d.). What Happens to My Old Phone? El-Kretsen. Retrieved May 14, 2021, from https://kunskapsrummet.com/en/articles/what-happens-to-my-old-phone/

El-Kretsen. (2019). Sustainaability Report 2018. https://kunskapsrummet.com/wp/wp-content/uploads/2021/03/Sustainability_Report_2018.pdf

El-Kretsen. (2020). El-Kretsen's collection and treatment of batteries. El-Kretsen. https://www.el-kretsen.se/english/sites/el-kretsen_eng/files/Press%20Release%202020-09-21.pdf

El-Kretsen. (2021a). Sustainability Report 2020. https://kunskapsrummet.com/wp/wp-content/uploads/2021/03/El-Kretsen_Sustainability-Report_2020.pdf

El-Kretsen. (2021b, March 22). How are Precious Metals Used in Electronics? El-Kretsen. https://kunskapsrummet.com/en/articles/how-are-precious-metals-used-in-electronics/

El-Kretsen. (2021c, March 22). Recycling Plastic – Step by Step. El-Kretsen. https://kunskapsrummet.com/en/articles/recycling-plastic-step-by-step/

El-Kretsen. (2021d, March 23). A Challenge for the Electronics Industry – Creating Closed Cycles. El-Kretsen. https://kunskapsrummet.com/en/articles/a-challenge-for-the-electronics-industry-creating-closed-cycles/

European Chemical Society. (2020). The Value is on Circularity – Recycling-Reusing-Reinvesting on Critical Raw Materials. https://www.euchems.eu/the-value-is-on-circularity-recycling-reusing-reinvesting-on-critical-raw-materials/

European Commission. (n.d.-a). A European Green Deal. European Commission - European Commission. Retrieved February 23, 2021, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (n.d.-b). EU Circular Economy Action Plan. Retrieved February 23, 2021, from https://ec.europa.eu/environment/circular-economy/

Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment, 32002L0096, EP, CONSIL, OJ L 037 (2003). http://data.europa.eu/eli/dir/2002/96/oj/eng

European Commission. (2018). The Waste Framework Directive. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

European Commission. (2019). Towards an EU Product Policy Framework contributing to the Circular Economy. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/1740-Towards-an-EU-Product-Policy-Framework-contributing-to-the-Circular-Economy_en

European Commission. (2020a). A new Circular Economy Action Plan For a cleaner and more competitive Europe. 20.

European Commission. (2020b). Critical materials for strategic technologies and sectors in the EU - a foresight study. file:///Users/wandahsieh/Downloads/Critical%20Raw%20Materials%20in%20Technologies%20and%20Sectors_foresight.pdf

European Commission. (2020c). Critical Raw Materials. https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

European Commission, Oakdene Hollins Ltd., & Fraunhofer Institute for Systems and Innovation Research ISI. (2013). Critical metals in the path towards the decarbonisation of the EU energy sector :assessing rare metals as supply chain bottlenecks in low carbon energy technologies. Publications Office. https://data.europa.eu/doi/10.2790/46338

Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088, Pub. L. No. 32020R0852, 198 OJ L (2020). http://data.europa.eu/eli/reg/2020/852/oj/eng

Eurostat. (2020). Total collection rate for waste electrical and electronic equipment. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Total_collection_rate_for_waste_electrical_and_electronic_equipment,_2017_(%25).png

Eurostat. (2021). Waste electrical and electronic equipment (WEEE) by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_waselee/default/bar?lang=en

Fang, F., Easter, K. William., & Brezonik, P. L. (2005). Point-Nonpoint Source Water Quality Trading: A Case Study in the Minnesota River Basin. Journal of the American Water Resources Association, 41(3), 645–657. https://doi.org/10.1111/j.1752-1688.2005.tb03761.x

Fleckinger, P., & Glachant, M. (2010). The organization of extended producer responsibility in waste policy with product differentiation. Journal of Environmental Economics and Management, 59(1), 57–66. https://doi.org/10.1016/j.jeem.2009.06.002

Flick, U. (2006). An introduction to qualitative research (Internationella miljöinstitutets bibliotek (IIIEE) Research methodology; 3. ed.). SAGE. http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.1631104&site=eds-live&scope=site

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The Global E-waste Monitor 2020. 120.

Furubotn, E. G., & Richter, R. (2010). Institutions and Economic Theory: The Contribution of the New Institutional Economics. University of Michigan Press. https://muse.jhu.edu/book/13446

Gereffi, G. (1994). The Organization of Buyer-Driven Global Commodity Chains: How U.S. Retailers Shape Overseas Production Networks (pp. 95–122).

Geyer, R., & Doctori Blass, V. (2010). The economics of cell phone reuse and recycling. The International Journal of Advanced Manufacturing Technology, 47(5), 515–525. https://doi.org/10.1007/s00170-009-2228-z

Gibbon, P., Bair, J., & Ponte, S. (2008). Governing global value chains: An introduction. 25.

Godoy León, M. F., Blengini, G. A., & Dewulf, J. (2020). Cobalt in end-of-life products in the EU, where does it end up? - The MaTrace approach. Resources, Conservation and Recycling, 158, 104842. https://doi.org/10.1016/j.resconrec.2020.104842

Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C., & Cook, M. (2006). Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. Science of The Total Environment, 359(1), 38–56. https://doi.org/10.1016/j.scitotenv.2005.07.001

Government Offices of Sweden, K. (2020). Circular economy—Strategy for the transition in Sweden. https://www.government.se/4ad42c/contentassets/d5ab250cf59a47b38feb8239eca1f6ab/circular-economy--strategy-for-the-transition-in-sweden

Grover, V., & Malhotra, M. K. (2003). Transaction cost framework in operations and supply chain management research: Theory and measurement. Journal of Operations Management, 21(4), 457–473. https://doi.org/10.1016/S0272-6963(03)00040-8

Hageluken, C. (2006). Improving metal returns and eco-efficiency in electronics recycling—A holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, 2006., 218–223. https://doi.org/10.1109/ISEE.2006.1650064

Hagelüken, C., & Corti, C. W. (2010). Recycling of gold from electronics: Cost-effective use through 'Design for Recycling.' Gold Bulletin, 43(3), 209–220. https://doi.org/10.1007/BF03214988

He, W., Li, G., Ma, X., Wang, H., Huang, J., Xu, M., & Huang, C. (2006). WEEE recovery strategies and the WEEE treatment status in China. Journal of Hazardous Materials, 136(3), 502–512. https://doi.org/10.1016/j.jhazmat.2006.04.060

Hofmann, H., Schleper, M. C., & Blome, C. (2018). Conflict Minerals and Supply Chain Due Diligence: An Exploratory Study of Multi-tier Supply Chains. Journal of Business Ethics, 147(1), 115–141. https://doi.org/10.1007/s10551-015-2963-z

Holgersson, S., Steenari, B.-M., Björkman, M., & Cullbrand, K. (2018). Analysis of the metal content of small-size Waste Electric and Electronic Equipment (WEEE) printed circuit boards—part 1: Internet routers, mobile phones and smartphones. Resources, Conservation and Recycling, 133, 300–308. https://doi.org/10.1016/j.resconrec.2017.02.011

Joshi, S., Baldock, C., & Awasthi, H. (2017). Dell: Environmental Net Benefit of Gold Recycling. Trucost, 38.

Kalimo, H., Lifset, R., Rossem, C. V., Wassenhove, L. V., Atasu, A., & Mayers, K. (2012). Greening the Economy through Design Incentives Greening the Economy through Design Incentives: Allocating Extended Producer Responsibility.

Kaplinsky, R., & Kaplinsky, R. (2013). Global Value Chains, Where They Came from, Where They Are Going and Why This Is Important. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.724.6304&rep=rep1&type=pdf

Khetriwal, D. S., Kraeuchi, P., & Widmer, R. (2009). Producer responsibility for e-waste management: Key issues for consideration – Learning from the Swiss experience. Journal of Environmental Management, 90(1), 153–165. https://doi.org/10.1016/j.jenvman.2007.08.019

Kiss, B., & Mundaca, L. (2013). Transaction Costs of Energy Efficiency in Buildings: An Overview. Undefined. /paper/Transaction-Costs-of-Energy-Efficiency-in-An-Kiss-Mundaca/6e822284b7f84157c81dea034fef899a7af5b59a

Kiss, Bernadett, & Mundaca, L. (2014). Exploring transaction costs in passive house-oriented retrofitting. Journal of Cleaner Production, 123, 65–76. https://doi.org/10.1016/j.jclepro.2015.09.035

Kollberg, M. (2003). Exploring the Environmental Effectiveness of Extended Producer Responsibility Programmes. IIIEE, Lund University, 81.

Krey, M. (2005). Transaction costs of unilateral CDM projects in India–results from an empirical survey. Energy Policy, 33(18), 2385–2397. https://doi.org/10.1016/j.enpol.2004.05.008

Lepawsky, J., & Billah, M. (2011). Making Chains That (un)make Things: Waste–Value Relations and the Bangladeshi Rubbish Electronics Industry. Geografiska Annaler: Series B, Human Geography, 93(2), 121–139. https://doi.org/10.1111/j.1468-0467.2011.00365.x

Levänen, J., Lyytinen, T., & Gatica, S. (2018). Modelling the Interplay Between Institutions and Circular Economy Business Models: A Case Study of Battery Recycling in Finland and Chile. Ecological Economics, 154, 373–382. https://doi.org/10.1016/j.ecolecon.2018.08.018

Lindhqvist, T. (2000). Extended Producer Responsibility in Cleaner Production: Policy Principle to Promote Environmental Improvements of Product Systems [Thesis/docmono, Lund University]. In IIIEE dissertations: Vol. 2000:2. http://lup.lub.lu.se/record/19692

Lukowiak, A., Zur, L., Tomala, R., LamTran, T. N., Bouajaj, A., Strek, W., Righini, G. C., Wickleder, M., & Ferrari, M. (2020). Rare earth elements and urban mines: Critical strategies for sustainable development. Ceramics International, 46(16, Part B), 26247–26250. https://doi.org/10.1016/j.ceramint.2020.03.067

Material Economics. (2020). Retaining value in the Swedish materials system. https://materialeconomics.com/new-publications/ett-vardebestandigt-svenskt-materialsystem

Mayring, P. (2000). Qualitative Content Analysis. 10.

McCann, L., Colby, B., Easter, K. W., Kasterine, A., & Kuperan, K. V. (2005). Transaction cost measurement for evaluating environmental policies. Ecological Economics, 52(4), 527–542. https://doi.org/10.1016/j.ecolecon.2004.08.002

Morana, R., & Seuring, S. (2011). A Three Level Framework for Closed-Loop Supply Chain Management—Linking Society, Chain and Actor Level. Sustainability, 3(4), 678–691. https://doi.org/10.3390/su3040678

Mundaca, L. (2007). Transaction costs of Tradable White Certificate schemes: The Energy Efficiency Commitment as case study. Energy Policy, 35(8), 4340–4354. https://doi.org/10.1016/j.enpol.2007.02.029

Mundaca, L., Mansoz, M., Neij, L., & Timilsina, G. R. (2013). Transaction costs analysis of low-carbon technologies. Climate Policy, 13(4), 490–513. https://doi.org/10.1080/14693062.2013.781452

Naturvårdsverket. (2019). Plastic in Sweden: Facts and Practical Advice (Mapping Plastic Flows in Sweden). https://www.naturvardsverket.se/Documents/publ-filer/978-91-620-8854-5.pdf?pid=26005

Naturvårdsverket. (2020a). Extended producer responsibility in Sweden: An overview of extended producer responsiblity in Sweden for packaging, newsprint, electrical equipment, batteries, end-of-life vehicles, tyres and pharmaceuticals. http://www.naturvardsverket.se/Documents/publ-filer/6900/978-91-620-6944-5.pdf?pid=27640

Naturvårdsverket. (2020b). Extended Producers Responsibility [Text]. Swedish Environmental Protection Agency. http://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Waste/Extended-Producers-Responsibility/

Naturvårdsverket. (2020c). Producer responsibility for electrical and electronic equipment [Text]. Swedish Environmental Protection Agency. http://www.swedishepa.se/Guidance/Guidance/Waste/Guidance-for-producers/Producers-electrical-and-electronic-equipment/

Nozharov, S. (2018). Transaction Costs in Collective Waste Recovery Systems in the EU. ArXiv:1804.06792 [Econ]. http://arxiv.org/abs/1804.06792

OECD. (2001). Extended Producer Responsibility: A Guidance Manual for Governments [Text]. https://www.oecd-ilibrary.org/environment/extended-producer-responsibility_9789264189867-en

OECD. (2006). Improving Recycling Markets. OECD. https://doi.org/10.1787/9789264029583-en

OECD. (2016). Extended Producer Responsibility: Updated Guidance for Efficient Waste Management. OECD. https://doi.org/10.1787/9789264256385-en

Pannell, D. J., Roberts, A. M., Park, G., & Alexander, J. (2013). Improving environmental decisions: A transaction-costs story. Ecological Economics, 88, 244–252. https://doi.org/10.1016/j.ecolecon.2012.11.025

REE4EU. (2015). REE4EU: Integrated High Temperature Electrolysis (HTE) and Ion Liquid Extraction (ILE) for a strong and independent European Rare Earth Elements supply chain. https://www.ree4eu.eu/wp-content/uploads/2017/11/REE4EU_Market-Analysis.pdf

Responsible Minerals Initiative, The Dragonfly Initiative, & Drive Sustainability. (2018). Material Change: A study of risks and opportunities for collective action in the materials suply chains of the automotive and electronics industries. https://eiccoalition.sharefile.com/share/view/s1787b0a407047d29

Riise, B. L., Allen, L. E., Biddle, M. B., & Fisher, M. M. (2001). Value added color sorting of recycled plastic flake from end-of-life electrical and electronic equipment. Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment. 2001 IEEE ISEE (Cat. No.01CH37190), 223–228. https://doi.org/10.1109/ISEE.2001.924530

Riordan, M. H., & Williamson, O. E. (1985). Asset specificity and economic organization. International Journal of Industrial Organization, 3(4), 365–378. https://doi.org/10.1016/0167-7187(85)90030-X

Singh, N., Duan, H., & Tang, Y. (2020). Toxicity evaluation of E-waste plastics and potential repercussions for human health. Environment International, 137, 105559. https://doi.org/10.1016/j.envint.2020.105559

Stena Aluminium. (n.d.). Stena Aluminium. Stena Aluminium. https://www.stenaaluminium.com/about-us/stena-aluminium/

Stena Metall. (2015, October 5). Stena Technoworld—Electronics recycling plant. https://www.youtube.com/watch?v=otaEqiYqq_I

Stena Metall. (2016, May 9). REE4EU - focus on recycling of rare earth metals within EU. https://www.youtube.com/watch?v=DUAxBCtvHB8

Stena Metall. (2017, November 7). Re-Made in Sweden—Partners in Sustainability. https://www.youtube.com/watch?v=bS2qwgFchss

Stena Metall. (2019, January 15). How recycling works at Stena Nordic Recycling Center. https://www.youtube.com/watch?v=07cV-3i_erk

Stenmarck, Å., Belleza, E. L., Fråne, A., Busch, N., Larsen, Å., & Wahlström, M. (2017). Hazardous substances in plastics (2017:505). Nordic Council of Ministers. https://doi.org/10.6027/TN2017-505

Terada, C. (2011). Recycling Electronic Wastes in Nigeria: Putting Environmental And Human Rights at Risk Student Article. Northwestern University Journal of International Human Rights, 10(3), 154–172.

Tojo, N. (2004). Extended Producer Responsibility as a Driver for Design Change—Utopia or Reality? [The International Institute for Industrial Environmental Economics]. https://portal.research.lu.se/portal/en/publications/extended-producer-responsibility-as-a-driver-for-design-change--utopia-or-reality(7b1d9fe0-1027-44ce-9ec5-55cb9be87db9).html

Tojo, N., van Rossem, C., & Al., E. (2007). The Producer Responsibility Principle of the WEEE Directive. http://lup.lub.lu.se/record/1023172

Tong, X., Tao, D., & Lifset, R. (2018). Varieties of business models for post-consumer recycling in China. Journal of Cleaner Production, 170, 665–673. https://doi.org/10.1016/j.jclepro.2017.09.032

Tostar, S. (2016). Mechanical and Thermal Properties of Recycled WEEE Plastic Blends. Department of Chemistry and Chemical Engineering, Chalmers University of Technology, 84.

Trucost. (2015). Valuing the net benefit of Dell's more sustainable plastic use at an industry-wide scale. https://i.dell.com/sites/content/corporate/corp-comm/en/Documents/circular-economy-net-benefits.pdf

UL. (2014). UL Environment Awards First Closed Loop Validation to Dell. UL. https://www.ul.com/news/ul-environment-awards-first-closed-loop-validation-dell

UN. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda

UN. (n.d.). Sustainable Development. https://sdgs.un.org/goals

UNEP. (2011). Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication—A Synthesis for Policy Makers. www.unep.org/greeneconomy

US EPA, OA. (2019, December 18). EPA Recognizes Electronics Industry Leaders for Achievements in Innovation and Recycling [Speeches, Testimony and Transcripts]. US EPA. https://www.epa.gov/newsreleases/epa-recognizes-electronics-industry-leaders-achievements-innovation-and-recycling

US EPA, OLEM. (2015, September 3). Basic Information about Electronics Stewardship [Overviews and Factsheets]. US EPA. https://www.epa.gov/smm-electronics/basic-information-about-electronics-stewardship

Uwin Nanotech. (2015). Recycling Today: A breakthrough technology from UWin Nanotech. https://www.uwin-nano.com/en/news.php?id=30

UWin Nanotech. (2016). Eco-friendly Recycling Process of E-waste. https://www.uwin-nano.com/en/news.php?id=52

van Rossem, C. (2008). Individual Producer Responsibility in the WEEE Directive—From Theory to Practice? The International Institute for Industrial Environmental Economics, 2(2), 119–120. https://doi.org/10.1016/0959-6526(94)90010-8

Verhaegen, I., & Van Huylenbroeck, G. (2001). Costs and benefits for farmers participating in innovative marketing channels for quality food products. Journal of Rural Studies, 17(4), 443–456. https://doi.org/10.1016/S0743-0167(01)00017-1

Wahlström, M., Youhanan, L., Stenmarck, Å., Punkkinen, H., & Mroueh, U.-M. (2017). Critical metals in end-of-life products. Nordic Council of Ministers. https://doi.org/10.6027/TN2017-531

Walls, M. (2006). Extended Producer Responsibility and Product Design: Economic Theory and Selected Case Studies. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.901661

Wang, X., Zhu, L., & Fan, Y. (2018). Transaction costs, market structure and efficient coverage of emissions trading scheme: A microlevel study from the pilots in China. Applied Energy, 220, 657–671. https://doi.org/10.1016/j.apenergy.2018.03.080

Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements. Resources, Conservation and Recycling, 155, 104669. https://doi.org/10.1016/j.resconrec.2019.104669

Werner, T., Mudd, G., & Jowitt, S. (2015). Indium: Key issues in assessing mineral resources and long-term supply from recycling. Applied Earth Science (Trans. Inst. Min. Metall. B), 1743275815Y – 0000000007.

Wistron Corporation. (2020). 2019 CSR report. https://www.wistron.com/CMS/SocialResponsibility?pageId=234

Wistron GreenTech Texas. (2014). Wistron GreenTech—Profile. http://greentx.wistron.com/en-global/Page/company_profile

Yin, R. K. (2003). Case study research: Design and methods (Biblioteket för arkitektur och design LTH 22 Yin; 3 ed.). Sage Publications. http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07147a&AN=lub.1463505&site=eds-live&scope=site

Ylä-Mella, J., & Pongrácz, E. (2016). Drivers and Constraints of Critical Materials Recycling: The Case of Indium. Resources, 5(4), 34. https://doi.org/10.3390/resources5040034

Zacho, K. O., Bundgaard, A. M., & Mosgaard, M. A. (2018). Constraints and opportunities for integrating preparation for reuse in the Danish WEEE management system. Resources, Conservation & Recycling, 138, 13–23. https://doi.org/10.1016/j.resconrec.2018.06.006

Appendix A. Interview Protocol

1. Overview

(1) Interviewee's Background and Organisation Overview

- Could you share your role in the team? How is your team structured?
- Could you describe your organisation's stance or strategy on electronic recycling?
- What are the main motivations for your organization to start involving in the recycling business? for example sustainability concerns, local regulations, or customers' expectations?

(2) Stakeholders' role

1.1 WEEE collection and sorting

- Is WEEE collected by formal (public collection schemes or organisatioanl take-back scheme) or informal collectors? Could you share what is the standard procedure for collection?
- In regard to WEEE collection, how do you set up collecting points in a cost effective way? How do you work with logistics? Is it rather easy or difficult to develop an association with them and monitor their performance?
- After containers are transported to pre-treatment facilities, the first stage is manual sorting. Are they already sorted out or are they mixed? Can you share the standard procedures of sorting e-waste?
- Do you provide training for employees? Does it also result in high operation costs in this process?
- Will circuit boards be handled separately or sent to specific recycling facilities? What are the main reasons?
- Could you explain why it is divided into these four categories? For metals, is it possible to identify and sort out in more detailed categories?
- For other materials, how are they handled after sorting? Are they sent to recycling facilities for further treatment? Who are your main partner?
- In your view, what is the role of collectors in shifting the electronics industry to be more circular?

1.2 Pre-processing by Recycling facilities

- Could you share what is the standard procedure for recycling? From receiving electronic containers to deliver to customers or smelter. Are electronics already sorted out when you receive them, or are they mixed so you have to sort out manually?
- Could you share how complex scraps increase the difficulties of sorting and processing? How does complicated product design and content affect Stena's work?
- Confidential destruction is an important step of electronics recycling. Could you share how do you destruct confidential information?
- Could you share what are the obstacles for recycling metal so far? Why it is difficult? What are potential solutions?
- Why circuit boards are treated differently? Can automated systems help saving time?
- How do you recycle mixed metals? Some metals are used in a relatively small amount, is it possible to separate them?
- How do you check the quality? Scraps are sorted out by what categories? Do they have to be processed again to meet the quality? What are main requirements from

customers? Who are the main customers (steelworks, smelters, foundries, plastic producers and other manufacturers)?

- Could you elaborate on quality assurance and delivery issue of iron and metal scrap?
- Does recycled plastic come from open source? What are the difficulties to make product solely from recycled plastic? Is quality the main concern? Do you have to alter your approach to meet producer's standard?

1.3 End-processing by refineries

- What are the main sources of scraps? Are they collected locally or transported from other regions? How would you describe your relationships with suppliers?
- Are scraps already sorted out when you receive them? or do you have to sort them by yourself? Are they sorted out by different waste streams (metals, glass, plastic)?
- Could you describe your relationship with suppliers of electronics scraps? Such as how much influence you has with suppliers? Is there any competition to choose from with suppliers? Or only a few available suppliers?
- What kind of materials are you currently targeted for recovering? What are the reasons or main considerations, such as with higher economic value, environmental concerns, or available technology?
- Could you elaborate on the process of sampling and shredding? Are they necessary steps to ensure the quality?
- Could you share some details of your collaboration with scraps suppliers? Such as how this collaboration initiated? Have you encountered any obstacles, such as different standards or specific requirements?
- Have you experienced any difficulties to pursue top management or other department (like supply chain management) to value the importance of recycled material more? especially when you also produces virgin raw materials. Are they quite supportive or did you need to convince them?
- How do you monitor the quality of recycled material? Is there any certification or standards for your reference?
- How do you manage this issue to decrease the negative environmental impact arising from electronic recycling?
- After materials are melted and extracted, who are the main buyers? Are they sold to common factories or if only a specific company has the ability to handle them?
- In your opinion, would price remain the main concern when customer purchase raw material? Or is there any other consideration?
- From a marketing perspective, can using recycled material attract more customers? Do you perceive this kind of product is more attractive to customers?
- Has Boliden experienced any trouble finding buyers for recycled material at a premium? In your opinion, do you think this might change as EU policy comes in pushing for more recycled content?

1.4 The use of recycled materials by producers

- Could you share your experience in looking for suppliers of recycled plastic? Have you encountered any difficulties to find suitable suppliers in Europe? Do you work with existing suppliers or find new suppliers?
- Could you elaborate on the quality issue? And what progress your organisation has made so far or plans to make in the future?
- In your opinion, would price remain the main concern when your organisation

purchases raw material? Or is there any other consideration?
- Could you describe your relationship with suppliers of recycled materials? Such as how much influence you have with suppliers? Is there any competition to choose from with suppliers? Or only a few available suppliers?
- "Could you share details of your collaboration with recyclers? Such as how this collaboration initiated? What are the source of recycled plastic? Is quality an issue? Have you encountered any obstacles?
- Have you experienced any difficulties to pursue top management or other department (like design or supply chain management) to use recycled material? Are they quite supportive or did you need to convince them?
- How do you monitor the quality of recycled material? Is there any certification or standards for your reference? Or do you have to test the quality by yourself?
- From a marketing perspective, can using recycled material attract more customers? Do you perceive this kind of product is more attractive to customers?
- Some companies choose to set up their own take-back scheme with an aim to build a closed-loop recycling system, while other prefer an open source for recycled materials. In your view, what are the advantages and disadvantages
- Extended Producer Responsibility (EPR) makes the producer responsible for the product, including take back, recycling and final disposal. In your view, what is the role of producers in shifting the electronics industry to be more circular?
- For a multinational corporation with a global take-back program, does the nature of the global supply chain increase the complexity of building closed-loop recycling?
- Is there any plan for further upscaling the recycling of plastic, gold, and rare earth magnets? Apart from these materials, have you considered expanding the use of recycled material to other materials

2. Regulations
    - How do regulatory requirements affect you in WEEE recycling? Which specific regualtions?
    - As you may already know, a circular electronics initiative was issued by the EU to promote longer product lifetime, also to improve the collection and treatment of waste electrical and electronic equipment. For the harmonisation and improvement of recycling infrastructure, it asked for a mandatory certification scheme for recyclers of electronics waste to guarantee efficient material recovery and environmental protection. What is your take on this development? Will it affect your business in any way?

3. Opinion on Industry Overview and Long-term Prospects
    - Is there any plan for further upscaling the recycling practices? such as expanding the scope to other materials or other regions?
    - What are the biggest challenges for WEEE recycling that you are facing now? for example searching for suitable suppliers, internal communication with different departments, or technology constraints?
    - How do you see the market to evolve? What are the opportunities do you see in the future?
    - Does the nature of the global supply chain increase the complexity of recycling? such as adding the difficulties to collect waste. Or it could be an advantage?
    - How does the informal recycling market (i.e. illegal export of e-waste and informal

recycling in third countries) affect your business?

Appendix B. Interview Lists

Respondents/ Job positions		Organisation (Types)	Time/ Location
1. Fredrik Benson	Business development, EVP	El-Kretsen	Zoom meeting 13.00-14.00 March 29, 2021
2. Xue Kullenius	Project manager	Sysav Industri AB	Microsoftteam 13.00-14.00 March 25, 2021
3. Per Eriksson	Business specialist for business area electronics	Stena Recycling AB, Setan Metall Group	Zoom 9.30-10.30 March 25, 2021
4. Sverker Sjölin	Technical specialist	Stena Recycling AB, Setan Metall Group	Call 13.30-14.30 March 23, 2021
5.	Sustainability Advisor	Boliden AB	Zoom 9.00-10.00 February 11, 2021
6.	Manager for copper raw materials		
7. Karl Edsjö	Director of resource efficiency policy and recycling	Electrolux Group	Zoom 14.00-15.00 April 30, 2021
8. Joel Lindquist	Offer manager	Atea Sverige AB	Call 9.00-10.00 March 1, 2021
9. Vivan Tai	Senior manager, Asia Pacific & Japan (APJ) product compliance & environmental affairs	Dell Technologies	Zoom 14.00-15.00 March 24, 2021
10.	Compliance manager producer responsibility	Dell Technologies	Mails
11. Reinhardt Smit	Director of supply chain	Closing the Loop	Google meeting 15.30-16.30 March 10, 2021
12. Alexandra Wu	Project Manager, Sustainable Consumption and Resource Flows	IVL Swedish Environmental Institute	Zoom 16.30-17.30 February 8, 2021
13. Yao-Hua Chang	Vice chairman of environmental safety committee	Taiwan Printed Circuit Association	Zoom 9.00-10.00 February 26, 2021
14.	Project Manager and sustainability coordinator	Reverse supply chain company	Call 12.00-13.00 February 7, 2021

15. Mei-Huei Tsao	Consultant	Environmental consulting corporation	Zoom 8.00-9.00 January 7, 2021