CHALMERS
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Closing the Loop on Electric Vehicle Charging

Exploring Circular Economy Principles for Resource Efficiency and Sustainability Across the Life cycle of AC Chargers

Master’s thesis in Sustainable Energy Systems

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Cover: Electric vehicle charging from an AC charger

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Abstract

This thesis investigates the environmental impact of AC chargers, focusing on European stakeholders and regulations, with a specific emphasis on the Swedish context. Employing a comprehensive approach, the charger's life cycle is analyzed across three stages: Beginning-of-Life, Middle-of-Life, and End-of-Life. Through interviews with stakeholders and a thorough examination of each life cycle stage, key contributors to environmental impacts are identified, and improvement measures are proposed. The findings reveal notable trends within the charger industry, such as producers' commitment to integrating sustainability in upcoming iterations and the importance of transitioning to renewable energy sources to reduce Middle-of-Life emissions for chargers. In the End-of-Life stage, sorting and pre-treatment processes enhance recyclable material recovery, which is an important factor for circularity.

The findings have implications for sustainable charging solutions, particularly in Europe. However, considering the regional focus, global applicability requires careful evaluation. This thesis sheds light on the primary factors influencing the environmental impact of AC chargers and presents practical improvement measures. The research contributes to the development of sustainable and circular charging solutions, particularly in the European context, for a sustainable future.

Keywords: sustainability, resource efficiency, electric vehicles, charging infrastructure, AC charger.

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Amanda Agnéus and Marika Carlsson, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
BEV	Battery electric vehicle
BoL	Beginning-of-Life
CRM Act	Critical Raw Materials Act
DC	Direct current
EEE	Electrical and electronic equipment
EoL	End-of-Life
EV	Electric Vehicle
FRP	Fiber-reinforced polyester
GHG	Greenhouse gas
ICE	Internal combusting engine
IK	Impact Protection
IP	Ingress Protection
LCA	Life cycle assessment
MoL	Middle-of-Life
PC	Polycarbonate
PHEV	Plug-in hybrid electric vehicle
PCB	Printed Circuit Board
PSS	Product Service Systems
RES	Renewable energy source
RoHS	Restriction of Hazardous Substances in Electrical and Electronic Equipment
TTW	Tank-to-wheel
USP	Unique Selling Point
V2G	Vehicle-to-grid
WEEE	Waste of Electrical and electronic equipment
WTT	Well-to-tank

Contents

1

Introduction

1.1 Background

Society faces a major challenge with the electrification of, among other things, the transport sector. Electrifying the transport sector aims to effectively reduce emissions from fossil energy sources and thereby reduce the impact on the environment with the long-term goal of reaching the goal of 1.5°C global temperature increase. Much focus today is on producing electric cars and charging infrastructure to increase the supply and enable the purchase of green sustainable means of transport for the masses. Today, less focus is on the environmental impact of the chargers and how its value chain can be optimized to minimize the impact on the environment throughout its lifetime.

In the coming years, a large expansion of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) in the Swedish car fleet is expected with a total share of 60% in new car sales in 2030 [1]. In addition, the corresponding figures for light trucks and heavy trucks are expected to be 26% and 20% respectively. To meet the need for charging infrastructure, the EU has developed a key figure of 0.1 public charging point per electric car to cover the basic need for charging. However, in countries that relies less on charging at home, this number tends to increase [2]. In 2030, the amount of chargeable cars in Sweden is expected to reach 1 500 000-2 500 000 [1]. It can therefore be stated that the number of AC chargers will amount to maximum the same quantity, only accounting for private and semi-public AC chargers. This will have a substantial affect on material demand to manage the electrification. Table 1.1 includes a representative material composition of an Alternating Current (AC) charger, highly suitable and most frequently used for EV charging [3]. Moreover, the table shows estimated quantities of materials required to facilitate 1.5 - 2.5 million charging points in Sweden by 2030, as described above. Based on these estimates, it is projected that Sweden would need up to 2 750 tons of casing material, 1 325 tons of polymers, 7 250 tons of metal, and 2 050 tons of electrical components to support the projected charging network. These figures shows substantial material requirements, necessitating a thoughtful approach to minimize environmental impacts and ensure sustainable practices throughout the entire charging infrastructure industry. Note that this does not take into account the need for fast chargers and DC chargers, which also require an extensive amount of materials.

Table 1.1: Material composition of an AC charger and estimation of material needed for Swedish charging infrastructure in 2030 [1, 3].

	Material composition	**Material needed, Sweden 2030**
# Charger	1	1 500 000 - 2 500 000
Casing [kg]	1.1	1 650 000 - 2 750 000
Polymers excl. casing [kg]	0.53	795 000 - 1 325 000
Metal excl. casing [kg]	1.8	2 700 000 - 4 500 000
Electrical components [kg]	0.82	1 230 000 - 2 050 000

As a distributor and supplier of charging infrastructure and connected services, E.ON plays a big role in the development of sustainable means of transport. To be able to meet both their own demands and goals in the business as well as to contribute to global sustainability goals, it lies in the interest of E.ON's Drive department to ensure that the chargers they provide are sustainable throughout their life cycle.

1.2 Aim

The purpose with this master thesis is to investigate how actors related to the life cycle of AC chargers can contribute to a more sustainable charging infrastructure. The thesis will provide a framework for actors in the value chain and offer a comprehensive understanding of how AC chargers should be handled in accordance with a more circular economy. Focus will lie on minimizing energy consumption as well as to maximize the utilization rate for every loop of the circular economy model. Furthermore, the thesis aims to examine the distribution of responsibility among the producer, distributor and end customer, with a particular focus on the ways in which distributors can assist other actors in the supply chain to adopt sustainable practices.

1.3 Limitations

The thesis aims to evaluate the environmental impact of private and semi-public AC chargers for EVs throughout their life cycle, utilizing a circular economy approach as a framework for analysis. The life cycle stages are limited to production, with focus on design perspective and material selection, as well as the use phase and end-of-life, consisting of waste management and recycling. The material selection is restricted to commonly used materials for the casing, i.e., plastic and aluminium. Also, electric components and its environmental impact will be investigated, due to it being a necessity in AC chargers. Focus will lie on the complexity of utilizing small quantities of scarce metals, and the potential consequences of inadequate waste management, including resource depletion.

Environmental impact measurements will be limited to carbon footprint and energy consumption. Furthermore, the thesis will be limited to European and Swedish legislating and standardization for electric equipment, producer responsibility, charging infrastructure and waste management.

2

Theory

2.1 The transition towards an electrified transport sector

In 2017, road transport was responsible for 21% of the European Union's total emissions of CO_2 [4]. Passenger cars alone accounted for 12% of the EU's CO_2 emissions. The corresponding data for Sweden is 30% of total emissions from road transport, and 20% for passenger cars [5, 6]. In order to reduce these emissions, the transition towards an electrified vehicle fleet is crucial. EVs could enable lower emissions than an internal combustion engine (ICE) vehicles since it does not create any tailpipe emissions. Volvo Cars has done an Life Cycle Assessment (LCA) study comparing the car model XC40 with a conventional petrol engine to the XC40 with a BEV powertrain. The comparison also includes different electricity mixes used for charging: average global energy mix, EU28 and solely wind power. The result can be seen in Figure 2.1, which shows that XC40 BEV has a lower carbon footprint than XC40 ICE in all cases of electricity mix used for charging. It also shows that the emissions could be cut in half by charging on wind power only.

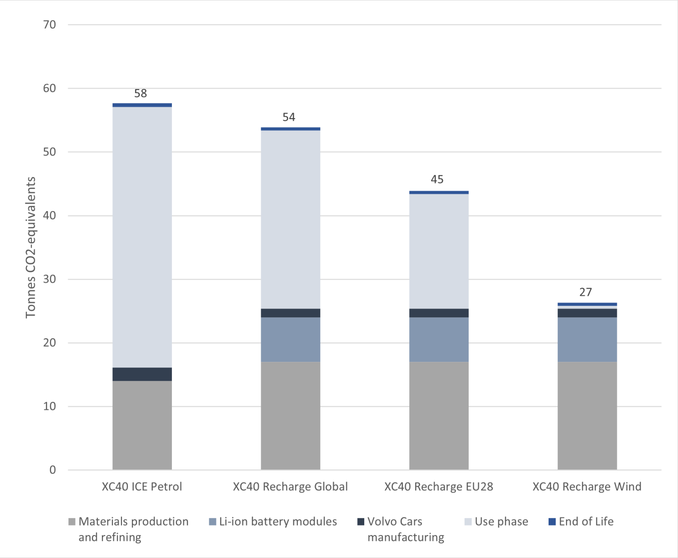

Figure 2.1: Carbon footprint of Volvo XC40 ICE and XC40 Recharge (BEV) with different electricity mixes used in the use phase for XC40 Recharge (BEV) [7].

Furthermore, EV's demonstrate higher energy efficiency in terms of tank-to-wheel (TTW) efficiency, which represents the percentage of energy converted from the fuel or energy source to useful work at the wheels of the vehicle. Electric motors in an EV typically have TTW efficiencies ranging from 73% to 90%, whereas ICEs in conventional vehicles generally have efficiencies of only 16% to 37% [8]. This means that EVs require less energy in total to meet the same driving demand, while also transitioning from fossil-based fuels to electricity as the fuel source.

The EU has set ambitious climate goals, with an overall target of climate neutrality by 2050. As an intermediate step, the EU has also set up a sub-goal of at least a 55% reduction in greenhouse gas (GHG) emissions by 2030, compared to the baseline year of 1990 [4]. *Fit for 55* is an EU package with the aim to review and propose changes in EU legislation, in order to meet the above mentioned climate goals. According to the European Green Deal Fit for 55, the EU's target is to reduce emissions from new cars and vans by 100% by 2035 [9]. This objective implies that all vehicles sold after 2035 should not produce any GHG emissions during operation.

The number of new registrations of electric cars in the EU has seen significant growth in recent years, as seen in Figure 2.2, which suggests an exponential growth. Between 2010 and 2021, the total number of new registrations of BEVs and PHEVs has risen from 600 to 1 729 000, representing an 18% share of new registrations in the EU-27 [10].

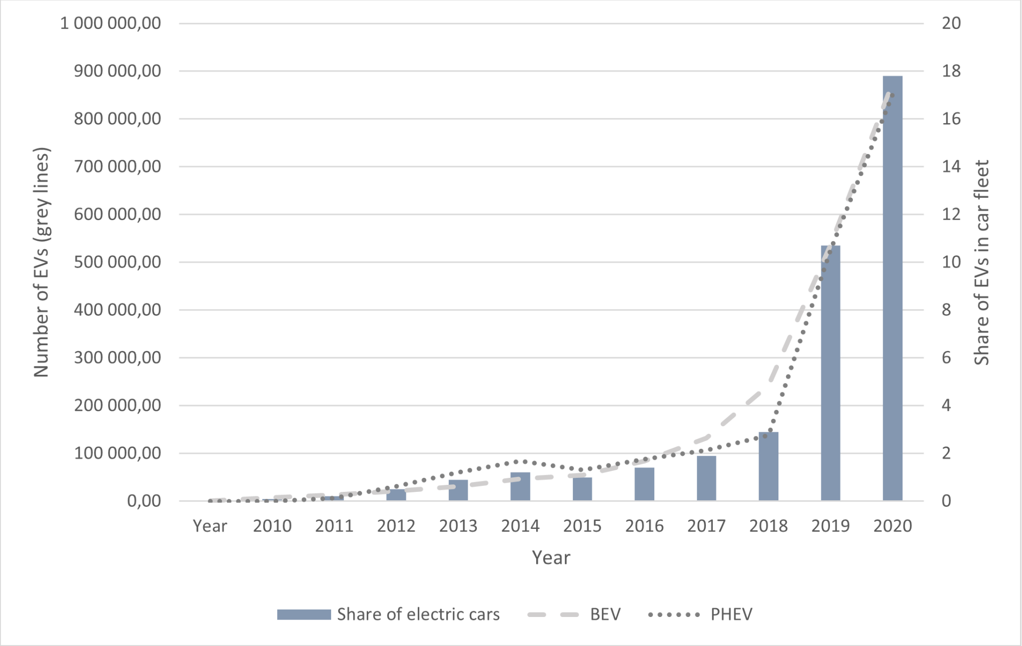

Figure 2.2: New registrations of electric cars in EU-27 during 2010-2021 [10].

The rapid increase of EVs in the car fleet will result in increased electricity demand. It is projected that by 2050, EVs will account for 9.5% of the total electricity demand in EU, assuming an 80% share of EVs [11]. This is a significant increase compared to the mere 0,03% share in 2014 [12]. Meeting this heightened demand for electricity will require additional generation capacity, estimated to be up to 150 GW [11]. To put this into perspective, the EU's total installed generation capacity in 2020 was 1000 GW [13]. It is suggested that the increments will come from wind, solar, nuclear and fossil [11]. A more sustainable mix is suggested as well, were the renewable energy sources (RES) as mentioned, together with bio and hydro, will replace fossil fuels fully.

It is also important to consider what kind of impact different charging patterns could have on the grid and the electricity mix. First, there are risks of substantial stress on the local grid infrastructures when a large number of cars are being charged at the same time. It is therefore suggested that smart charging will be of importance for those regions with weak network infrastructure, in order to facilitate the grid. Smart charging implies some kind of charging strategy for EVs in order to optimize the charging process. There are different strategies, e.g., network-oriented charging, RES-oriented charging and cost-oriented charging [11]. For network-oriented charging, it is suggested that EV charging should be scheduled during low demand hours, which typically occur during night. However, it should be noted that during these off-peak hours, fossil-fueled power plant with high GHG emissions often dominate electricity production in those regions with fossil-based power plants in the electricity mix. This in turn raises sustainability concerns. Therefore, RES-oriented smart charging suggest that EV charging should be aligned with hours of high renewable energy production, such as solar and wind, to promote the penetration of RES in the electricity mix. However, designing a universally applicable strategy for this is challenging due to significant variations in regional power systems and generation portfolios. Nevertheless, it is evident that different EV charging strategies can result in varying levels of sustainability for the overall system.

2.2 Sustainable Development Goals

The Sustainable Development Goals presents strategies and sub-goals to achieve in order to make sustainable choices that foster and support global sustainable development. The goals aim to guide companies and organizations in managing adjustments to produce or develop products and services in a more sustainable way. The following five sustainability goals has been identified as related to e-mobility.

7 AFFORDABLE AND CLEAN ENERGY

Sustainable Development Goal 7 is to "Ensure access to affordable, reliable, sustainable and modern energy for all" [14]. The goal aims to increase the share of people that can access modern and sustainable energy as well as decarbonize the energy available today. It also strives to increase the energy efficiency and promote investment in energy infrastructure. Goal 7 is related to charging infrastructure due to the fact that charging infrastructure enables less dependence on fossil energy sources and contributes to all health benefits connected to zero tailpipe emissions. Further, as explained before, electric propulsion serves higher TTW efficiency, hence, electrification promotes energy efficiency.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Sustainable Development Goal 9 is to "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" [15]. The goal aims to improve access to reliable, safe and modern infrastructure to support economic development and human well-being by increasing capacity, promoting sustainable industrialization and fostering innovation. The goal is connected to charging points through the promotion of sustainable transportation infrastructure. However, for EV's to be a viable transportation option, it is important to have a reliable and widely available infrastructure for charging them. By providing sustainable EV chargers, distributors such as E.ON can support the adoption of EVs and decrease dependence on fossil fuels which would reduce pollution and GHG emissions.

11 SUSTAINABLE CITIES AND COMMUNITIES

Goal 11, "Make cities and human settlements inclusive, safe, resilient and sustainable", presses on the importance of implementing sustainability to support and increase well-being regardless of where you live [16]. This goal includes important topics such as sustainable transportation and the need for improved health, especially with regards to air pollution. Distributors of AC chargers could make a contribution to goal 11 by distributing chargers that undergo thorough sustainability investigations. Their efforts enable sustainable transportation, leading to a substantial reduction in air pollution..

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Goal 12, "Ensure sustainable consumption and production patterns" aims to reduce or mitigate the negative impacts resulting from poor management of waste reduction and inefficient use of resources [17]. This is done partly by putting effort into increasing resource efficiency and proper waste management. Considering the vast amount of chargers that are expected in the near future, proper and sustainable management of material are critical to not further deplete finite resources. Goal 12 is connected to charging infrastructure by the immense amount of material needed to support the upcoming interest in sustainable transportation. Therefore it is important to ensure that the management of resources and waste is carried out in a sustainable manner. Thus, providing resilient and long-lasting charging points with a low environmental impact throughout its life-time is important in order to meet this goal and promote the use of sustainable transportation.

13 CLIMATE ACTION

Possibly the most prominent and self-explanatory goal related to EV chargers is goal 13: "Take urgent action to combat climate change and its impacts". One sub-goal strongly aims to integrate climate change measures into national policies, strategies and planning, which is heavily related to E.ON as distributors. The goal dives into many climate related issues, such as extreme weather and sea water rising [18]. Many of the consequences expected if not adhering to the goal is due to emissions from fossil sources. Hence, by mitigating fossil dependence, the severity of the consequences becomes less powerful. As stated in 2.1, passenger cars across EU accounts for a hefty part of their overall emissions. Also, this only accounts for the tailpipe emissions, thus not including neither well-to-tank (WTT) related emissions such as oil extraction and refining nor vehicle production related emissions. By providing sustainable infrastructure to support adaption of EVs, E.ON acts to mitigate the large tailpipe emissions connected to usage of combustion propulsion in the transportation system.

2.3 AC Charger Functions

AC charging is the most common version of charging, and dominates the market with a 75% global market share, while the remaining 25% is accounted for by DC charging [19, 20]. Figure 2.3 illustrates one example of how an AC charger can look like, serving as a representative depiction of the various designs found on the market [21]. When using an AC charger, the conversion from AC to DC is done in the EV by its on-board system, as an EV battery requires DC. This leads to a relatively slow charging rate, with a full charging time of 5-8 h [22]. This differs from DC chargers, where the conversion from AC to DC is done in the DC charging station instead [22]. This allows the DC current to be sent directly to the battery without having to pass through the EV's own conversion system. This enables faster charging since it is not restricted to the EV's on-board system.

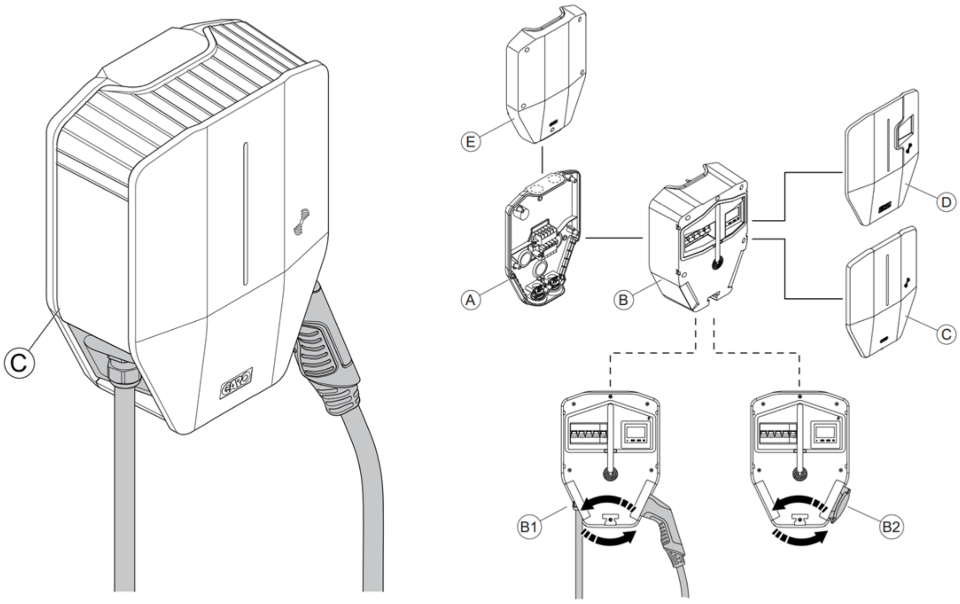

Figure 2.3: AC Charger schematic from GARO's model 'Entity' manual [21]

AC chargers have usually a maximum charging current at 16 A and a maximum charging power at 22 kW [22]. A safety measure to control the power output are usually included in all chargers. This is called load balancing, which regulates the power output to the EV while charging. This in order to prevent overloading the home's power grid and main fuses [23, 24, 25]. It could for example be important when using electricity demanding home appliances at the same time, such as electricity driven heating, oven and washing machine. Furthermore, load balancing ensures that the charger operates at its maximum power that is available, thereby optimizing its utilization rate. There are usually two types of load balancing - static and dynamic. With a static load balancing, a maximum power is set which the charger cannot exceed. With dynamic load balancing, an extra electricity meter is installed between the distribution board and the charger. The electricity meter continuously reads the house's electricity consumption and adjust the EV charging to available electricity level. With this, the household electricity is prioritized and the charging level to the EV adapts.

A multitude of AC chargers on the market have the capability to connect to either 4G or Wi-Fi. This function enables remote control of the charging process, as well as enabling firmware updates of the charger [26, 27, 28]. A part from the customer being able to have a high degree of control of its charger, it also enables the distributor to help the customer from the back-office if there are any software errors.

Chargers are also often equipped with the so-called ISO standard 15118. This international standard defines vehicle-to-grid (V2G) communication, which enables bi-directional charging and discharging of EVs [29]. This area is still being explored and there are both technical, legal, political and financial aspects that must be taken into account. One aspect highlighting the complexity is the location of the hardware responsible for enabling bi-directional charging. Different opinions exist within the industry regarding the party responsible for installing this hardware. The debate revolves around whether the hardware should be integrated into the charger or the EV. Notwithstanding these considerations, the theoretical idea is to use EV batteries both as energy storage and other support services for the electricity grid, such as frequency regulation. It has been suggested that 3,8 million EVs in the Swedish system could have a power potential between 14-114 GW, without affecting the driving demands [30]. This capacity is significant when comparing to the highest peak hour in Sweden, which is between 25-30 GW [31]. These findings show that a widespread adoption of EVs could replace the investments in other storage technologies. This is especially of interest when integrating more intermittent energy sources such as solar and wind power in the system.

Within the ISO15118 standard, V2G communication is one component, but the primary function that drives the industry is known as Plug and Charge [32]. This function is particularly relevant for public charging as it facilitates communication between the EV, the charging station, and the payment operator. In practice, the charging station receives information about the specific EV being charged, allowing the payment operator to debit the car owner's account linked to the vehicle. This automatic payment method eliminates the need for EV users to rely on a separate app or RFID card for payment, which simplifies the payment process for customers. It thereby reduces the complexity associated with different charging station companies typically having their own payment apps.

Lastly, in order to have all these technical functions, hardware is needed. The charge controller holds a lot of important functions as mentioned, e.g., dynamic load management, Open Charge Point Protocol (OCPP) transmission as well as ISO 15118 compatibility, which are all printed on a circuit board [33]. These characteristics makes the charge controller a high value component and makes up the vast majority of the total charger cost due to its importance and the valuable materials used.

2.4 Key Emission Contributors in AC Charger Life Cycle

To gain perspective on a charger's life cycle phases and its corresponding emissions, LCAs have been evaluated. There are few open sources of LCA for EV chargers, so three LCAs for three chargers have been found [3, 34]. Two of the chargers are AC chargers, with a casing of recycled aluminium. The third charger is a DC charger with a casing of virgin aluminium. Although the selection can be considered narrow, there are some common denominators for the three chargers. Excluding the use phase, it is notable that raw material and component production contribute the most significant emissions along all life phases of the investigated chargers. Of the material groups under consideration, electrical components have the highest related emissions for the AC chargers. For the DC charger, the electrical components and aluminium casing have the same rate of emissions.

Regarding the casing, evaluation of around 20 different charging manufacturers for AC chargers, shows that almost all use casing of plastic. There are a few found companies that stand out by having the casing in either metal or glass. This differs from DC chargers, which almost always in the found examples have a casing of some kind of metal, usually steel or aluminium.

Lastly, from a more holistic perspective, the emissions related to the use phase (i.e. during charging of the EV) varies a lot depending on the electricity mix available for charging. In one of the LCAs obtained, which uses Swedish energy mix in the calculations, the use phase stands for about 42% of the total emissions during its lifetime [3]. Another LCA uses a global energy mix, which results in the use phase standing for 97% of the total emissions [34].

2.5 Regulations and Directives Affecting AC Chargers

This section provides an overview of key regulations and directives from the EU that impact EV chargers. Specifically, it will cover safety regulations for electrical equipment, waste management regulations, and restrictions on hazardous substances. The goal is to bring perspective and present the main legal frameworks for EV chargers, especially AC chargers, which manufacturers and operators must follow in the EU.

2.5.1 Electrical Equipment Safety Regulations

Since AC chargers are considered electrical products, there are several regulations and directives they must follow for electrical safety. The Low Voltage Directive is an EU directive that ensures high level of protection for electrical equipment within a certain voltage range [35]. It has been in force since April 20, 2016, and is an updated version of older directives. The directive includes safety measures for mounting, connection and usage.

There are other international standards for EV charging stations. IEC 61851-1:2017 covers standards for characteristics and operating conditions for EV supply equipment, specification of the connection between the EV and the charger station as well as requirements for electrical safety [36]. IEC 61439-7:2022 covers standards for low-voltage switchgear and controlgear assemblies, which also applies for EV charging stations [37].

In addition, there are two main international standards regarding protection by electrical equipment which are highly relevant for AC chargers: Impact Protection (IK) and Ingress Protection (IP) rating. IK measures the resistance of electrical equipment to external mechanical impact [38]. The standard is written as IK followed by two digits. The digits represents the degree of impact resistance, where a higher digit indicates higher impact resistance. IP is a standardized classification that measures the level of protection provided by a device against water and dust [39]. It is applicable for electrical equipment that is protected by mechanical casings and electrcial enclosures. It thereby provide more detailed information beyond stating that a product is 'waterproof'. The IP classification is written as 'IP' followed by two digits. The first digit indicates the level of protection against solid objects, such as dust, while the second digit represents the level of water resistance. Just as IK rating, the higher the digits, the more protected the product is.

2.5.2 WEEE Directive & Extended Producer Responsibility

Waste of Electrical and electronic equipment (WEEE) is one of the fastest growing waste streams within the EU [40]. In order to manage WEEE in a sustainable way, the EU has implemented the WEEE directive [41]. It includes targets regarding collection, recycling and recovery for all electrical and electronic equipment (EEE). In Sweden, this has been implemented as an Extended Producer Responsibility (EPR) for EEE since October 2014 [42]. The purpose is to minimize generated waste through design and production methods, as well as handling the waste in a health- and environmental friendly manner. The waste should be handled with respect to the waste hierarchy and the recycling targets must be achieved.

The producer have several responsibilities within the EPR legislation. They are responsible for handling EEE when it becomes waste, which includes both collection and recycling. In practice, this is done by being a member of a collective collection system for WEEE [43]. Sweden has two approved collection systems: El-Kretsen and Recipo. The directive sets requirements for recycling based on the weight percentage of the product. This led to 80% of the 132 thousand tonnes collected through producer responsibility being recycled in 2016 [44].

In addition to this, a producer is also responsible for [42]:

- informing its customers how to hand in the used product
- report to the Swedish Environmental Protection Agency on volumes of sold electronic equipment
- correct labeling of products
- design product to enable re-use and material recycling
- inform waste handler which components and material are included as well as hazardous substances and mixture

The EPR legislation has been updated and entered into force January 1, 2023 [45]. The purpose is to increase circular waste management by higher requirements regarding reuse and recycling of EEE. This is done by increasing the responsibility for producers regarding waste prevention measures.

It is suggested that the recycling targets in the WEEE directive and EPR legislation are not based on which materials create the most value, but on total weight share [44]. Recycling heavy materials, and thereby fulfilling the recycling targets, is not necessarily the most value creating approach. The materials that are down prioritized are relatively light materials, such as plastics, and not as valuable metals that are difficult to extract. This order of priority can be exemplified with circuit boards. The ones with high proportion of precious metals go directly to smelters, while less valuable circuit boards are fragmented. In addition, it is also suggested that legislation should not promote recycling if reuse or re-manufacturing is possible. Rather, focus should be directed towards establishing a system that maximizes the overall material value. This concept aligns with the principles of a circular economy, which will be described further below.

2.5.3 EU RoHS directive

The RoHS directive is an EU directive from 2003 that aims to restrict the use of hazardous substances in EEE [46]. Harmful substances may be released during usage, collection, treatment and disposal of WEEE. The purpose of the directive is therefore to minimize environmental and human health risks connected to these substances. The directive includes ten substances, such as lead and mercury, which are limited to 0.1% of the total weight by weight [47].

2.5.4 Critical Raw Materials Act

An increased global demand for critical raw materials due to decarbonization of economies poses challenges regarding depletion and securing sustainable supply chains. Today, the EU heavily relies on imports, often from a single third country. Pushed by recent crisis, securing resilient and sustainable value chains has become increasingly important for the EU. Driven by this, the EU proposed the Critical Raw Materials (CRM) Act in 2023 [48]. The act aims to strengthen and diversify value chains of said materials as well as monitor and mitigate supply risks. It also promotes circularity and sustainability through benchmarks goals of extraction, production and recycling within the EU, thus enabling business models for recycling and production within the EU [48].

2.6 System Thinking for Sustainability

This section provides an overview of two selected frameworks for promoting sustainability: the circular economy and product-service systems. Circular economy is particularly relevant since it forms the framework of this thesis. In addition, Product Service System will be presented. It challenges the traditional model of producing, selling, and using products by complementing a product with a service, with goal to increase a product's lifespan and reduce waste. These frameworks bring perspective on alternative approaches to consumption and design as we know it today, with sustainability as the main driven force.

2.6.1 Circular Economy

Circular economy is the term for a model where circularity of material and resource flows are used in organizations and societies instead of linear flows popularized in many parts of society. An economically circular model promotes [49]:

- Eliminate waste and pollution
- Circulate products and materials at the highest possible value
- Regenerate nature

The butterfly diagram provides a visual representation of the principles of circular economy. The central focus of this thesis is to enhance the resource efficiency of charging stations with the aim of minimizing their impact on the environment. To achieve this, the focus will be on the technical life cycle, which places a greater emphasis on reducing the need for the production or extraction of new finite materials in the creation of man-made products.

It is important to note that charging infrastructure, as a product, is utilized rather than consumed. As such, it is crucial to optimize its resource utilization in order to reduce waste and promote sustainability. The technical life cycle aims to achieve this through minimizing the usage of new finite resources. In the following section, a brief description of the different loops in the butterfly diagram will be provided for a better understanding of the circular economy concept [50].

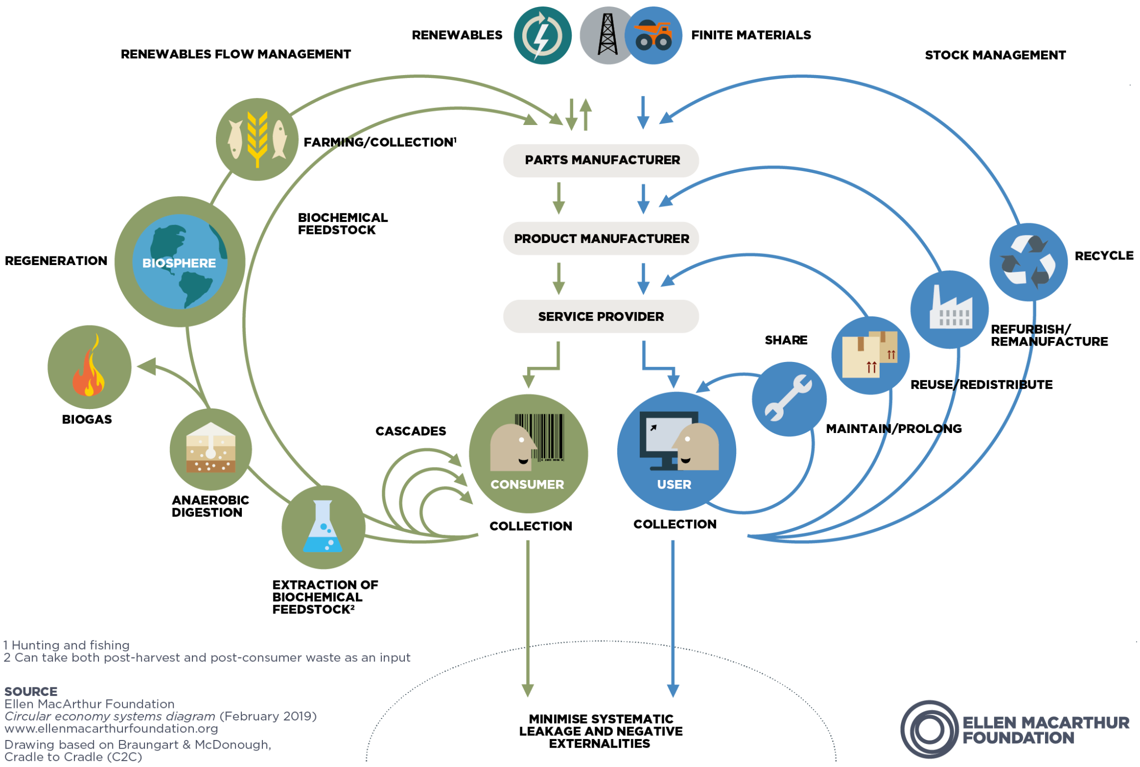

Figure 2.4: Circular economy butterfly diagram including both biological and technological cycles [51].

Sharing: The first loop in the butterfly diagram is known as sharing. While not all products may be suitable for this step, it has the potential to be applied to many products, particularly as servitization becomes a more widespread business model. Sharing refers to the practice of multiple individuals using a single product, rather than each having their own [50]. This approach helps to reduce the number of products in circulation, which in turn minimizes waste and promotes sustainability. Sharing is considered to be the least demanding solution in the technical cycle, as it requires minimal effort to implement. In many ways, it is the simplest and most straightforward step to take in order to adopt a more circular and sustainable approach.

Maintaining/Prolonging: The maintenance step in the butterfly diagram plays a crucial role in extending the life of a product and reducing its environmental impact. Regular maintenance helps to prevent component failures and deterioration of the product's material and quality. By taking proactive measures to maintain the product, degradation can be reduced or eliminated, thus increasing its lifespan. Maintenance can vary in scope and intensity, but it generally involves taking steps to minimize or eliminate risks that may impact the product's longevity. This could include regular cleaning, checking and repairing any defects, or replacing worn-out components [50]. By undertaking regular maintenance, the product's performance and functionality can be maintained, and its overall impact on the environment can be reduced.

Reusing/redistributing: Like the previous steps in the technological cycle, reuse and redistribution aims to extend the life of the product in its existing or minimally degraded state. Reuse and redistribution refers to the process of using a product either in its existing condition by a new user, or repurposing it for a different purpose when it is no longer suitable for its original use. This step prevents both a new product from being produced and a useful product from unnecessarily going to waste [50].

Refurbishing/remanufacturing: This step includes repairing or replacing parts of products that have broken or otherwise lost value with the aim of regaining this, but also re-designing the product to fit another area if its quality is not sufficient for the original purpose [50]. This step is a particularly important part in the circular economy as it means that the product gets new life when the previous step has been used until degradation or devaluation is unavoidable. In a way, it can be stated that after renovation or re-manufacturing, the product can be used again starting from the smallest loop, working its way outwards, thus that step constitutes the last step in a separate loop that completely excludes recycling.

Recycling: The last step in the technological cycle is recycling. Recycling means restoring and separating the materials in the product in order to be able to use these for the production of a new product. This step indeed removes the value of the energy and time spent on the product, but preserves and utilizes the value of the constituent materials and prevents new materials from being mined or manufactured. Many products cannot be circulated in previous loops and in these cases recyclability is an important part of the product's design to facilitate and make recycling available after the product has served its purpose [50].

2.6.2 Product Service Systems

Product Service Systems (PSS) is a business model that has the potential to revolutionize the way we approach product design, production, and consumption. The basic idea behind PSS is to offer a service that complements a product in order to increase its value, not only in the eyes of the consumer but also in terms of environmental impact. The aim is to create a symbiotic relationship between product and service, where the product is designed to provide opportunities for service, and the service is designed to enhance or prolong the value of the product [52]. PSS has many benefits compared to traditional business models that rely solely on selling products. By offering a service in addition to a product, PSS can create a more sustainable solution by increasing the product's lifespan and reducing waste [52]. This is in stark contrast to traditional business models, where the focus is on selling products that are often thrown away after a short period of use [52].

2.7 Material Production

This section will highlight the environmental impact of material production. It is of particular importance since it is one of the largest sources of emissions through an AC charger's life cycle. The materials investigated are restricted to the most frequently used materials for the casing of the charger, i.e., plastic and aluminium. Moreover, production of electric components also bear a high rate of emissions. Thereby, an overview of the complexity of these components and its production will also be presented.

2.7.1 Plastic

Polymers are known for their flexibility and fits within several societal functions. Due to properties such as lightweight and flexibility in terms of design and moldability, polymers are a common material to use for the casing in AC chargers. In Europe, around 40% of the plastic production goes to packaging products. In 4th place in terms of produced volumes, comes EEE at roughly 6% [53]. Polycarbonate (PC) and fiber-reinforced polyester (FRP) are common for casing applications due to their toughness and heat resistance [54, 55, 56].

PC is a thermoplastic used in several applications where transparency, durability and heat resistance are highly valued properties. The production of PC is rather complicated and involves the use of several fossil materials such as oil and natural gas [57]. Producing PC is highly energy intensive with an electricity demand of roughly 15-18 MJ/kg of pure virgin PC [57, 58]. This corresponds to approximately 4-5 kWh/kg produced virgin PC. In 2016, the world's largest PC producing companies were based in Germany and Saudi Arabia, with roughly 1.4 million tons/year [59]. Since PC is a thermoplastic, liquefying the polymers will enable the plastic to be remolded and used for other applications, which extends the usability of the material significantly. Further, in the heating process, the plastic will theoretically not degrade but instead keep its virgin properties.

FRP is a composite with high-performance fibers such as glass or carbon embedded in a polymer matrix to increase strength and durability in the material [56]. Due to its multiphasic nature, the composite can be structured to fit specific applications and is hence an attractive material to use. Common polymers used are epoxies and polyesters and dependent on what type of polymer used, FRPs can be either a thermoplastic or a thermoset plastic, which heavily affects its properties and ability to be recycled.

2.7.2 Aluminium

The primary and secondary production of aluminum combined contributed to approximately 3% of the direct CO_2 emissions from the global industry in 2021 [60]. Primary aluminium production is a energy intensive process and require around 17 kWh (61.2 MJ/kg) electricity per kg produced aluminium [61]. In contrast, recycling of aluminium only requires 5% of energy demand from primary production, which will be explored further in Chapter 2.8.2. The various phases of primary aluminium production, including bauxite mining, alumina production, anode production, electrolysis and casting, releases emissions. It has been estimated that 81% of the global emissions related to aluminium production is due to electricity use [62]. The remaining 19% is associated with fuel-related emissions, which are entirely consumed during the alumina production phase [62]. Electricity is predominantly used in the electrolysis phase, sourced either from the grid or captive power plants. Countries such as India, China, and Australia have high emissions per tonne of aluminium produced due to their significant share of fossil fuels in their electricity mix, as seen in Figure 2.5 [62]. Globally, coal is the dominant fuel source for power generation in aluminium production, accounting for 56% in 2020, higher than the global energy mix average of 39% in 2015 [60, 63]. This can be attributed to China, which is the largest producer of aluminium, accounting for 58% of global production in 2021 [64]. China's electricity mix heavily relies on coal, with approximately 70% of its electricity production derived from coal in 2015 [65]. Thereby, the higher share of coal in aluminium production compared to the global average can be explained. With this as a background, an effective measure to decrease CO_2 emissions from primary aluminium production is to use electricity sources with low CO_2 emissions.

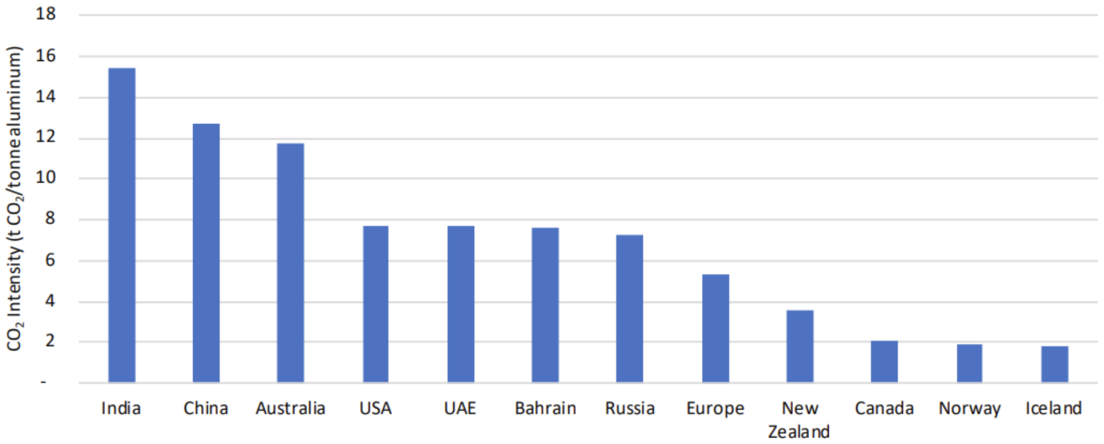

Figure 2.5: Final energy-related CO_2 intensity of aluminum production in 2019 [62].

From the perspective of the EU, a significant portion of the demand for aluminium is met through net imports. In 2021, approximately 47% of the European aluminium demand was fulfilled through net imports [66]. 14% was produced domestically within the EU, and the remaining 38% was sourced from recycling of aluminium within the EU [66]. Note that the provided percentages do not add up to exactly 100%, due to rounding or potential factors not accounted for in the data. Nonetheless, the reliance on net imports has steadily increased over time due to the growing demand for aluminium, and the challenges faced by European producers in remaining competitive with businesses from other countries. This in turn leads to large emissions from the aluminium usage in the EU, despite European produced aluminium has approximately 50% lower emissions than for example China, as seen in Figure 2.5.

2.7.3 Electronic components

EEE consists of a variety of components. This could for example be resistors, indicators and capacitors. EEE also consists of epoxy, glass fiber and flame retardants, thus consisting of a variety of materials, making them highly complex. The most valuable component is the Printed Circuit Board (PCB), seen as the core component for all EEE, where electric components are soldered on [67]. The PCB is also covered in some kind of casing, usually made of polymer and/or metal.

Regarding AC chargers, the main electrical component is the charge controller. This component holds a vast amount of metals, including copper, aluminium, silver and in some cases gold [68]. The metals used are more or less abundant in nature and some demands heavy processing and refining before it can be used in such demanding applications. Today, Chile is the world's largest producer of copper, producing 27% of the global demand, corresponding to 5,6 million tonnes in 2021 [69]. Second largest producer is Peru, followed by China. Although only producing 8% of global supply, China uses 54% of the refined copper produced globally [69]. This is tightly connected to China being the biggest manufacturers of PCBs, in terms of volume in the world [70]. The energy-intensive processes of mining and refining precious metals aside, manufacturing electrical components in China has a significant environmental impact. This is due to the country's heavy reliance on fossil fuels, primarily coal, which accounted for 83% of its energy mix in 2019, with renewable accounting for only 15% [71].

2.8 Waste Management & Recycling

This section provides an overview of waste management and recycling practises for three selected materials: plastic, aluminium, and electrical and electronic equipment. Focus will lie on technical aspects as well as practical applications in the EU and

Sweden. Given that energy use is the largest source of industrial GHG emissions, recycling can be an energy efficient measure to reduce GHG emissions from virgin material production [72]. In addition to mitigating GHG emissions, recycling is a crucial step towards a circular system with efficient resource usage, where materials are used to its fullest extent.

2.8.1 Plastic

Plastic is a common material used in charging stations due to its light-weight and durable characteristics, where the majority is used in the casing as well as internal structures. As for today, most of the plastic used in Sweden is incinerated upon end-of-use and used for energy recovery. Only around 8% of the plastic material flow in Sweden is recycled whereas closer to 77% is incinerated [73]. In Europe, close to 43% of the plastic produced is used for energy recovery through incineration. Further, roughly a third is recycled and the rest is put in landfill [53]. However, due to lack of capacity, available technology and financial resources, about half of the collected plastic for recycling was exported to non-EU countries in 2018 [53]. The demand for recycled plastics is growing, however accounting for only 6% of overall plastic demand in Europe in 2018. This is due to the cost-efficiency and customizability of virgin plastic as well as the complexity of recycling plastics due to the vast amount of diverse manufacturing methods and polymers used. Further, many types of plastics degrade when recycled, which limits their use as secondary materials [53].

Lack of knowledge makes recycling of plastic difficult and inefficient due to some products consisting of mixes of recyclable and non-recyclable plastics. Also, especially in electrical components, a big issue is the mixing of plastic material and non-plastic materials [74]. The plastic recycling process can be divided into several steps where the first step is collection of plastic waste. The collection is done by providing waste vessels exclusively for plastic waste and relying on consumers to discard their waste in the correct vessel. Secondly, when arriving at the recycling site, the plastic is sorted, either by chemical composition, color or thickness and is done both manually and by machines to ensure as homogeneous plastic fractions as possible. Next step is washing where contaminants such as adhesives are removed in order to avoid degradation of the material. The last steps include shredding to easier manage homogeneous piles and remelt and also extrusion where the plastic is re-formed and sold to manufacturers for new purposes [75].

As stated in Chapter 2.7.1, two of the most common plastics used in chargers are PC and FRP. Due to the intertwined mix of polymers and fibers, recycling of FRP faces many challenges. Chemical and thermal recycling of FRP reclaims the fibers fully, therefore these methods do not degrade the material in theory. However, due to high cost, these alternatives are hard to justify [76]. Mechanical recycling of FRP is the most viable option today. However, it is mostly used for a subcategory of

FRP, namely glass fiber-reinforced polymers. Also, mechanical recycling degrades the material significantly, which affects the after market and applications possible for recycled FRPs [76]. Whilst mechanical recycling is a possible way to go with FRPs, the cost-competitiveness of landfill, incineration or even virgin production poses a threat and hinders recycling development [76]. However, the energy demand for producing new FRP is significantly higher than recycling, with energy demands ranging from 0.17–1.93 MJ/kg for recycled and 13–54 MJ/kg for virgin fiber production [77]. Recycling PC is not as complicated and energy demanding as recycling FRP. More important is that due to its thermoplastic characteristics, polycarbonate is 100% recyclable and the material should in theory not be degraded upon recycling [55]. However, in reality this is hard to achieve. Its thermoplastic characteristics allows the polymer structures to easily remold into new shapes when liquid. Thus, recycled PC can mitigate production related emissions with at least 80% compared to virgin PC production [78].

To simplify the recycling process and enable better circularity of plastic in society, improvements can be done in several aspects. Already in the design stage of a product, the need for recycling is indirectly decided upon. By considering designing the product to simplify dismantling and using more sustainable and homogeneous materials, a lot of the problems with recycling can be mitigated. One important design aspect is the choice of color added to the plastic. Generally there are two types of colorants, where the most commonly used in plastic is dye. Dyes are organic and create bonds between the colorant and the plastic, thereby transforming the structure of the plastic [79]. Moreover, darker colorants contaminates batches of recycled plastics, making them darker and therefore harder to re-color with vivid and vibrant results, which means worse quality and lower value [80]. Further, black plastic tends to be underrepresented in recycling processes due to the automatic identifying and sorting technologies inability to detect black plastic, which further reduces recycling rates although the chemical composition might be viable for recycling [81].

It is important to note that the most effective management is to act in a way that does not create further need for recycling but instead keeps the product in the circular loop for as long as possible. By using already recycled plastic whenever possible, the production of new plastic is reduced, preventing both production related emissions as well as an increased demand for recycling and the emissions related to that matter, and also acts in favor of circular flows [74]. Lastly, it is also important to avoid mixing and strive for homogeneous flows, both regarding plastics with different chemical composition but also plastic and non-plastic components [74]. As a way to increase plastic recycling in Europe to 55% in 2030 the European Parliament would like to implement higher grades of design for recyclability, but also quality standards for secondary plastics and mandatory shares of recyclates in certain products [53].

2.8.2 Aluminium

Secondary production of aluminium, i.e. recycling, is an energy efficient measure in order to increase resource efficiency as well as reducing CO_2 emissions related to primary production. Aluminium could theoretically be recycled infinite times without loosing its properties, and the energy required is 5% of primary production of aluminium, provided clean scrap is used as raw material. There are however different kinds of scrap, which has different conditions for recycling. 'New' scrap as a raw material means generated aluminium scrap during the production stages. 'Internal' scrap refers to material generated during a company's production that can be recycled within the company. There is also 'old' scrap, which is aluminium that has passed its use phase. In order to obtain a high quality of the recycled material, it is important to pre-treat and sort the material, especially for old scrap. These process steps require additional energy, but it is still very energy beneficial to recycle aluminium rather than to produce new aluminium. To compare, primary production requires about 17 000 kWh electricity per ton aluminium, whereas the theoretical minimal value of remelting aluminium is 400 kWh per ton aluminium (if heat recovery is not implemented) [61, 82, 83]. In Sweden, recycling of post-consumer aluminium is handled by Stena Aluminium. Their process is considered energy effective with an energy consumption of 740 kWh/ton, which includes handling and sorting [82]. This is around 4% of energy consumption for primary production, which follows the literature stating a 95% reduction of energy consumption for secondary production.

From an European perspective, there is a well established market for secondary production of aluminium, which includes both refiners and remelters. Refiners use mostly scrap as raw material, while remelters use both scrap and primary aluminium as raw material. Estimated EoL recycling rates of aluminium depends greatly on sector, where the transport and building sectors in Europe has one of the highest rates between 90 and 95% [62]. Packaging has recycling rates between 25 to 75%, depending on the European country [62]. These rates resulted that domestic recycling accounted for 38% of the European demand in 2021, as described in Chapter 2.7.2 [66].

Despite the energy efficient method, the share of secondary production (where internal scrap production is excluded) has globally been fairly linear at 31-33% the last 20 years [60]. There was a small increment to 34% during 2021 due to global trend towards using more environmentally friendly production methods and resources [60]. Even though the secondary production may have increased in absolute terms, the relative increase is almost unaffected due to China's increasing primary production [60]. This as a result of large demand and high export rate, which leaves less recyclable materials within China's borders.

2.8.3 Electrical and electronic equipment

As described in Chapter 2.5.2, WEEE is one of the fastest growing waste streams within the EU. This type of waste is toxic due to containing hazardous substances, such as lead and mercury, requiring proper handling to avoid environmental and health problems. In addition, certain electrical components in WEEE may contain rare and expensive metals, which underscores the need to handle this waste stream efficiently. It is estimated that around $^1/_3$ of WEEE within the EU is reported as collected, whereas the remaining $^2/_3$ is unaccounted for, illegally exported or thrown incorrectly in waste vessels [84]. It has been reported that illegal exporting of WEEE ends up in developing countries, which typically have weaker waste management regulations than the EU [85, 86, 87]. This poses significant risks, as the hazardous substances found in WEEE can cause major environmental and health problems if they end up in open dumps. The theft of WEEE and its valuable components, such as circuit boards, results in a significant loss of materials and resources. Estimates suggest that this type of theft costs Europe between €800 million and €1.7 billion in lost value annually [84].

The WEEE directive therefore aims to prevent these issues. Member countries in Europe have different approaches how to implement the directive. As described in Chapter 2.5.2, Sweden has two collective collection system, but countries such as Germany has even more competitive actors in the same market. In Sweden, municipalities organize together with El-Kretsen household collection of electrical waste, called 'elretur' [88]. WEEE is firstly collected by El-Kretsen and transported to pre-treatment facilities [89]. This includes separation and dismantling, where hazardous substances must be treated at specific facilities. After pre-treatment, the waste is sent for recycling or other final treatment [90]. It is challenging to recycle WEEE, since WEEE is diverse and complex in terms of mixed materials, and consists of small quantities of precious metals. Boliden's Rönnskär smelter, located in Skelleftehamn, Sweden, is one of the world's largest recycling centers for metal from electronic materials [91]. They mainly operate to recover copper, but have also processes for gold, silver, selenium, palladium and nickel. However, Boliden's final product does not consist solely of recycled material, as it does not provide a sufficiently high quality. In this way, recycled material is mixed with mining raw material, where just under a tenth comes from recycled material [91]. Separating different materials prior re-melting is also discussed as a way to increase the quality of the final product.

3

Methods

3.1 Research design

The chosen data collection method for this study included semi-structured interviews. This decision was primarily driven by the lack of academic reports or research that specifically addresses the aspects relevant to this master's thesis. Consequently, the interviews became an invaluable method for obtaining direct insights and knowledge from industry professionals. The variety of interviews provided valuable information from multiple angles, enhancing the depth and quality of the thesis. The semi-structured interviews were conducted with a set of open-ended questions that were pre-determined, allowing for follow-up questions and exploration of topics as they arose [92]. This approach allow the interviewer to capture rich data, gain insights into the participants' experiences, and explore the subject matter from a range of perspectives.

The semi-structured interviews involved a range of stakeholders in the charging infrastructure, including producers, distributors, service and maintenance partners, end-of-life management, trade associations within the electromobility, and automotive industry. This approach enabled the researcher to gather insights into various aspects of the industry, including its challenges, opportunities, and trends.

The interview questions were carefully crafted to elicit detailed and informative responses from each stakeholder group. The questions were tailored to each group's expertise and focused on technical aspects as well as speculative questions regarding future challenges and opportunities related to electrification and charging infrastructure.

3.2 Participants

The selection of stakeholders is a critical step in conducting research as it shapes the quality and scope of the data collected. For this thesis, choosing the right stakeholders was of utmost importance to provide a comprehensive and diverse perspective on sustainability in charging infrastructure. To achieve this, a careful and deliberate approach was taken to select stakeholders representative of the various stages in the supply chain. The inclusion of stakeholders from each part of the supply chain ensured that the research covered sustainability aspects throughout the entire product life cycle. The stakeholders were identified based on their expertise, influence, and relevance to the research question, encompassing those involved in the design, development, manufacturing, distribution, installation, operation, and end-of-life management of the charging infrastructure. Table 3.1 display the selection of the stakeholders, company description, as well as the interviewee's role within the company. Also, each interviewee is identified by a unique ID, which will be used to reference them in the subsequent Result and Discussion chapters.

Table 3.1: Overview of interviews conducted

ID	**Company description**	**Role**
P1	AC charger producer A	Sustainability Manager
P2	AC charger producer A	Quality Manager
P3	AC charger producer A	Deputy CTO
P4	AC charger producer B	Sustainability Manager
P5	AC charger producer C	Regional sales Manager
P6	AC charger producer D	Environmental Engineer
D1	Distributor A	Operations Manager
D2	Distributor A	Product Test Engineer
MP1	Maintenance provider A	CEO
TA1	Trade association for electromobility A	Author
CM1	Car manufacturer A	Battery System Designer
WM1	Waste management & recycling company A	Project Manager
CS1	Collection system company for WEEE A	Operative manager

3.2.1 Producers

Given that the sustainability of a product is determined during the design phase, it was critical to obtain a comprehensive understanding of the early life of a charger. As such, emphasis was placed on including producers in the industry and obtaining their views on design for sustainability. The selected stakeholders comprised a diverse range of producers, each with their own niche in their product portfolio, targeting different customers or geographical areas. By including several of these niches, the thesis aimed to gain insight into the advantages and disadvantages of each one, and identify potentially significant impacts on the environment. The selected stakeholders shared common values, such as the pursuit of sustainable and user-friendly products to encourage sustainable transportation. However, each stakeholder had their own approach to fulfilling these values, providing diverse perspectives on fundamental sustainability concepts. These perspectives generated a holistic approach to sustainability, which was critical to understand the complexities and challenges involved in promoting sustainable charging infrastructure.

3.2.2 Distributors

The distributors play a crucial role in the value chain since they are the intermediary stakeholder between the producers and end customers. Distributors have the ability to affect both upstream and downstream in the value chain. The inclusion of distributors in the thesis provided insight into the sustainability aspects that mattered as an actor in the middle of the value chain.

3.2.3 Service & maintenance partners

In order to promote sustainability in charging infrastructure and prolong the lifespan of the chargers, the selection of a service and maintenance partner was critical for the upstream value chain. Including the available partner allowed for valuable insights on repairability, ease of maintenance, and ergonomics in the charging infrastructure. Since the research aimed to investigate the potential for prolonging the life of the chargers through effective maintenance and repair processes, reducing maintenance costs and increasing efficiency, and improving the usability and accessibility of the charging infrastructure, including the perspective of a service and maintenance partner was deemed highly important.

3.2.4 End-of-life management

Effective end-of-life management is critical for promoting sustainability and supporting the circular economy of EV chargers. Therefore, including end-of-life management stakeholders was crucial to gain insight into how to manage dismantling, sorting, and renewal of the materials used. The stakeholders were selected based on their expertise in managing the end-of-life of the materials chosen to limit this thesis as well as their commitment to sustainability. These stakeholders helped identify hotspots in environmental burden related to the materials used in the chargers and to explore possible solutions for managing these issues. Ultimately, effective end-of-life management is critical for promoting sustainability and supporting the circular economy by reducing waste and minimizing the environmental impact of the materials; issues that end-of-life management stakeholders hold huge expertise in.

3.2.5 Trade association

In order to gain a comprehensive understanding of the electromobility industry, it was crucial to engage with experts from key trade associations. The selection of these organizations was based on their relevance to the industry, their expertise in the field, and their commitment to sustainability and innovation. The insights and perspectives of these organizations were essential to gain a deeper understanding of both present and future challenges, trends, and opportunities within the industry. By engaging with these experts, the thesis was able to explore emerging ideas and best practices, as well as anticipate future developments and challenges.

3.2.6 Automotive industry

Including the perspective of the vehicle manufacturing industry will diversify the experienced challenges and possibilities with the expansion of charging infrastructure. It will provide a greater overall perspective and insight into how these neighboring industries perceive the distribution of responsibilities as well as possibilities of collaboration. Furthermore, it will shed light on how other manufacturing companies approach sustainability and circularity in their products, offering relevant perspectives and practices for consideration.

3.3 Data collection

To ensure efficient and flexible data collection, the interviews were conducted using online video conferencing software, Microsoft Teams. The use of Microsoft Teams enabled the researcher to conduct interviews remotely, allowing for a wider range of participants to be involved in the study. The transcription feature in Microsoft Teams was used to record the interviews, enabling the researcher to transcribe the interviews accurately and efficiently. This minimized risks of misinterpretations when analyzing the interviews afterwards. In addition, all participants were asked for their consent before the interviews began, and their responses were transcribed verbatim to ensure the reliability and validity of the data.

The use of semi-structured interviews as a data collection method for this study had several advantages. Firstly, it enabled the researcher to explore the subject matter in depth and gain a better understanding of the experiences, perspectives, and attitudes of the participants. Secondly, it allowed for flexibility in the data collection process, with the researcher having the freedom to explore topics in more depth based on the responses of the participants. Finally, it enabled the researcher to gain a rich understanding of the subject matter from multiple perspectives, providing a holistic view of the charging infrastructure industry [92].

3.4 Data analysis

The data obtained from the interviews, i.e. the transcripts, were read multiple times in order to ensure that the content was understood. In some cases, the transcripts were edited for clarity and accuracy, particularly in section that contained misspellings and incorrect sentence breaks. After this was done, the data was categorized in order to capture key concepts and patterns between the interviewees' responses. Since many of the questions were intentionally the same for all interviewees, the category division was facilitated. The themes can be seen in Figure 3.1. For each category, result was primarily based on specific stakeholders and their areas of expertise, as seen in coloured circles in the figure. I.e., not all interviewees work within all fields that the categories represent, which results in a differentiated knowledge base between them. This breakdown of categories is the same structure as for Chapter 4 which addresses the results as well as Chapter 5 where the topic is analyzed and discussed.

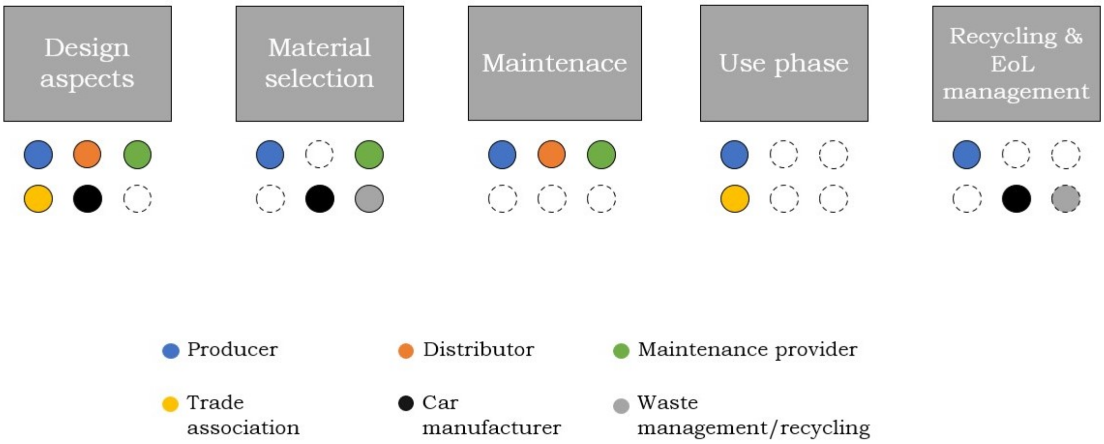

Figure 3.1: Analysis Categories for Interview Findings with Primary Stakeholders

4

Results

This chapter present the findings from the interviews conducted with stakeholders involved in the supply chain of EV chargers, where E.ON acts as a distributor. Firstly, a description is provided of the supply chain with explanation of in which life stage every stakeholder acts. The findings from the interviews are then presented and categorized according to the themes identified in the Method section: design aspects, material selection, maintenance, use phase, and recycling and end-of-life management.

4.1 Supply Chain Overview

From interviews with concerned actors, information has been gathered regarding the supply chain for AC chargers where E.ON act as a distributor. Key stakeholders, both for E.ON and this thesis, can be seen graphically in Figure 4.1.

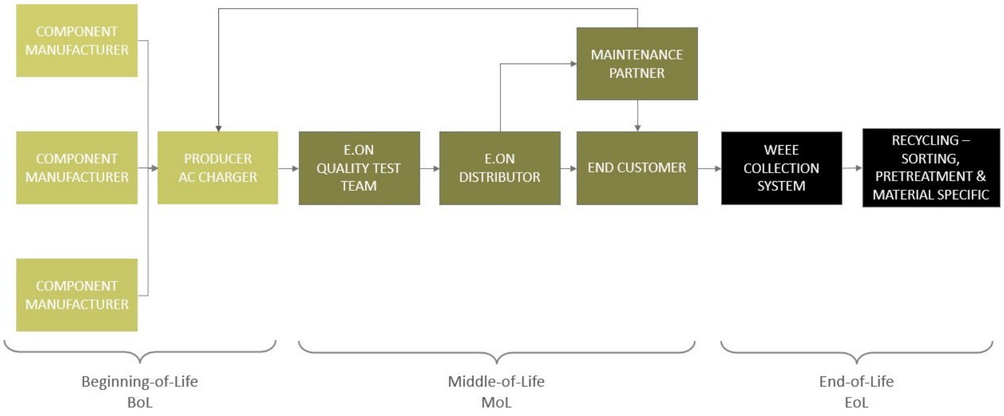

Figure 4.1: Value chain for AC chargers with E.ON as distributor.

Raw material extraction and component production is done by multiple suppliers worldwide for the interviewed producers. The components are sent to the AC charger producers, where assembly is being done. These actors compose the Beginning-of-Life (BoL) stage of the charger.

E.ON has dedicated departments responsible for conducting research and testing on AC chargers available on the market, including those from new producers of interest, as well as updated versions of AC chargers already in their portfolio. Currently, their testing procedures focus on ensuring that the charger's performance aligns with the technical documentation provided by the producer. Additionally, they control that the charger meets legal requirements as described in Chapter 2.5.1. Currently, there are no specific considerations or tests dedicated to sustainability aspects, but D2 highlights that they would like to incorporate such measures. After testing is done and an AC charger is approved of E.ON's quality and test teams, it can be sold to end-customers.

E.ON is responsible for installation and has collaborations with both producers and other maintenance partners to take care of faulty chargers. Preventing maintenance is carried out by E.ON's maintenance partners, which in practice usually occurs once a year. Repair on faulty chargers, depending on what type of error it is, is either being done by the maintenance partners or the producers. The producers interviewed indicated that they provide free repairs to end customers within the warranty period. Additionally, they offer paid repairs for cases where the warranty period has expired. The Middle-of-Life (MoL) stage reaches from product testing to end-customer use.

The End-of-Life (EoL) stage starts when collecting the waste and reaches through the recycling or incineration process. In compliance with the WEEE directive, end-customers are obligated to responsibly deliver their AC charger to an approved collection system when it reaches its end-of-life stage. This ensures that the charger is appropiately disposed of and not treated as 'regular' waste. In Sweden, the main collection system is organized by El-Kretsen, as described in Chapter 2.5.2. They are a producer responsibility organization, and thereby plays a pivotal role as the foundation of the collection system. The recycling process is then being done in several steps, where sorting and pre-treatment is being done first. The sorted materials are treated separately at specialized facilities. For instance, PCBs could be processed at a specialized facility that recovers critical metals like gold, silver, and platinum, while aluminum may be sent to aluminum recycling facilities.

4.2 Design aspects of AC chargers

The interviewed producers of AC chargers provided insights into the decision-making process behind the design choices and the parameters considered.

Common Unique Selling Points (USP) according to the interviewed producers are mostly a long lifetime of their chargers, electrical safety as well as aesthetic design. The interviewed producers also mean it is of high importance that they provide easy and trouble free ownership for customers. This was agreed by TA1 that mean consumers will choose convenience over price when asked generally on how the market will develop in the upcoming years. Further, TA1 also thought that design will be an important factor for customers when choosing their charger.

When it comes to incorporating sustainability into the charger's design practices, all of the interviewed producers emphasized that ensuring a long lifetime and durability for their AC chargers is their primary sustainability focus. For example, P4 states that the lifespan of their product is one of the most important aspects, and mean they can assure it by having high IP and IK class standards. P6 mean they focus on producing chargers that has the same lifetime as an EV, since it is a clear customer demand for them. However, some of the interviewed producers emphasize that their business and the infrastructure in whole is rather new, which results in a lack of experience and difficulty to do "everything correct from the beginning". They mean that during the charging infrastructures' first years, there was a greater focus on quantity to establish market share, and less attention was paid on manufacturing a circular product. These producers mean this view on production and manufacturing is starting to change, and that they now work actively to design a charger that incorporate more sustainability aspects than long lifetime.

For P6, the idea of functional groups may be implemented in the upcoming generation with the hope of increased individualization according to the customer's needs and wishes. The idea is to divide the charger's functions into individual and removable modules so that the customer can put together their own combination of desirable functions. P6 means that in addition to attracting more customer groups, the functional modules contribute to sustainability by enabling easier replacement of modules and if repair is needed, only the affected module is removed and repaired. P6 believes this can also help with sustaining the up-time compared to the case where the entire charger is brought for repair.

At a general level regarding the design, D2 noted that AC chargers have become smaller over time, with minimal impact on their weight. When asked about the reason behind this trend, D2 speculated that it could be attributed to the desire for a more aesthetically pleasing appearance when the charger is more compact. In addition, it has been noticed by both D2 and MP1 that the chargers contain more and more electrical components. This is confirmed by the producers who states that their chargers have become more technical over time, for example connection options such as Wi-Fi and 4G. D2 means there can be technical issues with having a lot of electrical components closed together at a small volume. D2 means that the problem which arises is the decreasing derating, which means the output current as a result of high temperature around the components. A smaller, more compact charger performs worse in these tests and by increasing the amount of surrounding air, the risk of overheating components decreases. D2 thereby indicate that the ratio between components and free space is an important factor to consider to prevent the components from overheating and losing their purpose or function. The trend towards more compact design may compromise this feature if not carefully considered. This design aspect is further emphasized by MP1 that explains that a larger, less compact charger is beneficial for maintaining and conducting service, regardless if asking a maintenance partner or repair technician. Due to more spacious design, MP1 means that it is easier to both troubleshoot as well as access all components, which also may improve uptime and lessen the time it takes to serve each individual charger. This further confirms that a too compact a charger may be problematic in several parts of the charger's lifetime. When asking the producers, all agreed that the inclusion of maintenance partners and electricians in the design phase, to increase ease of maintenance, modularity and ability to reuse or recycle would indeed allow for a higher degree of sustainability. P6 mean their vision regarding this is:

> *"The new generation should be a box that both electricians and customers love, since they are the main stakeholders in the future. So if our box should last 10 years, there needs to be a good relationship between us, the customer and the electricians."*

Another approach to incorporating sustainability aspects, as suggested by D1, is to have a detachable cord. D1 argues that customers often mishandle charger cords, such as not properly rolling it up while not being used, leaving it on the ground, or accidentally running over it with their car. With a detachable cord, it can be easily replaced if damaged, whereas with a non-detachable cord, the entire charger would need to be replaced. Furthermore, having a detachable cable allows for regular disconnection, which can help prolong the lifespan of the charger by reducing wear and tear on the contact surfaces of both the charger socket and the cable plug.

None of the interviewed producers mean that their AC chargers have actively been designed with recyclability in mind. They instead mean, as mentioned above, the design has primarily been based on longevity, electrical safety and/or aesthetics. However, the majority of the interviewed producers believe that design for recyclability is something that may get a more central part in their next generation of AC chargers. However, there are few interviewed producers that communicates a concrete plan how that should be incorporated in the design.

WM1 points out that design for recyclability in the industry could sometimes be misunderstood by saying:

> *"...many companies think that just because they have fixed their product with 1 screw that can be loosened with 1 screwdriver, it is well built. But our processes don't work like that, there's no one sitting around with a screwdriver, but everything goes into a grinder. What we are rather pushing for is that we don't want different materials that are tightly joined together, glued together."*

WM1 further means that some companies consult with them regarding design for recyclability. That area has recently grown and has now become a new business area focusing entirely on consulting. They provide their service to all companies that would like to improve their circularity in process-flows and products.

All producers are required to adhere to both national and European directives and policy instruments regarding the environmental impact of materials and components used in the chargers. They emphasize the importance of following these regulations not only to reduce environmental pressure but also to enhance social sustainability. A problem that is presented regarding materials and design is the lack of standards throughout the EU. In order to sell chargers to certain countries, some modification is required to comply with current national regulations, which complicates production and contributes to higher costs and slower electrification. Therefore, to enable using even more sustainable materials and minimize the need for national-wide modifications, more national and European policies, regulations and standards are needed to increase both the environmental and social sustainability of the chargers. This points to the fact that electrification is complex and needs attention from several levels of governing bodies throughout society to enable more sustainable materials and to enter the market. Further, when addressing whether or not there is an issue with the lack of EU standards, P6 said that:

> *"I got a colleague from the sustainability team that looked over the questions. His answer to the question was: "yeah, it's a problem.". For example, you have the UK and you have France. No other country needs it or regulates it, but they want another safety part on the wall box. It's about the plug being safe for children. So you have more regulations just for these two markets. Main focus in sustainable development or ecological development is to reduce the variance. It is the perfect scenario. If you have to develop another variant for another market, it is really a little bit against sustainability.“*

Moreover, this opinion was shared by P5:

> *"...we have a European Union, but why are all those regulations not harmonized on the European level?... And now we need a lot of resources for Germany, for the UK, for France, for all those countries. So it would be much easier if the regulations would be harmonized."*

These findings can be summarized to:

- Similar USPs for producers - long lifetime, durability, and electrical safety
- Functional groups could make the charger more modular, and thereby able to customize charger to the customer's need
- Chargers have generally become smaller over time - could impact functionality of electric components due to decreased heat transfer
- Detachable cord could be preferable to non-detachable
- None of interviewed producers have designed with recyclability in mind
- Lack of standards throughout the EU which complicates sustainable design

4.3 Materials

The most commonly used material for the casing by the interviewed producers is plastic. The choice of casing material is primarily driven by durability for all interviewed producers. All interviewed refers to the IP and IK classifications, which are the most important requirements regarding the durability. P1 means the choice of casing material for their AC chargers, except its durability and costs, is mainly driven by pre-knowledge for the specific product i.e., the company has not further evaluated, from an in-depth sustainability point of view, the casing material. However, P1 emphasizes the rate of change and that thanks to increasing awareness both internally and externally, economic benefits and regulations, the choice of casing material will in upcoming models be carefully evaluated. P4 means their company chose their casing material mainly from a design aspect. It was also important that it should be recyclable and also make them differentiated from their competitors. P5 suggests that while the specific type of material used may be of lesser significance, verifying the origin of materials holds greater importance for securing social sustainability through their supply chain. P6 holds the belief that polymers are the optimal choice for their needs, as additives can be incorporated to create a material that meets their specific requirements. P6 follows up by sharing that the casing of their current best-seller is made out of glass fibre-reinforced polycarbonate, which is notoriously bad for recycling purposes, but that the company have other plans for material selection in upcoming models and will not continue using this material in the future. Additionally, P6 means legislation and electricity safety is easier to meet with polymers than metal. However, possible problems with electricity safety as a result of using a metal casing has been questioned by other interviewees. MP1 means all chargers are grounded with safety fuses, meaning the casing has little influence of the electricity safety. D1 agrees, and also add that the large majority of DC chargers (with a lot higher voltage than AC chargers) have casings in some kind of metal, without issues regarding electricity safety.

When discussing other casing materials, P1 and P2, who work for the same company which uses plastic casing for AC chargers, mean that metal is of interest for them. P1 highlights the sustainable advantages with using metal instead of fossil-based plastic, due to its ease of achieving circular flows compared to plastic. P1 would prefer to use aluminium, and also states that there are no great difference in cost between the two materials from a sustainability context. P1 further explains that recycling of plastic is more complex, leads to degradation and has lower reuse rates than aluminium. Lastly, P1 mentions that apart from a sustainability point of view, an aluminium collection system could very well be economically feasible and should not impede sustainability. P2 agrees with using aluminium and adds that metal in general have much better thermal conductivity than plastic, which is a very important aspect when designing an electrical product in order to achieve high electrical efficiency and safety. P2 also highlights that metal can resist scratches better than plastic, which could make the product more aesthetically pleasing over time. However, P2 disagrees with P1 regarding the cost, and mean aluminium would be more costly than plastic. P6 works for a company that also uses plastic for the casing, but does not agree with P1 and P2 in some points. P6 rather mean that metal casing for AC chargers are the wrong way to go since it requires more electrical safety measures, which in turn could risk that they cannot go on to the market. P6 also highlights the cost differences between using plastic and some kind of metal for the casing.

Alternative materials for AC chargers in general have also been discussed. P1 indicates that their company is interested in bio-based materials as a potential more sustainable alternative. While this topic is being discussed, it has not yet been implemented in practical applications. P4 also indicates that their company is researching available alternative materials and identifying plastics that are environmentally friendly. P4 emphasizes that it is challenging to completely transition away from plastics. However, they also highlight the availability of more sustainable alternative plastics in the market. These alternatives are based on second generation renewable feedstock (such as tall oil).

Recycled materials as an alternative material has also been discussed. WM1 means their company has seen an overall increasing interest and demand on recycled materials from the manufacturing industry the last few years, but that it is a relatively new insight. WM1 means that around 5 years ago, it was price that ruled, but that it is changing nowadays. CM1 expresses that their company is actively seeking ways to incorporate recycled materials into their products and are looking for suppliers to fulfill this goal. CM1 also notes that they have observed similar efforts among their competitors. Additionally, CM1 mentions ongoing research into potentially revising the quality requirements of their products in order to facilitate the use of recycled materials. CM1 further highlights that using recycled materials from pre-consumer or industrial waste is more feasible and practical for their company, since it in general have a higher quality and is more accessible than post-consumer.

Regarding using recycled plastic in AC chargers, both P1 and P6 highlights the difficulties connected to it. They both mean it is very difficult to control the content of the plastic unless there is a closed system, which does not currently exists. They mean there could be additives, plasticizers and other pollutants in the recycled plastic that can not be ensured. This affects the safety and quality of the product, which is of high importance when producing electrical equipment. P6 mean:

> *"...And these additives. Maybe you don't want to have it in your materials. And there are pollutants in recycled materials that you don't wanna have in. It is not possible to get every material into the laboratory and test it on every pollutant. And there are pollutants with regulations as well. So, that's not*

> *possible from a cost perspective. That's not possible from the manpower behind it. So you need to know what is inside your material, and with recycled material, it's difficult. And I think it will get harder and harder as there are so many materials and varieties and additives out there. You need to have a close circle economy for this, otherwise it's not possible."*

Finally, the interviewed producers emphasizes the sustainability challenges associated with utilizing electrical components, as there are limited alternatives available. They unanimously acknowledge that meeting customer requirements often necessitates the use of specialized electrical components, which currently lack sustainable alternatives. None of the interviewed producers actively explore the incorporation of alternative materials in electrical components in their products. However, many of the interviewed producers suggest that efficient recycling of used products could be a viable approach towards resource-efficient material utilization. This will be further discussed further down in this thesis.

These findings can be summarized to:
- Casing in some form of plastic is most common
- Metal casing is of interest for some interviewed producers - both environmental and functional advantages
- Use of recycled plastic is seen as difficult, may compromise quality and electrical safety
- Bio-based materials is discussed, but not implemented in practical applications
- Limited options for electrical components that are more sustainable

4.4 Use phase

According to the LCAs studied, the use phase have a great impact on the overall environmental burden of the charger. The majority of those interviewed stated that it is a complex subject when asked how stakeholders within this sector could help to decrease the emissions related to electricity used for charging. Most interviewees indicated that it is ultimately the end-customer who could affect the emissions related to the use phase by choosing where and how to charge their vehicle. The interviews did not yield any clear suggestions on how to tackle this problem, other than emphasizing its importance. In addition, when discussing stand-by energy, the LCAs show fairly low values. However, many producers state that in their upcoming models, this aspect will be reviewed and developed. P4 describes their vision where their future products will be better than the previous ones. P4 draws an analogy with TVs, which had very poor energy efficiency rating, but have significantly improved with increased regulations. P4 mean there are currently no equivalent energy certifications for EV chargers, but expresses hope for their implementation in the future. Along with other interviewees, P4 emphasizes the importance of political and policy instruments in developing this aspect further, as it constitutes a significant adjustment, not only to the electricity system, but for society as a whole.

On a more technical note, TA1 sees opportunities rather than challenges regarding use phase related emissions and says that due to the time consuming and extensive work of expanding the power grid capacity, there are business opportunities in investing in stationary batteries connected to the grid. For customers, this could mean that households could smoothen the demand for high power consumption throughout the day and avoid power tariffs without changing consumer patterns. For the power system, peak demand could be reduced and therefore, peak power production related emissions could to a larger extent be avoided. TA1 also adds that stationary batteries could be a potential source of passive income for households, not only by providing the grid with excess energy not needed in the household, but also by providing ancillary services such as frequency regulation to support the grid. Lastly, TA1 mentions that combining stationary batteries and solar panels would be a very time efficient way to reduce emissions as well as strain from the grid. This idea is also brought up in the interview with D2:

> *"And what I personally would like to see is this EV optimized charging so that the wallbox only charges with the energy from photovoltaic systems... I was a bit shocked that the market still doesn't have a solution to this."*

P2 and P3 have both been involved in the product development team for a new AC charger in their portfolio, which is an upgrade of an AC charger that was first released on the market around 7-8 years ago. One of the many new functions added are related to compatibility. The possibility to connect the AC charger directly to solar panels are under consideration and is expected to be included as a function during this year as stated by P3. One example could be to let the EV charge from the excess electricity produced by the solar panels after all household electricity demand is covered. P3 means this function may be of higher interest in countries that have restrictions on electricity sold to the grid produced via solar panels by end-customers, e.g. Germany. So, the stated function would maybe not be as interesting in the Swedish system, according to P3. Nonetheless, P3 mean it is very likely that the system will be more interconnected with the electricity grid, charging system and EVs in the future.

Related to this, a fully implementation of V2G has been discussed. All producers mean their AC chargers are prepared for V2G communication according to the ISO standard 15118. However, more technical aspects must be considered than the communication standard. This includes, among other things, mechanism for the conversion from AC to DC, and DC to AC. As described in the Theory section, the conversion from AC (from the grid) to DC (needed in the EV's battery) is done in the EV when charging with an AC chargers. But, to convert the electricity back from DC to AC, additional technical equipment is needed. P3 believes this type of bi-directional converter should be in the EV, and not in the charger, and highlights their new AC charger in the market is prepared for V2G in terms of hardware. P3 also explains this is already included in two different EV models in the market; the Polestar 3 and Volvo EX90. In addition to technical considerations, a majority of the interviewees mean that there are numerous aspects and issues that need to be addressed before V2G can be fully realized. These include financial incentives, legal matters, and coordination among various stakeholders. It is clear that the industry have a long way to go before this could be realized, which the interviews confirmed.

These findings can be summarized to:

- End-customers are seen as responsible for use phase emissions for some interviewed stakeholders
- V2H and V2G are emerging technologies - V2H could be implemented at the end of 2023
- V2G is often presented as more of a concept than something feasible for implementation in the near future

4.5 Maintenance

In terms of faulty components or reported error, P5 claims that the most common components to break are the PCB, display, or actuator, although such occurrences are unusual. Most errors are usually due to installation errors and are detected within three months of the installation date, according to P5. MP1 suggests that the type of errors has changed over time as the market has matured. A couple of years ago, most errors were related to software, but nowadays MP1 encounters more cases of wear and tear issues, such as connector problems for the charging cable, resulting from product usage. P3 also emphasizes that mechanical components that rotate have a higher risk of breaking.

Most manufacturers allow for electricians to carry out installation and maintenance provided they have received certification from the producer in question. This is to ensure that the installation is done correctly as the functions and design differ between the different producers. Since all producers interviewed had a B2B business model, the distributor is crucial as a middleman when it comes to maintenance. In the case of error detection, the distributor can monitor the charger from the back office and solve some software related issues. Otherwise, the distributor often has partnership with a producer-certified partner to manage more complicated issues.

For repair, the different manufacturers act in different ways. The more Europe-wide established producers insist on the customer sending the charger back to the factory. In these cases, the customer's charger is replaced with a new one and what happens to the old one after repair seems to be unclear. For the more nation-wide producers, the strategy is instead to have close collaboration with service partners and provide spare parts for them to repair and substitute faulty parts or chargers. For maintenance, the two Europe-wide producers collaborate with certified maintenance partners and electricians in most of the countries where they do not have their own sites. If a customer has neither a connected service partner nor a factory in their country, they will need to send the charger to the factory. For the nation-wide producers, the maintenance partners or their network of certified electricians act in the entire country.

P2 emphasizes that their company is undergoing a strategic shift towards increased focus on in-house refurbishment. They have upgraded their AC charger, which boasts a more modular design. The new model includes a separate back panel, where all the cables are fixed, which is assembled and installed by a certified electrician. The main part of the AC charger can then be easily attached to the back panel, either by an electrician or the end-user itself. According to P2, this will enable a refurbishment unit in their company with greater ease. The concept is simple: if a customer discovers an issue with their AC charger, they can by easily detach it from the back panel themselves and send it to the producer's refurbishment unit. P2 explains that with this system, the customer can receive a refurbished charger directly (which may not necessarily be the same unit they sent in), eliminating the need for a lengthy wait to obtain a functioning charger once again.

When asked upon what the end-customer can do to prolong the chargers life span, many interviewees stated that the customer can maintain their chargers by exercising the ground fault circuit interrupter (GFCI) and that this measure would extend the life of the charger. However, evidence that this measure extends the lifetime has not been demonstrated by the interviewees. Instead, as for all electrical products, this should be done to maintain electrical safety as the product is connected to the grid for several years according to both D1 and MP1. Exercising the GFCI is rather important in order to protect the charger in case of electrical disruption and would in that sense make sure the charger can operate normally and not break prematurely. The perception amongst the interviewees is that this measure and the reason behind it is not communicated properly to the customer. It might be due to the fact that electrical safety is assumed to be implied amongst customers without reminders from your charger producer or distributor.

Unanimously amongst the producers, service partners and operations managers, it can be said that a combination of infrequent need for maintenance and the fact that nation-wide service providers utilize electric cars for transportation, makes the maintenance related emissions of a charger's lifespan rather small. The use of EVs contributes to sustainability through two aspects. Partly, the climate impact from the chargers use phase is reduced as transportation to the charger to perform maintenance is only connected to the national electricity mix, which in Sweden's case means close to climate-neutral. Partly, the maintenance company is given the opportunity to test the charger after maintenance or repair has been carried out to ensure function and reliability. This enables national service and maintenance partners to in greater extent control and reduce the scope 3 related emissions of the charger. MP1 highlights that this is a prerequisite for doing their job effectively.

These findings can be summarized to:

- Wear and tear due to usage is most frequent issue
- Exercising GFCI is recommended for end-customer
- Repair is either being done in-house or outsourced
- Recommended to use EVs when traveling to do repairs and maintenance at customers

4.6 Recycling and end-of-life management

There is in general little knowledge from the interviewed producers regarding the end-of-life (EoL) stage of their sold AC chargers. According to the producers, this is due to several factors. Firstly, many of the producers point out that the responsibility of the AC charger after the warranty period has passed lies on the customer, not on the producer nor the distributor. This results in a knowledge gap, since EoL management is not within the producers' nor the distributors' business scope. Instead, the interviewees refer to the WEEE directive and believe the end customer takes their responsibility by handing in the charger to an approved recycling center for electrical equipment. Secondly, many of the interviewees point out that there are few AC chargers that have reached their EoL, which results in little overall knowledge for the whole industry.

WM1 can not ensure that AC chargers have been received, but believes it is handled in the same way as other electric and electrical equipment during its EoL stage. Regarding all recycling of electrical components, they have to be recycled according to the WEEE directive, WM1 means. That means that batteries and certain toxic materials has to be removed. The following steps, WM1 explains, are optimized to extract as much valuable metals and plastics as possible, which is some cases entails shredding to enable easier sorting, and in some cases manual removal of valuable components to sell separately to smelters. WM1 mean all valuable metals such as gold, silver and copper from circuit boards are recycled today. However, other metals such as gallium and indium are often lost in downstream melting processes due to low concentrations, hence, they follow the slag phase from the recycling process. WM1 continues by saying that new processes needs to be developed in order to fully recycle these metals. WM1 believes recycling of such rare metals will not be realized before there are legal requirements for it since the value and concentrations are low and recycling is complicated. WM1 also emphasizes that such legislation must be well-thought-out and that it is essential for all actors to comply with the same requirements to minimize the risk of companies that follow the rules being out-competed due to gray areas in the legislation.

CS1 expresses concern that much manual preparatory work for electronic recycling has been streamlined and replaced with various technical separation steps. Such technical system requires large investments in order to obtain materials with as high quality as possible for further recycling, and to extract as much value as possible in subsequent steps. However, CS1 also highlights that some manual preparatory work is still done, either because it is required of legal reasons, or because there is a big enough value in it. CS1 also mention that there are collaborations between recycling companies and municipal activities for manual preparatory work in Sweden. The idea is to improve the quality of recycled materials by having manual preparatory work before it is sent to recycling facilities. The preparatory facilities are driven by municipalities, and the workers get directions from the recycler in how to dismantle the electronic waste. CS1 believes there are strong financial benefits with such a system, but also social advantages as the municipal facilities are labor market initiatives, which reduces labor costs as businesses receive grants to employ these people.

Lastly, recycling of metals may impact the quality of the material due to the mixture of different metal alloys, as discussed in the Theory chapter. This could potentially result in a more limited after-market for selling recycled metals. However, according to WM1, this issue is perceived as relatively minor and can be effectively addressed through effective sorting prior to re-melting. Furthermore, WM1 believes that this challenge has decreased over time since recycling processes has become more refined and efficient.

These findings can be summarized to:

- Little knowledge about EoL of AC chargers
- Manual preparatory work could increase quality on recycled EEE
- Sorting before re-melting increases quality of recycled aluminium

5

Analysis & Discussion

5.1 Design

The results indicates that the EV charger market is relatively new. It lacks clearly differentiated brands, a part from one that emphasizes an aesthetically pleasing design as their main USP. The rest of the producers interviewed have somewhat common USPs, with a focus on a long technical life time as well as safety. This could be compared with more mature markets. For example, the market for smartphones provides a variety of models and price ranges, with different levels of features. There are high-end smartphones with high resolution cameras, large storage and well-designed interfaces, as well as simpler models with more basic features at lower prices. The concept of ’one size fits all’ is more widespread in the market for AC chargers, where all interviewed producers provide one or two different types of AC charger.

Common to all interviewed producers is that they work mainly with sustainability by offering a product with a long technical life time. It does not inhibit the sustainability of the product, but does not necessarily coincide with circular economy. For example, a product could still be expensive and/or difficult to repair, which increases the risk of a product being discarded instead of repaired. However, a majority of the producers interviewed stated their intention to incorporate additional circular economy principles into their forthcoming products, primarily by adopting a more modular design. This approach aligns with the idea of promoting maintenance, as modules can be replaced either temporarily for repair purposes or permanently if they become defective. Further, one of the producer interviewed meant a modular design could potentially decrease the number of components in circulation. This is because customers could customize their chargers with the specific functions they desire. The idea is that customers could add or remove functional groups during its lifetime, which leans towards a service-based system. On the contrary, another producer stated that all necessary hardware is already incorporated in their new AC charger. This raises the questions: do all customers want every possible function? Or is it wasteful to include a large number of electric components in one specific product in order to cater to all customer segments?

Furthermore, there are more ways to enable maintenance and repair into the design. Several of the producers interviewed mean they have consulted maintenance providers and electricians in order to design their charger in order to facilitate their work. It has been found that wear and tear is one of the most common issues with AC chargers, as a consequence of them being used. It is thereby essential from a sustainability aspect that these components are easily replaceable, e.g. the charger socket. In addition, some producers interviewed mean customers tend to be careless with the charger cord, with risks of it needing to be replaced. To mitigate this issue, it is recommended to opt for a charger with a detachable cord. This allows for easier replacement than with a charger with fixed cord, since only the cord must be replaced, and that this can be done without any bigger obstruction on remaining parts. However, there is a risk of rust occurring between the surface areas of the charger socket and cord if the cord is not regularly disconnected by the customer. It is therefore crucial to effectively communicate to customers the importance of regularly removing the cord. In cases when chargers with fixed cords are provided, it is imperative that an easy-to-use suspension system is included in order to minimize the likelihood of cord mishandling by customers.

In addition to considering modularity in the design of the charger, it has been noted that the charger's size is also significant. The general trend goes towards a smaller charger, only for aesthetic reasons as found in the interviews. A smaller charger require less material for the casing, which could have sustainability advantages in itself. However, it is important to consider how a smaller size might affect the performance of the electrical components, as discussed in Chapter 4. Therefore, a spacious design is preferable to ensure that the charger functions optimally.

5.2 Material

During the thesis, the choice of casing material has been well discussed. Polymers seems to be an easy way to go when choosing material for the casing. Many producers states that due to its cost-effectiveness and ease to design and mold, plastic is an excellent material. Whereas metal is presented as heavy and expensive, plastic is highlighted as equally as durable and easy to customize. However, evaluation shows that, even though plastic in most cases is fully recyclable, the variety of polymers with vastly different molecular structures impedes large-scale recycling. Further, to mitigate the sight of the inevitable yellowing of plastic, many producers choose to dye the casing dark or even black. Since dye changes the molecular structures and bonds the polymers to the color, coloring further inhibits recycling and degrades the material upon recycling. Further, using black dye to increase coverage hinders identification in the sorting process, making the recycling even harder. All of the above acts to hinder a recycling loop that could make plastic a sustainable way to go and is a problem that aluminium does not face. Recycling of aluminium is an established process and fully scaleable to match an increased material flow. Further, given the demand for smaller and more compact chargers, the risk of overheating the electrical components increases. One way to reduce the risk of this consequence is to consider the thermal conductivity of the materials. Metal has a significant advantage compared to plastic with regards to this aspect and can definitely be incorporated in smart ways as a measure to prolong the life of the charger.

During our interviews with charger producers, it became clear that achieving a high IK and IP classification is a top priority for their products. However, since the occurrence of private chargers being hit is rare, it is worth considering whether the IK classification should be as prominent as it currently is. The IK classification might impact the choice of material thickness and ability to withstand mechanical resistance, leading to more complicated, expensive and heavier product compared to what is necessary. Re-evaluating the need for state-of-the-art IK classification, could yield significant gains in terms of sustainability and resource efficiency. However, its worth pointing out that the IP classification can indeed serve the charger to increase up-time and life span. Since the chargers, in most cases, are positioned outdoor, the need to withstand harsh conditions in terms of weather alterations is highly important to prolong life spans. However, an important difference in these classifications is that it can not be assumed that the thickness of the material decides upon it resistance to particles and moisture. Rather the materials permeability of such particles plays a significant role. Hence, a thin resource efficient layer of casing could be equally as resistant to real time harmful particles as thicker casings, and there should not be a wrongful parallel drawn between the two.

In today's society, the dependence of electronics makes exchanging or simplifying electrical components not feasible for most industries. There is a strong focus on further developing these kinds of products and slowing down is not a way to go. Hence, regarding the production stage, not much can be done at the moment to reduce carbon footprint of the product, apart from ensuring a greener electricity mix at the production site. Furthermore, while it is possible to sort and recycle critical materials found in products like PCBs, the cost of doing so is not currently economically feasible. Also, it can be stated that previously there has been little incentives to recycle such materials in Europe due to the fact that Europe imports most of these products and do not produce them themselves. However, the CRM Act might incentivize a higher degree of recycling of these materials in the coming years. Thus, a centralized collection system and smelter site for these materials in Europe could create a viable business for recycled critical metals, thereby reducing the carbon footprint of electronic components. Such a solution would require strong and unified collaboration between European countries.

Some producers shared that they are looking into incorporating bio-plastics in parts of their products. This could indeed reduce overall footprint and create a more sustainable product since fossil dependence decreases with this solution. However, it is important to closely evaluate all alternative materials and what they can be used for. Many kinds of plastics, especially recycled, perform worse with regards to flame retardancy, which compromises safety aspects. It is evident, based on the interviews, that the producers care about creating sustainable products. However, as mentioned earlier, the market is young and so far, the market share has not yet been established, thus competition arises on product development.

5.3 Use phase

The level of GHG emissions associated with the electromobility sector is largely dependent on the electricity production mix in a given region. In regions with high share of fossil fuels, the emissions associated with charging EVs are high. However, in countries with larger share of RES in the electricity mix, emissions associated with charging EVs are significantly lower. This could be seen as a matter of course, but the distinction is important when discussing emissions related to the use phase of EVs, and thereby EV chargers. The result from the interviews shows that use phase related emissions is a complex subject and most stakeholders interviewed mean they have no to little mandate to control or influence this stage of the life cycle. They rather suggested that the end-customer should take responsibility for making sustainable decisions by charging their EVs in a smart manner. However, it could be argued that it is difficult for an end-customer to affect the emission rate of their regional electricity mix by controlling their charging pattern. Achieving this would require significant effort and knowledge about the electricity system and power production, which may not be feasible or practical for most customers. This raises the question of whether it is reasonable to shift responsibility downstream to end-customers.

On the contrary, the electromobility sector could possibly help increase the penetration level of renewable energy sources in the electricity mix by V2G implementation. This concept fundamentally changes the way we view the transport sector by using private individuals' vehicles as a source of electricity storage and ancillary services for the regional grid. All interviewees had knowledge about this subject, and enhanced the image that this is a complex subject where a lot of different stakeholders must be involved. The interviews suggested that there is a lack of collaboration, or rather, a lack of platforms to discuss these issues between stakeholders in the value chain. In many ways, V2G as a concept is still a theoretical perception. V2G communication as the ISO standard 15118 was highlighted by many interviewed producers, but it should be seen as just a first, small piece of this puzzle.

Functions related to Vehicle-to-home (V2H), on the other hand, is closer to implementation. Possibilities for private households to utilize their EV as a storage unit for excess electricity produced in their solar PVs could be seen realized in close time. The potential of this function may vary depending on regional regulations governing the sale of solar PV-produced electricity to the grid. However, as the sale of solar PVs to private households continues to increase globally, there could be reasons to believe that more countries will implement restrictions on selling solar PV-produced electricity to the grid. Such restrictions may be driven by concerns over grid stability, especially if the power grid is not designed to handle high levels of distributed energy from private households. There may also be concerns regarding market distortion if solar PV generators become more cost-effective than conventional energy producers. With this as a background, there are reasons to believe it is of importance that more charging manufacturers should offer V2H related functions in the nearby future.

Lastly, it appears that opinions on the importance of energy efficiency measurements of AC chargers vary among the producers interviewed. According to the LCA analyses and information obtained from the interviews, lost energy levels are already quite low, so improving energy efficiency in this area may not be a top priority for all manufacturers. It could be argued that there are other areas that could be prioritized for improving the sustainability of AC chargers and have a greater impact.

5.4 Maintenance

Although it was found that maintenance has little impact on the total footprint due to the high quality of the charger, it enables a proactive approach to prolong lifetime, which indeed is important for sustainability. Further, during the interviews, the way of maintaining heavily differs between producers. Common for the national producers is the utilization of third party partners to drive to households to maintain chargers. For the European-wide producers, it was found that the winning concept is to send the faulty charger to the production site for repair or maintenance.

External maintenance puts pressure on the third party partners to ensure competence enough to manage all cases. However, the total travel distance may decrease when utilizing several decentralized actors to perform maintenance and service compared to one national site. Further, close collaboration and common core values among the producer and service partners resulted in tailpipe emission free travel to chargers in need of maintenance due to the companies using BEVs or PHEVs in all cases. This results in less emissions related to scope 3 of the business, hence reducing the overall footprint. This business model has thus a higher degree of affecting and improving emissions related to scope 3 compared to the alternative.

In-house maintenance means having a centralized site where chargers are sent whenever service is needed. This solution puts higher pressure on in-house competence and ensuring capacity to effectively manage all chargers that are brought in. However, compared to the external option, it can be stated that in-house maintenance require less spare parts in total and the ability to instead refurbish chargers increases. With this, it is also important to consider the potential risks associated with not ensuring full utilization the back-end office if the system primarily prioritizes sending chargers back to the in-house maintenance unit. Many issues can be effectively managed from the back-end office as long as the charger remains connected. However, in cases where the connection is lost, there are advantages to having a technician visit the site and troubleshoot the charger before considering sending it back to the in-house maintenance site. Regardless of such risks, in-house maintenance seems to be an advantage that even national producers approaches, especially since connection issues is not brought up as neither regular nor severe problems by any stakeholder. However, since connection ability is crucial for enabling in-house solutions, it could be recommended that producers further prioritizes and follows up on the connectivity to fully mitigate this risk. If successful, in-house solutions results in enabling more modular designs, which favors circularity and a sustainable system. Another aspect to take into account is the ability to affect logistics and scope 3 emissions, which disconnects with the in-house business model compared to external solutions. Currently, as mentioned in Chapter 4.5, external service and maintenance partners uses electric vehicles for transportation to a customer. Thus, the scope 3 emissions of said company is controlled, which is not the case if implementing in-house services. Since end-customers themselves decides upon logistics in the case of in-house service, the producers have less impact in making the logistics sustainable or emission free. Instead, logistics related emissions becomes a more national sweeping issue.

Another aspect brought up in almost all interviews was that exercising the ground fault circuit interrupter (GFCI) could prolong the life span of the charger. What was found was that the actual result this measure brings is reduction of a faulty breaker, which in turn protects the charger itself, as for all electrical appliances. Thus, although this is an important measure, it should not be promoted as a measure for end-customers to affect the life span of their charger. The perception is that neither of these aspects are communicated properly to end-customer, which might affect user perception of the product and possibly the electrical safety of the product itself.

5.5 Recycling and end-of-life management

Information gathered from the interviews show that there is a lack of knowledge about the EoL stage of AC chargers. The market is fairly new and due to the already long life span, there are relatively low volumes of circulating AC chargers.

One main aspect in regards of this subject is the use of electrical components and PCBs. The interviews show that some valuable metals in PCBs are recycled today, but that the process itself could be questioned. It is believed that a higher degree of manual preparatory work could increase the recycling process's efficiency and the final material's quality. Given this, the AC charger industry has the opportunity to contribute to a more resource-efficient use of materials used in electrical components and PCBs. By collaborating on manual preparatory work, as described in Chapter 4.6 by CS1, the AC charger industry could take a proactive position in the responsibility for recycling and EoL management of critical metals in electric components.

It was found that although metals such as silver and gold are recycled, many of the more critical metals that are used in very small amounts are not. Instead, they disappear in larger amounts of mixed metals and plastics. Due to the small amounts, at first sight, this seems to be an equally small issue. However, by factoring in the huge development and advancement of PCBs and charger functions, in the future, there might emerge an issue with resource depletion. However extensive or insignificant this issue might be, the current system is linear, whereas a circular system should always be prioritized. To make the system for these rare metals more circular and at the same time financially incentivized an idea would be to arrange a European-wide collection system and smelter site in order to manage quantities that would be economically feasible. This proposal is also aligned with the CRM Act set in place by the EU in order to strengthen European independence of critical material value chains.

Regarding plastic, most of the investigated plastics used is thermoplastics, which indeed is fully recyclable. The recycling of thermoplastics is functional, however, the vast amounts of variety impedes recycling. However, there are ways to increase circularity and utilization rate of thermoplastics. By using transparent plastics in those areas where it is not visible from an outside perspective, companies can increase the utilization rate of plastics and ensure that it can be used in as many recycling circuits as possible, thus reducing production of new plastics. Further, seeing that producers strives for similar plastic properties in terms of flame retardancy and impact resistance, policy instruments could be set up to homogenize polymers for chargers and comparable products to extend recycling ability, resulting in less incineration or even landfill.

6

Conclusion

In conclusion, this thesis has successfully accomplished its objectives by elucidating the key contributors to the environmental impact of AC chargers, identifying influential stakeholders capable of affecting these impacts, and presenting clear examples of improvement measures for each life cycle stage and stakeholder. The research has primarily focused on European stakeholders and regulations, with a particular emphasis on the Swedish context.

The findings revealed notable trends and considerations within the charger industry. While sustainability was not the primary focus in the earlier generations of chargers, all interviewed producers underscored their proactive commitment to integrating sustainability in upcoming charger iterations. Recycled aluminium emerged as the casing material with the highest degree of circularity when compared to virgin aluminium or plastic alternatives. This superiority stems from well-established recycling processes, energy savings during production, and its thermal conductivity advantages. Notably, the increasing popularity of small compact chargers further underscores the suitability of aluminium due to its thermal properties, enabling such design choices without compromising component performance. Also, it was emphasized in the interviews that plastic is still required for internal components. Therefore, it is recommended to utilize recycled or recyclable thermoplastics derived from non-fossil feedstocks, as they offer the highest degree of circularity among the considered plastics. This choice of plastic implies the exclusion of dark colors, particularly black.

Regarding the Middle-of-Life stage, the research unveiled that most breakages was attributed to wear and tear, such as charging cord breakage. To mitigate the environmental impact, the thesis recommends the adoption of detachable cords. By incorporating this design feature, the entire charger does not require replacement in the event of cord breakage, minimizing material waste and promoting a more circular product. Furthermore, this study could not determine the optimal approach to repairing faulty chargers, i.e., whether it should be done in-house or outsourced. Both approaches have advantages and disadvantages that need to be considered. In general, it is crucial for producers (or distributors) to offer some form of repair service to end-customers. It is essential to effectively communicate this information to end-customers to reduce the risk of them disregarding a faulty charger that could actually be repaired. Distributors play a significant role as they act as a communication bridge between end-customers and producers. Simultaneously, producers must dedicate effort and resources to manage faulty reports and the repair process.

It was found that emissions related to the use phase is highly complex in terms of division of responsibilities. The most effective approach to significantly decrease emissions during this phase involves replacing fossil-based energy sources with renewable alternatives. However, this transition is of enormous magnitude and requires the involvement of numerous stakeholders beyond just the charging industry. Instead, the charging industry can contribute to the increased utilization of renewable energy sources by implementing V2H and V2G technologies. It was discovered that V2H is expected to become available in the near future, possibly even by the end of 2023. However, the implementation of V2G will require time, effort, and dedication from multiple stakeholders.

In the End-of-Life stage, the research confirmed that increased levels of sorting and pre-treatment processes yield higher quantities of pure recyclable materials while reducing the flow of waste to incineration. Currently, upstream actors possess limited knowledge regarding the End-of-Life stage; however, the thesis identified potential entry points to increase recycling rates. Collaboration between waste management companies, producers, and distributors to facilitate pre-dismantling of products before entering the recycling site can enhance the recovery of critical metals, preventing their mixing with larger material flows. Such initiatives hold the potential to enable the recycling of scarce metals, contributing to the avoidance of resource depletion.

Table 6.1 - 6.5 provides a comprehensive overview of the key improvement measures identified for all investigated stakeholders, highlighting their contributions to circularity through the implementation of these measures within their respective business operations. Note that Table 6.3 also includes key recommendations for end-users, since they were considered as a contributor to a circular system as well.

Table 6.1: Improvement measures for producers

Life stage	**Circular economy loop**	**Areas**	**Improvement measures**
BoL	Recycle	Material selection	Recycled aluminium for casing, preferably from European actors
BoL	Recycle	Material selection	Recycled (or at least recycable) thermoplastics for necessary internal structures, preferably from non-fossil feedstock. Transparent or light colours - avoid darker colours, especially black
BoL	Prolong / Reuse	Modularity	Maintenable and replacable modules to expand customer segmenation
BoL	N/A	Compatibility	Offer V2H, i.e., compatibility between charger, EV, and solar PV
BoL	Prolong / Reuse	Design input	Engage value chain actors (e.g., service partners, distributors, recycling experts) in design phase to increase sustainability aspects
N/A	N/A	Collaboration	Engage in forums with the electromobility sector in order to realize V2G implementation
EoL	Recycle	Manual preparatory work	Engage in collaboration on manual preparatory work before recycling, thereby increase value of recycled materials

Table 6.2: Improvement measures for distributors

Life stage	Circular economy loop	Areas	Improvement measures
BoL	Prolong / Reuse	Design input	Engage in producers' design phase to increase sustainability aspects
MoL	Prolong / Reuse / Refurbish / Recycle	Portfolio selectivity	Include sustainability requirements in testing routine. E.g., material selection, modularity, V2X
MoL	Prolong / Reuse	Customer care	Provide extensive information and service to end-customer to enable educated decisions and prolonging life time of carger. E.g., correct handling of charging cord
MoL	Prolong / Reuse / Refurbish / Recycle	Value chain relations	Act as a middleman between BoL and EoL, communicate customer demand both upstream and downstream to unite value chain and optimize product sustainability
EoL	Recycle	Manual preparatory work	Engage in collaboration on manual preparatory work before recycling, thereby increase value of recycled materials
N/A	N/A	Collaboration	Engage in forums with the electromobility industry in order to realize V2G implementation

Table 6.3: Improvement measures for end-customers

Life stage	Circular economy loop	Areas	Improvement measures
MoL	Prolong / Recycle	Informed decision making	Choose a charger with detachable charging cord and casing of recycled aluminium. Avoid casing with black plastic from fossil feed-stocks
MoL	Prolong / Reuse	Placement	Install charger where it is protected from harsch weather, e.g., in garage or under roof
MoL	Prolong / Reuse	Maintenance	Perform correct maintenance, e.g., disconnect charging cord regularly

Table 6.4: Improvement measures for maintenance providers

Life stage	**Circular economy loop**	**Areas**	**Improvement measures**
BoL	Prolong / Reuse	Design input	Engage in producers' design phase to increase sustainability aspects
MoL	Prolong / Recycle	Error statistics	Follow and understand error statistics in order to effectively contribute to design and material alterations in the BoL stage
MoL	Prolong	Prolong life time	Ensure correct service and maintenance by educating personnel
MoL	Prolong	Ensure electrified logistics	Electrified means of transport in case of external service to ensure functionality, and to reduce overall carbon footprint
EoL	Recycle	Manual preparatory work	Engage in collaboration on manual preparatory work before recycling, thereby increase value of recycled materials
N/A	N/A	Collaboration	Engage in forums with the electromobility industry in order to realize V2G implementation

Table 6.5: Improvement measures for waste management and recycling actors

Life stage	**Circular economy loop**	**Areas**	**Improvement measures**
BoL	Recycle	Design input	Offer expertise on how to increase recyclability
EoL	Recycle	Manual preparatory work	Engage in collaboration on manual preparatory work before recycling, thereby increase value of recycled materials
EoL	Recycle	Increase recycling rates	Contribute to a system that sorts and recycles materials to a high extent

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