PRODUCT CARBON FOOTPRINT LIFE CYCLE ASSESSMENT OF KEMPOWER SATELLITE AND KEMPOWER POWER UNIT

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Environmental Technology - Sustainability Science and Solutions

Master's thesis

2024

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ABSTRACT

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Keywords: carbon footprint, life cycle assessment, greenhouse gas emissions, environmental impacts, electric vehicle charging, public charging infrastructure, electric vehicle charger

The climate change and rising greenhouse gas emission levels have sped up the shift from conventionally fueled vehicles to electric vehicles. The environmental impacts of this shift depend on many factors, highlighting the significance of investigating and understanding the full range of its consequences for informed decision making. One aspect of the shift is public charging infrastructure. The sustainable development of public charging infrastructure plays a pivotal role in the electric vehicle uptake as well as in mitigating the indirect environmental impacts of traffic system electrification.

The aim of this master's thesis is to determine environmental consequences of electric vehicle chargers by defining the carbon footprints (CFs) of Kempower Satellite and Kempower Power Unit. Based on the results of these CF assessments, recommendations for reducing them are announced. Prior to the CF study, a concise review of the environmental benefits of public charging infrastructure uptake, state of the art, and prospects of the European public charging infrastructure, along with the methods used for CF assessment, are presented.

The CF assessments are conducted following ISO 14067 and with the cradle-to-grave principle. The system boundaries were set to include all unit processes and flows defined as significant to the products' life cycles. The determined CF for Satellite was 922 kgCO_2e and for Power Unit 27047 kgCO_2e. The product component manufacturing, spare part manufacturing, energy dissipation during use, and energy consumption in standby state were found to be the most contributing processes in the CF of both products. Conclusively, the reduction recommendations applied to these processes.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUTin energiajärjestelmien tiedekunta
Ympäristötekniikka

Veikka Vauhkonen

Kempower Satelliitin ja Kempower Power Unitin tuotehiilijalanjäljen elinkaariarviointi

Diplomityö
2024

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Avainsanat: hiilijalanjälki, elinkaariarviointi, kasvihuonekaasupäästöt, ympäristövaikutukset, sähköauton lataus, julkinen latausinfrastruktuuri, sähköautolaturi

Ilmastonmuutos ja alati kasvavat kasvihuonekaasutasot ovat kiihdyttäneet siirtymää polttomoottoriajoneuvoista sähköajoneuvoihin. Tämän siirtymän ympäristövaikutukset ovat moninaiset, korostaen niiden laaja-alaisen tutkimisen ja ymmärtämisen merkitystä. Eräs siirtymän osa-alue on julkinen latausinfrastruktuuri, jonka kestävällä kehittämisellä on keskeinen rooli sähköautojen käyttöönotossa sekä liikennejärjestelmän sähköistymisen välillisten ympäristövaikutusten lieventämisessä.

Tämän diplomityön tavoitteena on selvittää sähköautojen latauslaitteiden ympäristövaikutuksia määrittelemällä Kempower Satellite ja Kempower Power Unit tuotteiden hiilijalanjäljet. Tutkimustulosten perusteella pyritään antamaan suosituksia kyseisten tuotteiden hiilijalanjälkien vähentämiseksi. Ennen hiilijalanjälkitutkimusta esitetään tiivis katsaus sähköautojen julkisen latausinfrastruktuurin ympäristöhyötyihin sekä Euroopan julkisen latausinfrastruktuurin nykytasoon ja näkymiin. Lisäksi hiilijalanjäljen laskennan metodologia ja periaatteet esitetään lukijalle.

Hiilijalanjälkiarvioinnit tehdään ISO 14067-standardin mukaisesti cradle-to-grave-periaatetta noudattaen. Järjestelmän rajat asetettiin sisältämään kaikki tuotteiden elinkaaren kannalta merkittävät yksikköprosessit ja -virrat. Satelliitille hiilijalanjäljen määriteltiin olevan 922 $kgCO_2e$ ja vastaavasti Power Unitille 27047 $kgCO_2e$. Tuotteiden komponenttien valmistus, varaosien valmistus, käytönaikaiset energiahäviöt ja valmiustilan energiankulutus osoittautuivat merkittäviksi prosesseiksi kummankin tuotteen hiilijalanjäljen suuruuden kannalta. Täten vähennyssuositukset kohdistuivat kyseisiin prosesseihin.

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Viisi vuotta hurahti yliopistossa melkoisen nopeasti. Vaikka korona-aika sävytti opintojen ensimmäisiä vuosia ja kuritti näin ollen opiskeluelämän sosiaalista puolta vahvasti, tarttui tästä huolimatta mukaan ystäviä, joihin tulen varmasti pitämään tiiviisti yhteyttä tulevaisuudessakin. Kiitokset etenkin Esalle ja kaikille muille opiskelutovereilleni mieluisasta opiskeluajasta. Mieleen on erityisesti jäänyt lukuisat nokipannukaffet, jotka etäopiskelu mahdollisti – vaikka kesken päivän.

Lopuksi haluan kiittää vanhempiani, perhettäni ja muita läheisiäni mittaamattoman arvokkaasta tuesta koko opintojeni ajan.

Lahdessa, 17.01.2024

Veikka Vauhkonen

SYMBOLS AND ABBREVIATIONS

Roman

E	energy	[Wh]
P	power	[W]
V	voltage	[V]

Greek

η	efficiency	[- , %]

Subscripts

DC	direct current
DIS	dissipated
sbs	standby state

Units

°C	Celsius degree
a	year
CO_2e	carbon dioxide equivalent
d	day
g	gram
h	hour
kg	kilogram
t	ton, tonne
TEU-km	twenty-foot equivalent kilometer
tkm	ton-kilometer

Abbreviations

AC	alternating current
AFIR	Alternative Fuels Infrastructure Regulation
AFID	Alternative Fuels Infrastructure Directive
CF	carbon footprint
CH_4	methane
CO_2	carbon dioxide
DC	direct current
EoL	end-of-life
EPD	Environmental Product Declaration
EV	electric vehicle
GHG	greenhouse gas
HQ	headquarters
ICEV	internal combustion engine vehicle
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
N_2O	nitrous oxide, dinitrogen oxide
NA	North America
PCF	product carbon footprint
PCR	product category rule
PSR	product specific rule
RoE	Rest of the Europe
RoW	Rest of the World
RSL	reference service life
TEU	twenty-foot equivalent unit
WTW	well-to-wheel

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Appendices

1 Introduction

Climate change, undeniably caused by us, humans, and by our activities, has driven humankind to a challenging situation. Alternation in climate can be seen in every continent and the recent changes have been rapid. The Paris Agreement's global goal of limiting the temperature below 2 °C from pre-industrial levels and aim to 1,5 °C may be out of reach if remarkable reductions in greenhouse gases (GHGs) are not reached. This global goal can be reached by reducing the GHG emissions from pre-industrial levels by 45 percent by 2030 and by reaching net zero emissions by 2050. (IPCC 2021.)

The energy sector, as one of the main contributors to global GHG emission levels, battles with too little renewable energy. The European energy sector, in particular, has sparked an energy crisis for breaking free from fossil fuels due to Russia's invasion in Ukraine. Crisis, and many other factors, have driven the decision-making authorities, from government- to local-level, to roll out different policies to accelerate clean energy investments. (IEA 2022, 19-20, 236.) The European Union (EU) is aiming to reduce GHG emissions of the transportation sector by 90 percent by 2050 from 1990 levels, as part European Green Deal that was announced in 2019. Electrification of road transport in particular has been chosen as a GHG mitigating action because the whole transport sector was responsible for 25 percent of the EU's total GHG emissions in 2020, which of 71 percent through road transport (European Commission 2020; ECA 2021, 7-9). The Green Deal anticipates approximately 13 million zero and low-emission vehicles on the EU's roads by 2025, with a high share of electric vehicles (EVs) (ECA 2021, 8). In line with this, establishing a comprehensive network of public charging stations is crucial for meeting the GHG emission reduction targets. Moreover, it is essential to gather information also on indirect GHG emissions emerging from the manufacturing of EVs and the associated charging infrastructure, to gain a thorough understanding of the environmental impacts of electrification. (EAFO 2023; ECA 2021, 7, 9-10; LaMonaca & Ryan 2022, 1.)

Climate change and its consequential technological needs can offer remarkable opportunities for companies, but at the same time increase the importance of reporting their environmental impacts. As awareness about climate change intensifies and concerns thrive, the stakeholders require more transparency in the company's actions. The consumers are looking for greater clarity and environmental answerability and investors information about actions in all fields of sustainability. Companies must be able to understand and manage, especially, their supply chain- and product-related GHG emissions, to guarantee long-term prosperity in competitive business environment. This way the companies are also prepared for any future policies or regulations associated emission reporting. (GHG Protocol 2011, 5.)

One of the most popular standardized method for uncovering and quantifying the environmental impacts of human activities, such as products, services, or processes, with a system perspective, is life cycle assessment (LCA). LCA can be used to report the environmental performance of a company and its activities for the obligatory directions as well as to improve the marketing of the company by sharing the results, for example, in the form of an environmental claim. (ISO 14040:2006, v; Hellweg et al. 2023.) According to Hellweg et al. (2023), LCA can form paths toward a more sustainable future and assist in prioritizing the actions to achieve it. When LCA is narrowed down to quantify only one impact category, climate change, it becomes a carbon footprint (CF) study. In CF studies, the results are given in units of carbon dioxide equivalents (CO_2e) which is a unit of measurement that compares the global warming potential of the released GHGs by the system under study to the most typical GHG, carbon dioxide. (ISO 14067:2018, 5, 12.) When a CF study is conducted for a product and in accordance with the International Organization for Standardization's (ISO) standard 14067:2018, like in this thesis, it is called a product carbon footprint (PCF) study.

There are very few public LCA or CF studies made about EV chargers in general, and especially about public chargers (e.g., Dahlberg & Rodriquez 2023; Nansai et al. 2001; Zhao et al. 2021). The majority of LCA studies that assess the environmental impacts of the electrification field, seem to concentrate on the impacts of EVs alone. The main reason behind the lack of studies about the chargers could assumably be the shortage of publications from the major EV charger manufactures, such as Tesla, ABB, Tritium, Siemens. Thus, there are no benchmark values set. Publicly available EV charger LCA studies would not only provide information about the environmental impacts of charging infrastructure, but they would also be beneficial for the development of the charger industry field by increasing competition between manufacturers in the form of more sustainable product design, for example (GHG Protocol 2011, 10).

This master's thesis has been commissioned by Kempower and conducted as a part of the EU's project PowerizeD. The objective of this master's thesis is to define product carbon footprints of Kempower's two main EV charger products; Kempower Satellite and Kempower Power Unit. The second objective is to recognize the hotspots of greenhouse gas emissions associated with the life cycles of the products and suggest practices for reducing them.

The research questions in this master's thesis are the following:

1. What are the carbon footprints of the example products and what are the greenhouse gas emission hotspots associated within the life cycles?
2. How could these hotspots associated within the life cycles be reduced?

The PCF study is carried out following ISO 14067:2018. The PCF study is outlined to contain every life cycle stage from raw material extraction to disposal of the products. Data for the study is provided by Kempower and its stakeholders and supplemented with data from scientific literature sources. Calculations and life cycle modeling are made with Excel.

The first part of this master's thesis is a literature review that introduces the reader briefly to the state of public charging infrastructure in the EU area and possible environmental benefits of public charging infrastructure uptake. After that, the methodology and principles behind the PCF study are presented. The PCF study itself, the results, and recommendations according to the PCF study are gone through after the methodology. Lastly, discussion and conclusions are introduced.

2 Public charging infrastructure in the European Union's area

This chapter reviews the state of public charging infrastructure in the European Union area and reviews some possible environmental benefits of public charging infrastructure uptake. The first subchapters will introduce some basic terminology about EV chargers to help understand the following chapters, the EU's main legislative targets set for the public charging infrastructure, and the state of art in terms of the number of public charging infrastructure. After that, the prospects of public EV charging in the EU area are discussed and possible environmental benefits of EV charger uptake are listed. All of the above-listed chapters are written with the geographical scope of European Union countries, i.e., EU27, and with focus on public light-duty electric vehicle (LDEV) charging infrastructure.

2.1 Terminology and categorizing

EV charging is a relatively new field of technology and as a result of this, plenty of various terms and definitions are used, usually referring to the same phenomenon. The European Alternative Fuels Observatory (EAFO) (2023) has announced the following definitions (Figure 1), and those are used in this paper.

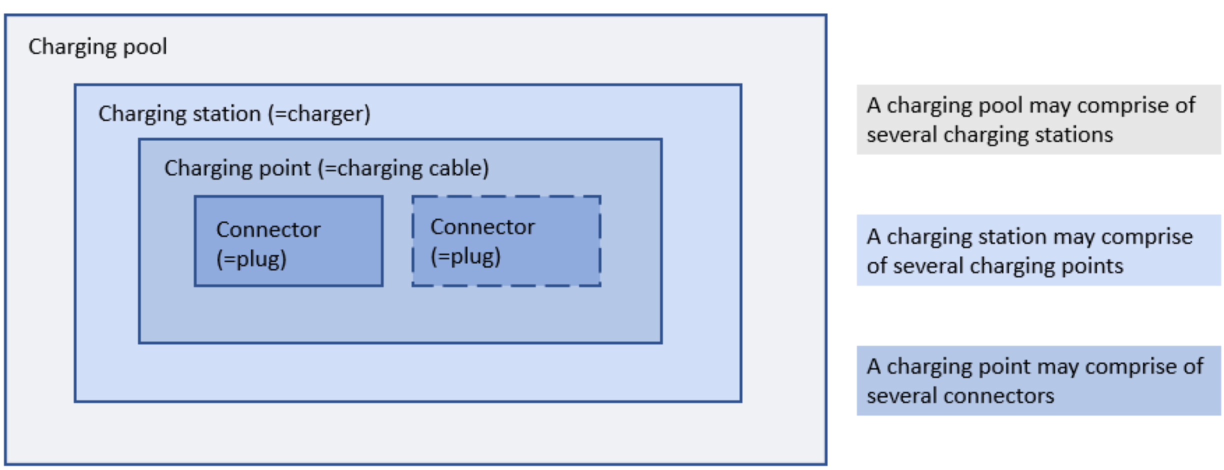

Figure 1. The charging infrastructure definitions commonly used in European Union area (imitating EAFO 2023). The terms in parenthesis refer to the word that is used of it commonly in colloquial language.

For categorizing and classifying EV charging stations, several different styles exist which of many are dependable on geographical location. The categorizing usually bases on several characteristics, which of the most common ones are output current type, alternating (AC) or direct (DC), and maximum power output. (EAFO 2023.) Currently in the EU, the charging points are grouped into two main categories, the AC and DC. These are then subcategorized by the power output, as Table 1 shows. This categorizing is based on EU's Alternative Fuels Infrastructure Regulation (AFIR). (EAFO 2023.)

Table 1. Charging point categories and sub-categories based on AFIR's proposal. The regulation additionally defines chargers with power output under 22 kW as "normal power charging points" or as "slow charging points" and the chargers with power output over 22 kW as "high power charging points" or as "fast chargers". (EAFO 2023.) The AC stand for alternative current and DC for direct current.

Category	Sub-category (charger speed and type)	Maximum power output, P [kW]
Category 1 (AC)	Slow AC charging point, single-phase	$P < 7{,}4$
	Medium-speed AC charging point, triple-phase	$7{,}4 \leq P < 22$
	Fast AC charging point, triple-phase	$P > 22$
Category 2 (DC)	Slow DC charging point	$P < 50$
	Fast DC charging point	$50 \leq P < 150$
	Level 1 – Ultra-fast charging point	$150 \leq P < 350$
	Level 2 – Ultra-fast charging point	$P \geq 350$

What comes to EV charger plugs, in other words, the vehicle connectors, not all EVs can recharge at every charging point, since the plug types and vehicle inlets alter across the world and EV models. For EU area, the AFID (Alternative Fuels Infrastructure Directive) has set its own requirements for interoperability reasons. Currently, all of the medium- and fast-speed category 1 (AC) EV chargers have to be equipped at least with Type 2 plugs, i.e., Mennekes, and category 2 (DC) with CCS2 (combined charging system) plugs, also known as, Combo 2. The CCS2 plugs are interoperable only with EVs using CCS2 vehicle inlet, whereas the Type 2 plugs are with Type 2 and CCS2 vehicle inlets. However, the EU has not forbid the use or adding other connectors to the chargers, and therefore others plug types can be also seen in the public charging points. (EAFO 2023.)

2.2 Legislative targets

The 2014 introduced directive on Alternative Fuels Infrastructure (AFID) and the aforementioned AFIR are the key policies and the “backbones” within the overall strategy of the EU for developing public charging infrastructure. They aim to overcome the so-called chicken-and-egg problem between EV charger uptake and EV uptake and to try to keep up the number of public chargers with EV amount. The AFID set a requirement for member countries to set deployment targets for public chargers for 2020, 2025, and 2030 with an indicative ratio of one charging point per ten electric cars. (ECA 2021, 8-11; EPRS 2023, 2, 7-8.)

The AFIR, which is a regulation improved from AFID, as a part of the Fit for 55 package, announced a set of concrete targets regarding public charging infrastructure in the whole EU and individually in the member countries. Some of the targets concerned the TEN-T network. TEN-T can be divided into core and comprehensive networks. The core TEN-T consists of nine traffic routes or roughly 50 000 kilometers of road, that are considered the most important traversing the EU. Whereas the comprehensive TEN-T ensures accessibility to all over the EU region. (ECA 2021, 10-11; EPRS 2023, 2.) The AFIR targets, particularly for LDEV charging infrastructure, are listed down below:

- Charging pool at least every 60 kilometer on main roads, i.e., core TEN-T network by 2025, and by 2050 for comprehensive TEN-T network. These charging pools in the core TEN-T network must deliver at least 400 kW and include a minimum of one charging point with a power output of at least 150 kW by the end of 2025. Similarly, by the end of 2027, the respective numbers should be 600 kW and 150 kW.

- EU member countries must install them in accordance with vehicles registered in their area. One kilowatt per BEV (battery electric vehicle) registered and 0,66 kW per PHEV (plug-in hybrid electric vehicle) registered. (EPRS 2023, 2, 7-8.)

Additionally, AFIR set requirements for new chargers. These requirements include enabling ad hoc, i.e., spontaneous, charging without registration, accepting electronic payments, and providing transparent information to users about charging session pricing. (EPRS 2023, 7-8.)

In addition to AFID and AFIR, several policies have been announced over the years, for instance European Strategy for Low-Emission mobility, for enhancing the work towards adapting alternative fuels and related infrastructure in the European transport sector. However, these have not directly set any legally binding targets or such for the public chargers. (ECA 2021, 9-12.) Additionally, there were found no direct EU policies or targets concerning the indirect environmental impacts of charging infrastructure.

2.3 Current trend

The number of public charging points in the EU area has been growing from roughly 34 thousand in 2014 (ECA 2021, 21) to 442 000 in 2022, as Figure 2 shows (European Commission 2023). According to European Alternative Fuels Observatory (EAFO) (2023) statistics, the 2023 year-to-date number of public charging points was 603 000 in September.

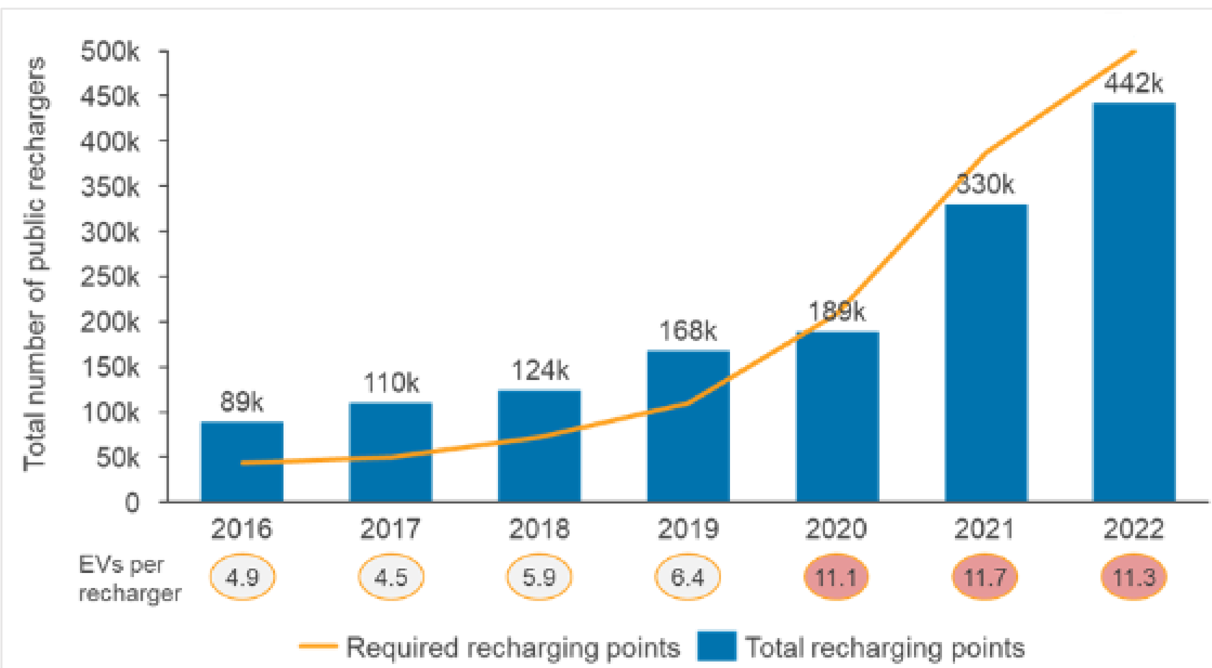

Figure 2. Public charging point amounts and required charging points according to AFID's recommendation ratio of 10 EVs per charging point (adapted from European Commission 2023).

From 2019 on, the deployment rate of chargers has not been able to keep up with the EV adoption growth, as the EV's per charging point ratio of over 10 indicates. From 2016 to 2022, EVs' compound annual growth rate has been 50 percent, whereas chargers' 31 percent in the same period. One explanatory factor for lagging behind the EV-charger-ratio, is massive variations on country-level across European Union in this ratio. In Figure 3, the number of EVs per charger and the ratio of EVs of the total vehicle fleet, for each of EU's 27 countries and for the United Kingdom in 2022 are shown. (European commission 2023.)

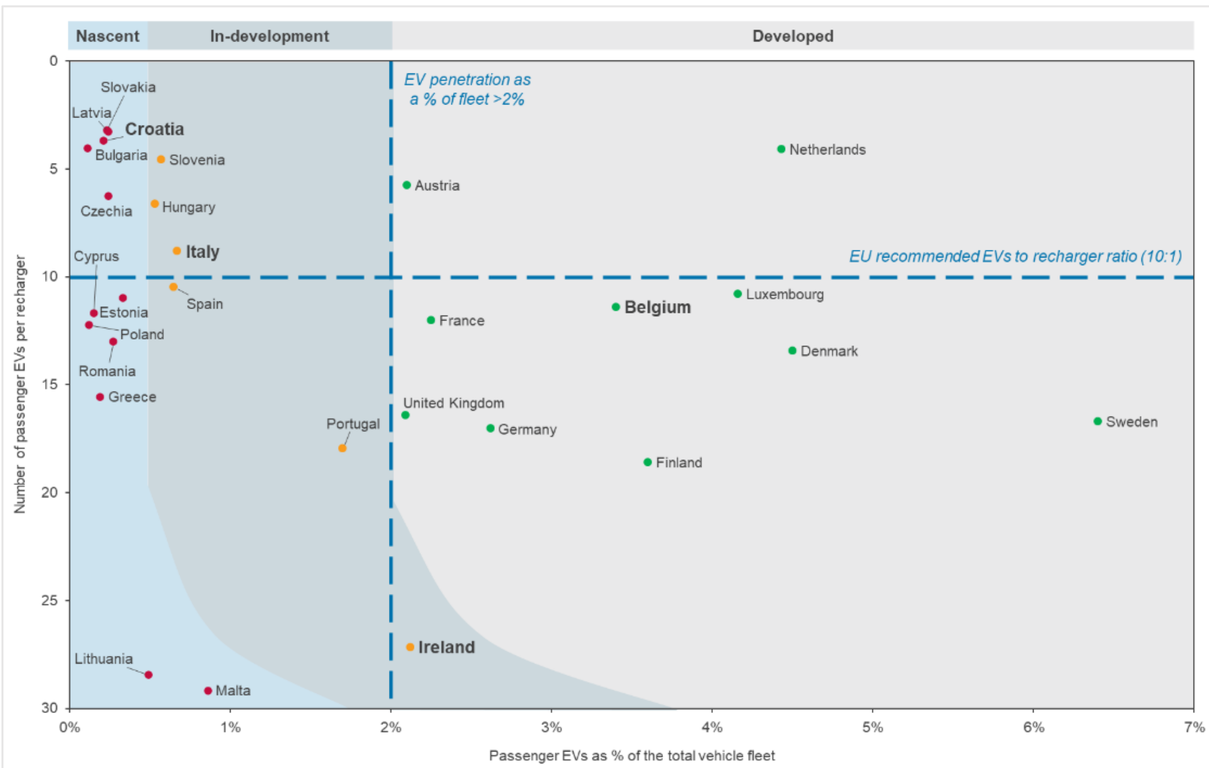

Figure 3. EU27 countries and the United Kingdom categorized by EVs per charging point and the EV share of total vehicle fleet. Data from year 2022. (adapted from European Commission 2023.) The term recharger in this context refers to a single charging point.

The Figure 3 shows that only two of the EU member countries fulfill both of the ratios, EV penetration fleet and the charging points per EV. When investigating only the EV penetration fleet recommendation, the number of member states fulfilling the criteria jumps up to eleven. Nine of the member countries do not fulfill either of those recommendations.

Another target for public charging infrastructure proposed in AFIR, was the installed charging power capacity of one kilowatt per registered BEV and 0,66 kilowatts per registered PHEV. In 2021, all of the member countries exceeded this target, and 20 of the 27 states had more than twice the capacity required. In Figure 4 the public charging power output in kilowatts per electric passenger car, i.e., LDEV, fleet is shown for each EU member state, expect Slovenia, for which data was not available. The yellow dashed line symbolizes the EU average and the red dashed the AFIR targets. The redline is weighted, according to the electric passenger car ratio in EU countries which of is 53 and 43 percent mix of BEVs and PHEVs, respectively, (Bernard et al. 2022, 2.)

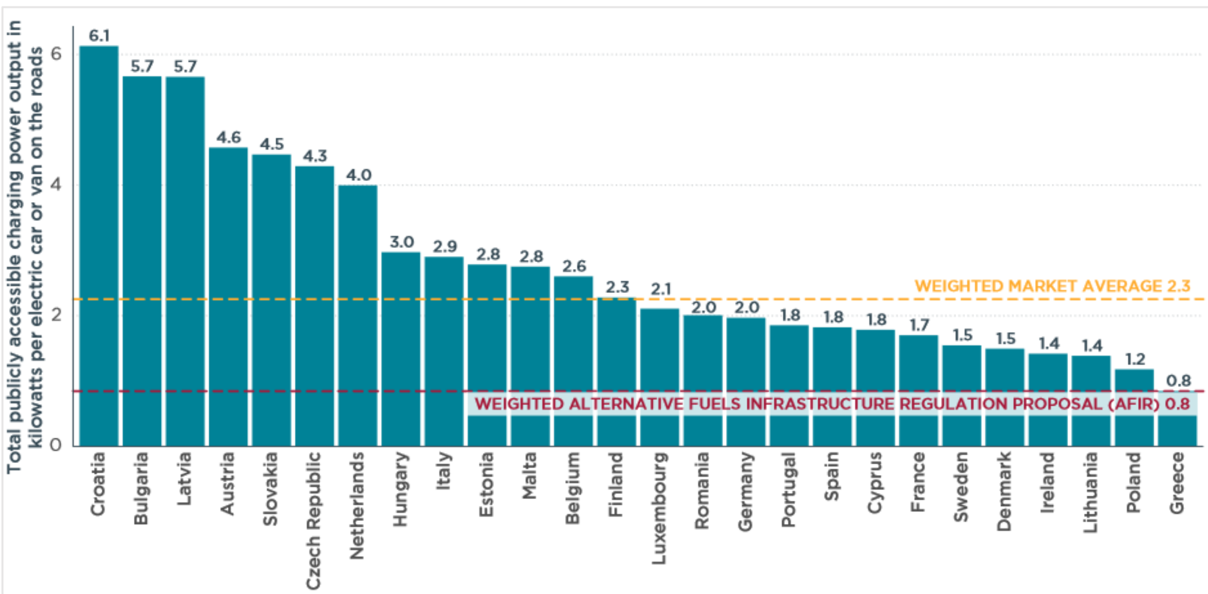

Figure 4. Total public charger power output per electric car fleet at the end of 2021 for every European Union (EU) member state. The electric car refers in this context light-duty battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). The weighted ratio is calculated with mix of 53 percent BEVs and 47 percent PHEVs of the passenger car fleet. (adapted from Bernard et al. 2022, 2.)

When comparing the Figures 3 and 4, it can be detected that the countries which were at the worse end in first chart (Figure 3), are at the top in the Figure 4. Although, seven of those have EV fleet of under one percent of total vehicle fleet, which points out a serious problem with these AFID proposals and AFIR targets. The regulation in current form does not compel additional public charging infrastructure construction. In EU member countries with low EV fleet the installed public charger power capacity can be easily reached, and those with already high EV fleet, for instance Sweden, the capacity is hard to catch up with the current EV uptake pace. (Bernard 2022, 21.)

2.4 Prospects

The projected deployment of public charging infrastructure in EU, and commonly on global level, will follow couple of main trends. Firstly, it is assumed that slow home charging will be the dominant charging style because it supports overnight charging. Additionally, the slow home charging is compatible with bidirectional and smart charging, that puts less strain on the electricity grid than public charging pools with fast chargers. Some scenarios by IEA (2023, 124) predict that in 2030, around 60 percent electricity delivered to LDEVs will come from home chargers, 30 percent will be provided by public chargers, and rest by workplace chargers. It is also projected that public charging will gain more importance over time as EV uptake increases. This is because more people without home charging access have started to buy EVs. In 2020, approximately 65 percent of the electricity supplied to LDEVs came from home chargers, while around 25 percent was from public chargers. This indicates a gradual shift toward a more public-dominant charging trend, aligning with the aforementioned projected numbers for 2030. (ECA 2021, 8; IEA 2023, 123-124.)

In light of a prospected number of charging infrastructure needed in the future, there can be found several different studies. For charging infrastructure needed to fulfill the EU's electrification and decarbonisation targets, a white paper named EV charging Masterplan for EU-27 has been conducted by the European Automobile Manufacturer's Association (ACEA) (2022). According to ACEA's utilization-driven pathway, roughly 2,9 million charging points, with a high share of fast chargers, are needed by 2030, when assuming balanced charger utilization (15 percent) and even LDEV adoption. When assuming a more demand-driven pathway where the charging network is built quickly with EV adoption and tackling the chicken-and-egg-problem in mind, but lower utilization rate (5 percent), ACEA predicts that 6,8 million charging points would be required by 2030, with a high share of AC slow chargers. Both of these assumable pathways would end up with 10 to 11 million charging points by 2050. (ACEA 2022, 22-24.)

The IEA's Global EV Outlook (2023) does back up the ACEA's utilization-driven pathway by predicting around 2,3 million public charging points in Europe by 2030, from which two million would be in the EU area (IEA 2023, 127). When predicting the number of public charging points in 2030 based on the annual growth rate of 31 percent and 442 000 charging points in 2022 (chapter 2.1), the number would be around 3,8 million.

The ACEA's (2022, 27-28) paper does also provide insight about public charging infrastructure requirements for fulfilling the AFIR's target of at least one charging pool every 60 kilometer in TEN-T core network. The prediction is that, by 2030, around 85 000 fast charging points would be deployed along the core TEN-T network to fulfill the target and serve the LDEV fleet on these roads, even on the peak times.

2.5 Possible environmental benefits of public EV charging infrastructure uptake

This chapter reviews some of the environmental benefits of public charging infrastructure. Some of the chapters have also numerical values of the benefits to provide perspective of the potential.

Decreased reliance on non-renewable resources

By replacing the conventional fossil fuel stations with electric vehicle charging stations, the dependency on non-renewable energy sources could be reduced. While fossil fuel stations rely on fossil fuels, such as gasoline and diesel, electric vehicle chargers utilize electricity from regional grid. This electricity can be produced entirely from renewable sources like wind or solar. (Filote et al. 2020; Raugei et al. 2018.) There have been several studies investigating the environmental benefits of usage or charging the EV instead of using or fuelling conventional internal combustion engine vehicle (ICEV). For example, Faria et al. (2013) found that, depending on the electric grid supply mix, driving and charging an EV, emerges roughly 60 percent less GHG emissions with respect to same size ICEV. Gargia et al. (2015) investigated the environmental impacts of changing the whole passenger car fleet of Portugal, composing of 33 percent petrol ICEVs and 67 percent of diesel ICEVs, to merely EVs. The result was 37 percent reduction in overall GHG emissions, whilst keeping the carbon intensity of electricity grid mix constant. Conclusively, the environmental benefit is proportional to the carbon intensity of the electricity grid which of the charger gets its energy. (Raugei et al. 2018.)

Reduction of GHG emissions with smart and bidirectional charging

Smart charging of EV refers to controlled charging session which is designed to optimize it considering various factors. The charging session controlling usually happens with algorithm, and these considerable factors can include, for example, the electricity demand of the grid, GHG-intensity of the grid production mix, cost of electricity, or some other preferences of the charger user. Especially, when controlling the charging sessions considering the GHG-intensity, i.e., renewable share, of the electricity production, remarkable environmental benefits can be reached compared to uncontrolled charging. (Liu et al. 2023.) According to (Dixon et al. (2020) and Liu et al. (2023), the relative GHG emission benefit of using public smart charging over uncontrolled charging is usually in the range of 16 to 30 percent.

The bidirectional charging is smart charging where the EV's battery is connected to the grid and returns excess energy to the grid when needed. In addition to the above-mentioned environmental benefits of smart charging, bidirectional charging can reduce grid frequency fluctuations, preventing breakdowns and indirect GHG emissions from repairs, grid infrastructure support which potentially could reduce the need for GHG emissions of grid upgrades, and return excess energy to the grid when the electricity production would be otherwise with non-renewable sources or demand is high. (Blumberg et al. 2023.)

Minimal infrastructure impact and surrounding nature disruption

The public electric vehicle chargers are compact and occupy minimal space. The adoption of public vehicle charging infrastructure is easy since it can be integrated into various areas and leverage existing electrical grids. Thus, removing the need to make substantial infrastructural modifications around it. When compared, for example, with fossil fuel stations, where there is a requirement for storage tanks, pipelines, and transportation networks, the environmental impacts of the surrounding infrastructure of public charging stations are minimal. (Huang et al. 2019.)

The minimal surrounding infrastructure need comes in hand-to-hand with flexible positioning. The flexible positioning enables the positioning in places where they curtail the environmental impacts in terms of land use and habitat disruption. (Filote et al. 2020; Huang et al. 2019.) Pardo-Bosch et al. (2019) also highlight how easily public chargers and stations can be repositioned. This capability helps to reduce the environmental impacts by possibly avoiding the need to manufacture new charging stations.

3 Principles and methodology of Product Carbon Footprint assessment

This chapter will go through the basic methodology and principles that will be used in this master's thesis to conduct a Product Carbon Footprint (PCF) assessment. Since performing a PCF study is based on Life Cycle Assessment (LCA), the first subchapter 3.1 will have an overview about the standards ISO 14040 and ISO 14044 that are the main standards for LCA. The second subchapter 3.2 will introduce the main standard for PCF assessment ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and Greenhouse Gas Protocol's (2011) Product Life Cycle Accounting and Reporting Standard (referred to as the Product Standard).

In the ISO standards and GHG Protocol's guidelines, terms "shall" and "should" have precise meanings. "Shall" indicates a requirement and "should" indicates recommendation. (GHG Protocol 2011, 13.) These term principles are also followed in this master's thesis.

3.1 Life Cycle Assessment – ISO 14040 & ISO 14044

LCA usually divides to four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and result interpretation. The LCA studies base on and conform to the ISO standards 14040 and 14044. (ILCD 2010; ISO 14040:2006.) Next up, the four forementioned phases are introduced.

Goal and Scope definition

The goal and scope definition phase is the first step when conducting a LCA. The goal of the study has to define the planned application, the motive for performing the study, target audience and publicity of the study. (ISO 14040:2006, 4.) The scope of the study should describe at least the upcoming items.

Product system under study and the functionalities of it. Product system describes the whole scheme with all the individual unit processes, elementary flows, product flows and models the life cycle of the product (ISO 14040:2006, 4). Unit processes are the individual functions throughout the product life cycle, such as material manufacturing process. Between the unit processes there can be multiple flows, like energy, water, co-products, waste. (ISO 14040:2006, 9-10.) The product system is outlined with system boundaries. System boundaries describe which of the unit processes are part of the product system and which are left out. The criteria used in outlining shall be transparently shown. (ISO 14040:2006, 5, 7). A picture is a common way to illustrate system boundaries.

The functional unit (FU) and reference flow. FU is a quantified description of the product system or function of a product, and it acts as a reference basis for the calculations. For instance, FU for electronic device could be 100 kW of power provided in a day. Reference flow is the quantified amount of outputs from the product system under study to fulfill the performance described in the functional unit, e.g., one product with spare parts. (ISO 14040:2006, 4-5.)

Allocation methods. Shortly, allocation means dividing the input and output flows of a process between the product system, due to the fact that few processes produce a single output or have linearity between inputs and outputs. Allocation is generally avoided by either dividing unit processes into two or more smaller sub-processes or by expanding the whole product system. Either way, the allocation cannot be avoided all the time and then it is based on the product's physical characteristics or other characteristics like economical value. (ISO 14044:2006, 14.)

Data requirements. Indicates the characteristics of the data required for the study. Gathered data is typically categorized into two different sets: primary and secondary data. Primary data is data collected from direct measurements or calculations at its original source. Secondary data is data obtained from other sources than primary data, such as scientific articles or related studies. The data requirements may vary during the work while the system under study becomes more familiar. (ILCD 2010, 137; ISO 14040:2006, 13.) For the data, also quality requirements are set in the scope phase. Quality requirements include, for example, the sources, exactness, time-related coverage, geographical coverage, and representativeness of the data. Also, the missing data has to be reported and the reason for lacking it. (ISO 14044:2006, 10.)

Assumptions and limitations. Major assumptions of the study should be introduced in the scope phase. The assumptions are usually modified and revised during the study. Assumptions and limitations also have effect to the comparability of the study to other studies and therefore they should be set carefully. (ISO 14044:2006, vi, 7.)

Some other elements that should also be introduced in the scope phase are value choices and optional elements, LCIA methodology and types of impacts, and interpretation to be used. Furthermore, the type and format of the report required for the study and type of critical review, if any, have to be stated. (ISO 14044:2006, 7.)

Life Cycle Inventory analysis

Life cycle inventory analysis is about collecting data, quantifying the relevant inputs and outputs of the product system, and presenting the calculation methods behind the quantification. The goal and scope phase provides a preliminary plan for performing the LCI stage. (ISO 14040:2006, 13; ISO 14044:2006, 11.) The main stages of the LCI phase are presented in Figure 5.

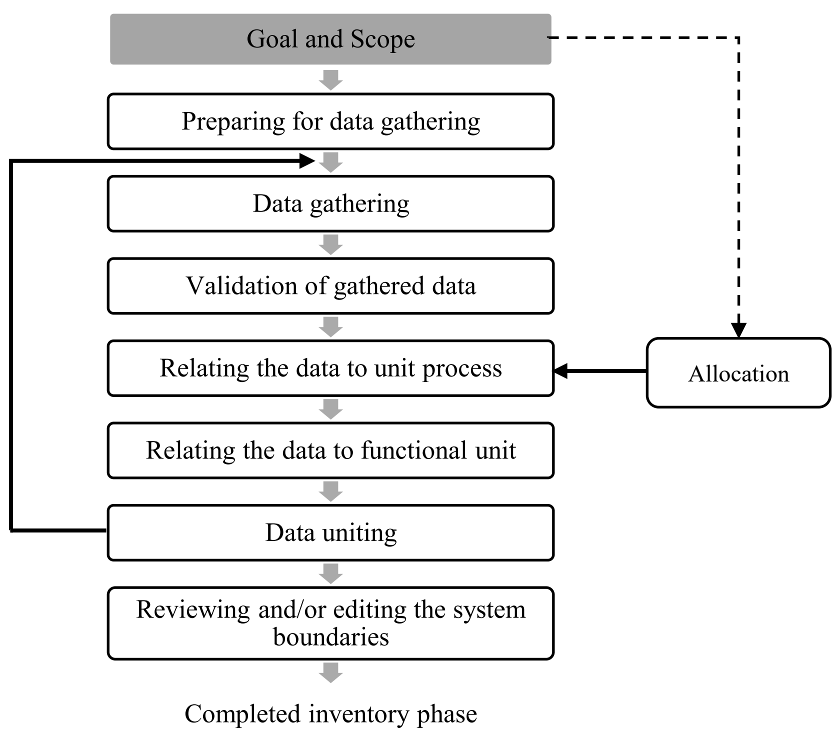

Figure 5. Main stages of the life cycle inventory analysis (imitating ISO 14044:2006, 12).

Data for every unit process inside the system boundaries should be presented. Data includes flows for products, co-products, waste, emissions to air, discharges to soil and water, other environmental attributes, energy, raw material, supplementary inputs, and other physical inputs. This activity data can be either aforementioned primary or secondary data. Data gathering does also include collection of emission factors (EF), that are used in the data relation. EFs are numbers that describe the GHG emissions per unit of activity data, for example carbon dioxide released per kilometer driven, CO_2/km. The source of the data and description of each unit process should be described according to goal and scope of the study to avoid any misunderstandings. Data collection is time-consuming process, and enough time should be allotted for it. (GHG Protocol 2011, 52, 88; ISO 14044:2006, 11; ISO 14040:2006, 13.)

After data collection, the calculation methods are presented. All of them should be thoroughly presented with the assumptions and explanations. When determining the elementary flows related to the production, the production mix should be clearly stated whenever possible. As an example, for the used electricity the production and delivery of electricity, the efficiencies of fuel combustion, transmission, conversion, and the distribution losses shall be considered. When converting combustible material input or output to relevant energy flow, the calculation formulas shall state the used heating value, whether it is lower or higher. (ISO 14044:2006, 13.)

Validation and relating the data to unit processes as well as to the functional unit are the next steps in the LCI phase. Validation of data can be executed, for instance, by conducting mass and energy balances or using comparative analyses of the EFs. For each unit process, a quantified input and output flow shall be formed. (ISO 14044:2006, 13). This is usually done by multiplying the collected activity data with the corresponding EF (eq. 1) (GHG Protocol 2011, 88).

$$unit\ process\ flow\ \left[\frac{GHG}{unit\ process\ flow}\right] = activitity\ data\ [unit] \times EF\ \left[\frac{GHG}{unit}\right] \qquad (1)$$

Lastly, if not already done in data data-gathering phase, all the unit process flows should be related to the FU. The ‘inventory result’ or ‘completed inventory’ terms refer to a sum of the unit process flows that the product system consists of and are in unit of GHG/FU. (ISO 14044:2006, 13.)

Due to the iterative nature of the LCA process, the system boundaries are typically modified in the data-gathering and calculation process. Thereby, all decisions regarding data incorporation in the study shall be based on a preliminary analysis. As a possible consequence of the preliminary analysis, there may be an exclusion of unit processes, inputs, or outputs due to lack of significance. On the other hand, there may be the inclusion of new unit processes, inputs, or outputs if they are proven significant. (ISO 14044:2006, 13.)

The last part of LCI is allocation. As mentioned earlier, the main type of action with allocation is to avoid it by unit process subdivision or product system expansion. These terms as actions, indicate literally the words themselves. In cases where the subdivision or system expansion actions are not possible, then the partitioning of the flows according to the physical properties of them is the primary method. The secondary method after physical property-based allocation is to use other relationships that reflect the best way possible input and outputs of the process under allocation. (ISO 14044:2006, 14.) An example of two different physical property-based allocation methods is illustrated in Figure 6.

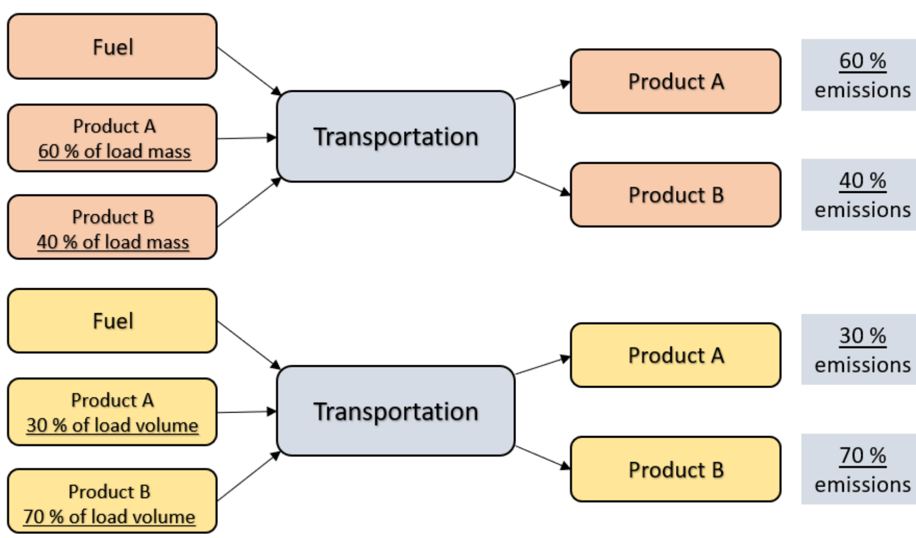

Figure 6. Example of mass- and volume-based allocation methods for transportation process. The results can be quite different and therefore the method that is considered to be the most conservative is chosen. (imitating GHG Protocol 2011, 68.)

For recycling and reuse impact allocation, ISO 14044:2006 (14-15) identifies closed-loop or open-loop allocation procedures. These allocation methods are introduced in more depth in chapter 3.2.2 More information and illustrative examples of allocation can be found from ISO 14049:2012 Environmental management – Life cycle assessment – Illustrative examples of how to apply ISO 14044 to goal and scope definition and inventory analysis -standard.

Life Cycle Impact Assessment

The life cycle impact assessment stage in LCA aims to assess the importance of plausible environmental impacts on the grounds of the LCI results. Generally, the data results from LCI are connected to the specific environmental impact categories and category indicators chosen under study. One function of the LCIA phase is to grant information for the interpretation phase. The chosen impact categories, category indicators, and characterization models shall be transparently presented with the correct names and the outlining and choices must be justified. (ISO 14040:2006, 14.) Figure 7 presents the mandatory and optional elements of the LCIA phase including an example of climate change as a chosen impact category.

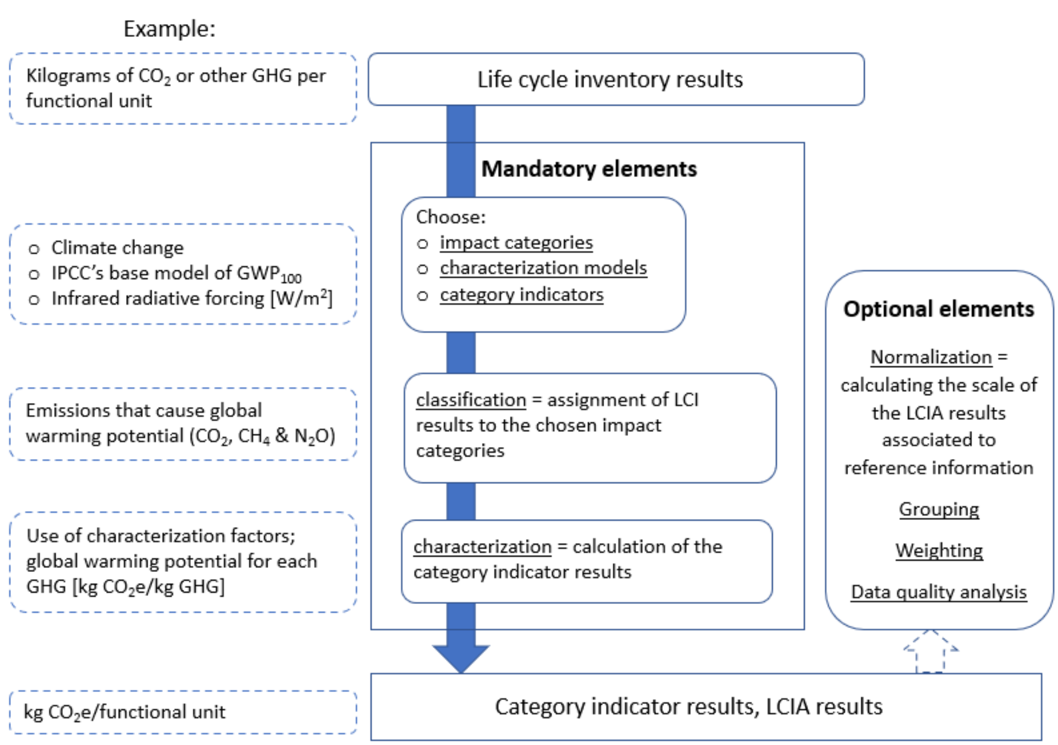

Figure 7. Mandatory and optional elements of the life cycle impact assessment phase in life cycle assessments. Examples of the elements are presented on the left, where climate change has been selected as an impact category. (imitating ISO 14040:2006, 13-14; ISO 14044:2006, 18).

Since the emissions come in different shapes and formats from actions and processes, impact categories are needed. With impact categories the different kinds of emissions are translated into uniform numbers by classifying. This means that different emissions that cause the same impact are converted into one unit that indicates a certain impact category. For instance, the impact category climate change is indicated in kilograms of carbon dioxide equivalents, $kgCO_2e$. The relationship between LCI -stage results, category indicators and possible category endpoints are described with characterization models. The characterization, i.e., quantification of the category indicator results, happens by using characterization factors that are selected according to the characterization model chosen. (Ecochain 2023; ISO 14044:2006, 6, 17, 20.) The calculus of characterization is shown in equation 2 (GHG Protocol 2011, 88). More examples of impact categories and characterization models can be found from ISO 14049:2012.

$$category\ indicator\ results\ = inventory\ results\ \times characterization\ factor \qquad (2)$$

The optional elements can be included in the LCIA phase if stated in the goal and scope definition. The optional elements are normalization, weighting, grouping, and data quality analysis. Normalization expresses the impact potentials to reference information to provide the study in a standard scale that can be understood. The reference information can be, for instance, the chosen reference unit. Weighting uses value-based numerical values to combine or convert the category indicator results. Weighting is always done after the normalization. Grouping sorts of the impact categories and plausibly ranks them. The reliability of the category indicator results is checked in the data quality analysis. (ISO 14044:2006, 20-21.)

Life Cycle Interpretation

The main goals of the life cycle interpretation phase are to analyze the results, explain the limitations, give recommendations based on the findings from the preceding LCA stages, and draw conclusions. The interpretation phase can be divided to three parts: recognition of the major issues, evaluation part where completeness, sensitivity and consistency check are made, and lastly the conclusion drawing, limitation explanation and recommendation part. (ISO 14040:2006, 16; ISO 14044:2006, 23-24.)

Identification of the significant issues is usually made by structuring the LCI and LCIA data in different kinds of tables. These tables can be, for example, conducted by individual life cycle stages in function of the LCI input and output flow data. After that, the tables can be used to recognize the most dominant, contributing, or influencing flows or unit processes. The identification of the significant issues can be only done after the LCI and LCIA results have met the demands of the goal and scope of the study. (ISO 14044:2006, 25.)

The evaluation part of the interpretation shall consolidate, increase the reliability of, and enhance the assurance of the results of the LCI and LCIA phases. A completeness check investigates how complete the inventory formed is and are the cut-off criteria fulfilled. If not complete, the preceding phases should be visited and more and better data gathered. A sensitivity check assesses the reliability of the final results and conclusions. It is usually conducted through scenario analysis and uncertainty computations. The consistency check is for evaluating the data, assumptions, and methods consistent with the goal and scope. Especially, the data quality, references, allocation criteria, normalization, and weighting are usually factors that have inconsistencies and therefore should be paid attention to. (ISO 14044:2006, 25-27.)

The final, conclusion and recommendation step, shall interpret the results to the intended audience, and determine the most impactful life cycle stages or products for human health and the environment. The recommendations shall be based on final conclusions and relate to the planned application. (ISO 14044:2006, 27.)

3.2 PCF – ISO 14067 & GHG Protocol's Product Standard

In this chapter, the ISO 14067 -standard and GHG protocol's Product Standard (2011) are presented since those are used as guidelines for calculating the CFs of the example products in this work (chapter 4). The focus is on additional information these standards provide in addition to ISO 14040 and ISO 14044.

3.2.1 ISO 14067:2018

ISO 14067 -standard uses the same four stages as used in LCA; goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation phase. (ISO 14067:2018, 9.) Next up, we will go through these four main stages individually and introduce the additional information the ISO 14067 -standard provides to chapter 3.1.

Goal and Scope

The functional unit is always based on the product since the results are GHG emissions produced per product. The functional unit should be adopted from product category rules (PCR) or, if available, from product-specific rules (PSR). This way the comparison between similar products can be carried out. In addition, reference flow shall be defined. (ISO 14067:2018, 22.) The PCR and PSR are standardized LCA "recipes" that provide specified instructions for how the LCA should be conducted for a particular product or service.

Regarding the system boundary and the geographical scope, ISO 14067:2018 (23) states that requirements from PCR shall be adopted, if available. Usually, the PCF studies are conducted with a cradle-to-gate- or a cradle-to-grave principle. With the cradle-to-grave principle, the system boundary includes all life cycle stages from raw material acquisition to end-of-life treatment, whereas cradle-to-gate is only from raw material acquisition to the end of the manufacturing stage. (ISO 14067:2018, 23.)

The primary data has to be used, at least, in the most important unit processes. The definition of the most important process in ISO 14067 is that it contributes a minimum of 80 percent to the total CF after cut-offs. (ISO 14067:2018, 22.)

The fossil and biogenic, aircraft, and GHG emissions that arose due to direct land use shall be included in the PCF study and reported separately from each other. Optional ones to include are GHG emissions or removals of indirect land use. Also, the biogenic carbon may be included in the report if calculated. (ISO 14067:2018, 30-34.)

Other things that should be stated in the scope phase are verified service life, user of the product, and use profile information. The use profile should represent the typical usage pattern of the product in the selected market. Help for defining the use profile can be found, i.e., from PCRs, PSRs, or national guidelines. (ISO 14067:2018, 25-26.)

LCI, LCIA, and interpretation

The PCF study's LCI and result interpretation phases follow the same structure as in ISO 14040 and ISO 14044. Yet again, if PCR is available, these phases shall be performed corresponding to the requirements introduced in it (ISO 14067:2018, 27, 36-37).

LCIA of PCF study focuses on relating the emissions data of the LCI phase to product life cycle environmental impacts. The PCF study focuses only on one impact category, climate change. In PCF studies, the characterization model is the International Panel on Climate Change's (IPCC) baseline model of global warming potential over 100 years (GWP_{100}). The characterization factor of that model is the global warming potential for each greenhouse gas in unit of kilogram of carbon dioxide equivalent per kilogram of greenhouse gas, $kgCO_2e/kgGHG$. (ISO 14067:2018, 36.) The GWP_{100} values for GHGs relative to the climate change impact category are presented in Table 2.

Table 2. GWP_{100} values relative to CO_2 according to IPCC's fifth assessment report. (Myhre et al. 2013, 731).

Greenhouse gas	GWP_{100} value [$kgCO_2e/kgGHG$]
Carbon dioxide, CO_2	1
Methane, CH_4	28
Nitrous oxide, N_2O	265

As a result of the multiplication (equation 2) of inventory results and GWP_{100} values, the category indicator results are received, which are in the CFP study in unit of $kgCO_2e/FU$. If other time horizons for the global warming potential are included in the study, they must be reported separately. Whilst calculating the emissions from biogenic carbon, they must be characterized as +1 kilogram of CO_2e per kilogram of CO_2 of biogenic carbon. The carbon dioxide removal of biomass that is incoming to the product system is characterized as -1 $kgCO_2e/kgCO_2$ (ISO 14067:2018, 36.)

3.2.2 GHG Protocol's Product Life Cycle Accounting and Reporting Standard

In addition to ISO 14067, the Product Standard provides more precise information about the steps of the study and calculation guidelines. On the other hand, as not being an international standard, Product Standard based studies cannot be officially compared to competing products. (GHG protocol 2012, 5-6.) In Figure 8, the main phases of product GHG accounting and reporting according to the Product Standard are illustrated. A product's environmental impact study conducted in accordance with Product Standard, shouldn't be called by the name PCF, since this term is ISO 14067 exclusive. In the Product Standard the study is often referred to as a "product GHG inventory" or as a "GHG inventory" but to keep this paper consistent, the term PCF is used.

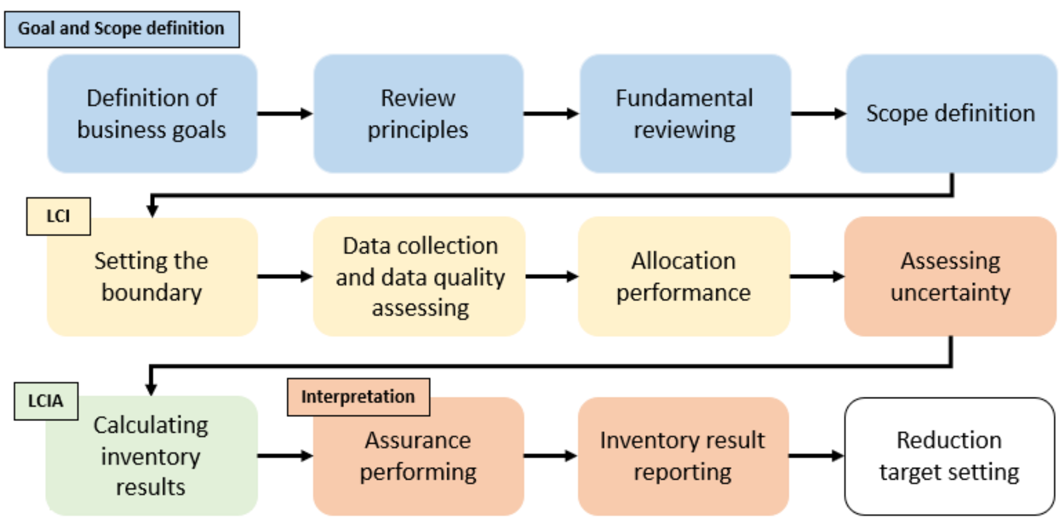

Figure 8. Main phases of PCF study conducted in accordance with GHG Protocol's Product Standard. The colour coding shows the relatedness of the stages of a CF study conducted by following Product Standard to ISO 14040 and 14044 LCA stages. (imitating GHG Protocol 2012, 13, 23.)

As we can see from the Figure 8, the Product Standard classifies the GHG inventory study to 14 different stages. The supplementary information provided by the Product Standard established in 2012, which was years before the earlier introduced ISO standards, is rather minor.

Nevertheless, some guidelines concerning the background information and recycling allocation methods are included in the following chapters.

The definition of business goals -stage (Figure 8), emphasizes the significance of reporting the reason behind conducting the PCF study. Product Standard states that business goals shall be defined before carrying out a PCF study to bring clarity and assist in selecting appropriate methodology and data for the data collection phase. The PCF study is usually conducted to serve the following business goals; climate change management, performance tracking, supplier and customer stewardship, and product differentiation. The climate change management is about identifying climate-related impacts and risks in the life cycle of the product. Performance tracking focuses on improving the environmental and economic efficiency of the product and on setting GHG emission reduction targets for the product. Product differentiation is about gaining a competitive advantage by optimizing the product to a low-emitting one and/or redesigning the product to satisfy customer preferences. (GHG Protocol 2011, 9-10.)

The Product Standard introduces more in-depth the earlier-mentioned open-loop and closed-loop allocation methods. For open-loop method, it introduces the so-called recycled content method. It is also known as “the cut-off” or the “100-0 method”. In the recycled content method all the related, i.e., attributable, unit processes for virgin and recycled material are included in the system boundary. In addition, the waste material output processes at end-of-life are included but the attributable processes due to recovered material output are left out. In the closed-loop allocation, the processes only for virgin material acquisition and pre-processing are considered in the production phase but at the end-of-life stage, both waste and recycled material attributable processes are involved inside the boundary. (GHG Protocol 2011, 72-73.) Figure 9 illustrates both closed-loop and recycled content allocation method system boundaries and attributable processes.

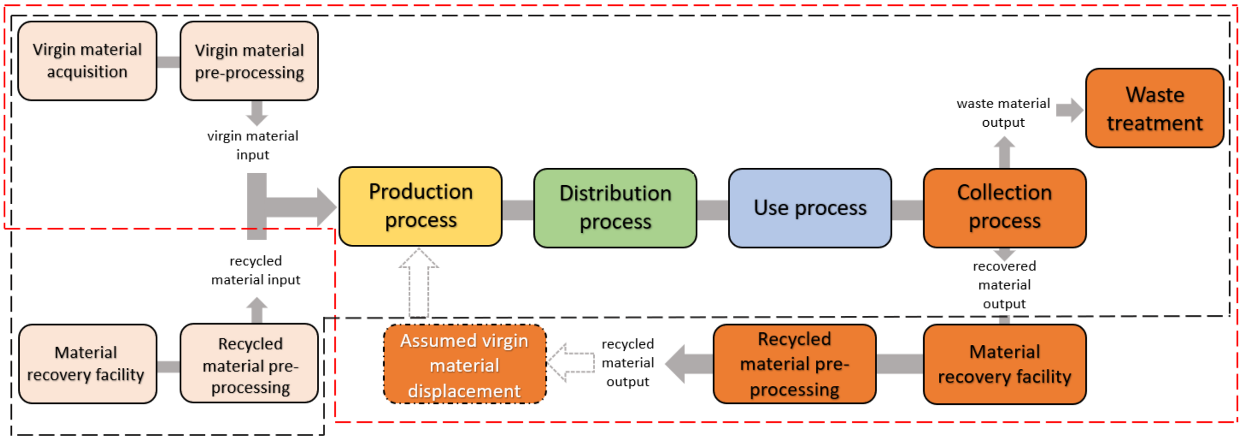

Figure 9. System boundaries and attributable processes of closed-loop and recycled content allocation methods (imitating GHG Protocol 2011, 72-73). The recycled content method's boundaries are marked with black dashed line and closed-loop's with red one.

Two potential benefits are reached with the recycled content method; the reduction of waste entering the waste treatment and reduction of the virgin material amount needed. It is possible that the virgin material acquisition and pre-processing is less GHG intensive than the recycling processes and result in lower inventory results with the virgin material input only. This is the downside of focusing only to one impact category and not considering the avoided impacts of using recycled content, like virgin material depletion. (GHG Protocol 2011, 73-74.)

For the closed-loop method, a virgin material displacement factor can be calculated. It is also known as credit or avoided emissions of virgin material displacement or substitution. This is obtained by multiplying the share of recycled material output from virgin material input by the emissions of virgin material acquisition and pre-processing. The avoided emissions of virgin material displacement have to be reported separately from the end-of-life stage total emissions. (GHG Protocol 2011, 15, 72.)

The decision between closed-loop and recycled content should be based on the following guidance. The situations when to pick the recycled content method are:

- the product contains recycled input, but no recycling happens downstream;
- the content of recycled material in the product is in hands of the company alone and thus they have control to how much recycled material input to acquire;

- the product's lifetime is long or highly unsure and therefore the amount of recoverable material is highly uncertain. (GHG Protocol 2011, 74.)

The situations when to pick the closed-loop allocation method are:

- the recycled content of the product is unknown due to the indistinguishability of the recycled material from the virgin material in the market;
- the product's lifetime is known to be short or well-known;
- the inherent properties of the recycled material do not go through remarkable changes. (GHG Protocol 2011, 74.)

In some cases, neither of the methods seem to be appropriate for the recycled content of the system. Situations like that, guidance can be acquired from product category rules, product specific rules, technical reports, or from different kinds of standards. When it is unclear which recycling allocation method is the most suitable, a scenario uncertainty analysis, for example, sensitivity analysis, should be performed and the results be reported in the interpretation stage. (GHG Protocol 2011, 74.)

4 Product Carbon Footprint assessment of Kempower Satellite and Kempower Power Unit

This chapter introduces the ISO 14067 -standard-based PCF assessment of Kempower's two EV charger products; Kempower Satellite and Kempower Power Unit. The first subchapter (4.1) will have a short review of Kempower as a company and of the products covered in this study. The rest of the subchapters (4.2 to 4.4) will follow the basis of the PCF study set by ISO 14067. The interpretation stage is included in chapter 5 and recommendations are given in chapter 6.

4.1 Kempower, Kempower Satellite, and Kempower Power Unit overview

Kempower is a Finnish listed company that designs and manufactures charging solutions for all kinds of EVs, with a main focus on direct current (DC) fast chargers for passenger cars. Kempower had about 600 employees and revenue of 72,5 million euros at the end of June 2023. Kempower's products are designed to be user-friendly, modular, and scalable. User-friendliness is achieved with Kempower's ChargEye -cloud software that provides real-time information about the charging, for example, pricing, charging status, and charging time estimates for other drivers on the move. Additionally, ChargEye reduces the downtime of the products because irregular operation can be noticed remotely, and total breakdown is avoided with preventive maintenance. Modularity and scalability of the charging systems are achieved with a chance of installing more Satellites and Power Units on existing charging sites. Since the designing and manufacturing site of Kempower products is located in Lahti, Finland, products are designed and built to withstand the harsh weather conditions of the Nordics. (Kempower 2023a.)

In this study the chosen example products are Kempower STC5ESC0 Satellite (referred to as Satellite) and Kempower C501P160ND4C0 Power Unit (referred to as Power Unit). They represent the most sold products from Kempower. Table 3 has the summarized technical data of the Satellite. A more detailed version can be found in Satellite's Technical Datasheet (Kempower 2023b).

Table 3. Product overview of Kempower STC5ESC0 Satellite (Kempower 2023b).

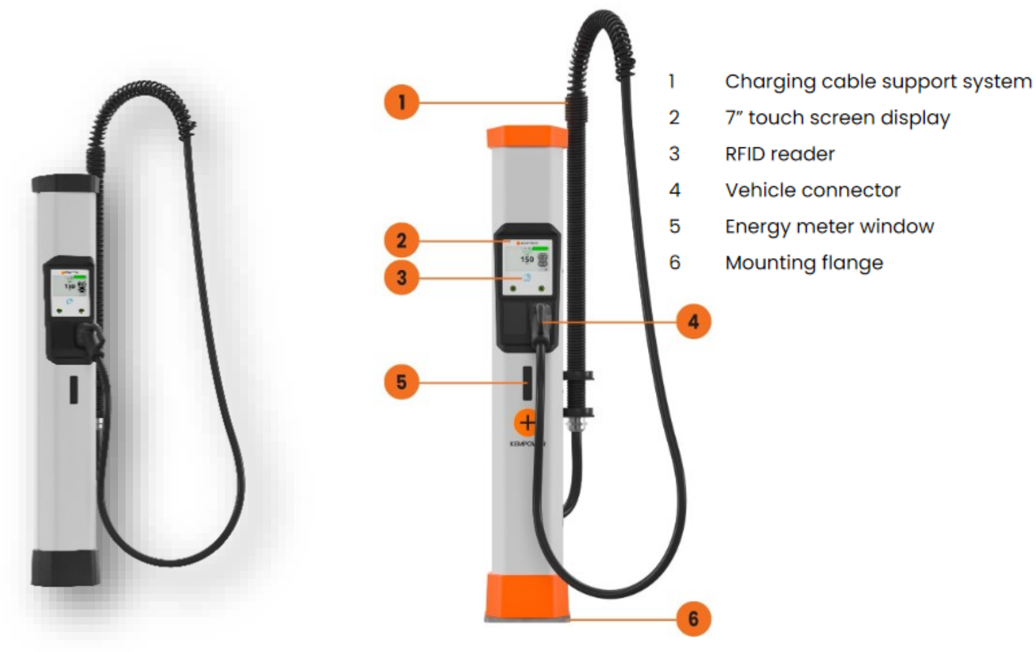

Figure 10. Kempower STC5ESC0 Satellite on left and the main components of it displayed on the right (adapted from Kempower 2023b).

Reference product	Kempower Satellite (STC5ESC0)
Description of the product	Satellite is a DC charging system for public charging. It is connected to Kempower Power Unit to provide power for it. The advantages of Satellite are an advanced cable support system, touch screen display, and connection to Kempower ChargEye which enables charging control and customization with real-time charging status tracking.
Dimensions (height & weight (including packaging))	1,7 meters & 109 kg
Output type	1 x 5-meter charging cable with CCS2 -vehicle connector
Max. charging current	300 A
Charging power at 400 V_{DC}	122 kW
Other information	The STC5ESC0 -model is unbranded (no stickers and basic, black color roof and base)

The summarized product information about the Power Unit is presented in the Table 4. More detailed version can be found from Power Unit's Technical Datasheet (Kempower 2023c).

Table 4. Product overview of Kempower C501P160ND4C0 Power Unit (Kempower 2023c).

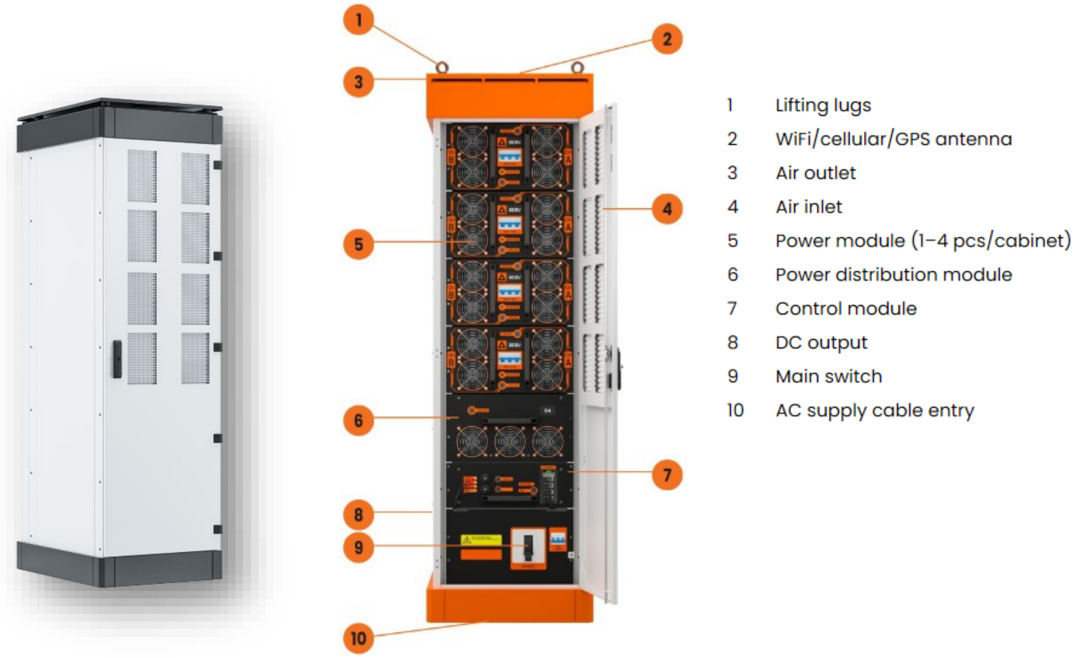

Figure 11. Kempower C501P160ND4C0 Power Unit on left and the main components of it displayed on the right (adapted from Kempower 2023c).

Reference product	Kempower Power Unit (C501P160ND4C0)
Description of the product	The Kempower Power Unit is the 'heart' and power distributor of the modular and scalable DC charging system. The Power Unit utilizes Power modules (see number 5 on Figure 11), on its unique power management system. The dynamic power management and load-sharing feature allows for the utilization of the full potential of on-demand power routing, leading to energy and cost savings.
Dimensions (width x height x depth & weight (including packaging))	650 x 2195 x 841 mm & 469 kg
Number of (50 kW) Power modules	4
Number of outputs (300 A -cables)	Up to 4 adaptive dynamic outputs 150-1000 V_{DC}
Charging power (continuous operation)	160 kW
Input current of supply cable at 400 V (continuous operation)	290 A
Other information	The C501P160ND4C0 -model is unbranded (no stickers and basic, black color roof and base)

4.2 Goal and scope definition

The goal of this study is to quantify the CFs of one Kempower Satellite and one Kempower Power Unit with cradle-to-grave principle in kilograms of CO_2 equivalents (kgCO_2e). Other goals are to determine the GHG emission hotspots within the life cycles of the products and recommend ways to reduce them. The motive of performing this study is the constantly growing environmental awareness of company stakeholders, especially customers. The results are intended for Kempower's external communicating and internal use, such as company's emission reporting and product development. The end results of this study are planned to be publicly available, since the study is conducted as a master's thesis that is uploaded to a public database. However, the detailed, provisional results, have restricted access as an Appendix 3 and may be accessed when contacted to author.

The study is conducted in accordance with ISO 14067, which was introduced in chapter 3.2.1. Some more detailed requirements and guidelines are adapted from GHG Protocol (2011) Product standard and European Standard EN 50693:2019 Product category rules for LCAs of electronic and electrical products and systems. This study is outlined as a CF study, with climate change as the impact category, instead of full LCA with multiple impact categories, due to a limited timeline, absence of an LCA modelling software, and lack of data from the component supply chain. The impact to climate change is characterized with IPCC's baseline model of global warming potential over 100 years and results are presented in unit of kilograms of CO_2 equivalents per functional unit (kgCO_2/FU). Next up, the rest of the mandatory items of the scope phase are introduced.

System under study and cut-off principles

In this study, the product system for selected products is similar and both life cycles have been studied with the cradle-to-grave principle. The life cycle is divided into six stages; component manufacturing, assembly, distribution, use, maintenance, and end-of-life. The geographical scope of the study is global. The manufacturing takes place in Finland, but the components and their materials partially originate from outside of Finland. Additionally, the distribution, use, and end of-life stages are partially modelled by using scenarios with global geographical coverage. The product system with all relevant unit processes is illustrated in Figure 12.

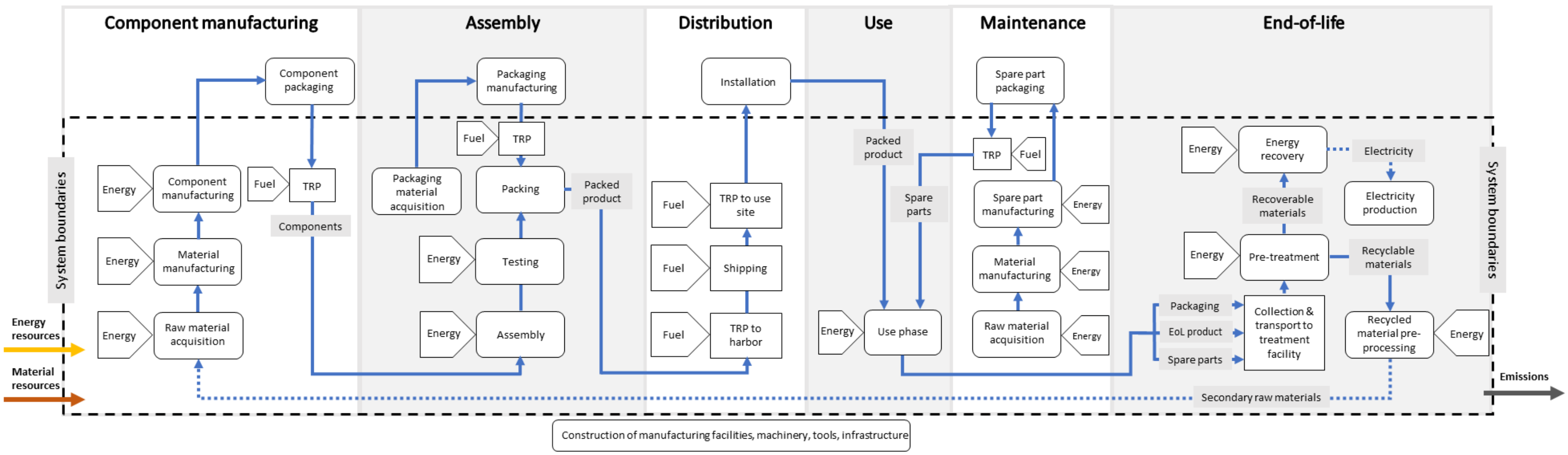

Figure 12. Product system figure with the stages of the life cycle included for the products under study (imitating EN 50693:2018, 14). TRP stands for transportation. The dashed line represents the secondary material flow derived from recycling the end-of-life product, using closed-loop allocation.

System boundaries are set to include all the relevant flows to the system, such as energy and material resources as well as emissions to the environment. Capital goods, like machinery, buildings, tools, and infrastructure are left outside the system boundary. The PCR (EN 50693:2018, 15) states this can be done when these items and their impacts are relatively hard to allocate to the reference product.

Packaging of the components and spare parts and related indirect emissions are left out of the study because information about them is challenging to obtain and the impact on the result is assumed to be negligible. For the product packaging, packaging material acquisition and transportation are included, but the product packaging manufacturing unit process is left out due to assuming its impact to results insignificant. The installation phase is left out the system boundaries because it is very site- and customer-specific.

Emissions emerging from component and spare part manufacturing from raw material unit processes are included if there are primary data available or if combined EF covering the GHG emissions of the whole component manufacturing process is found from a scientific source. Otherwise, emissions emerging from component and spare part manufacturing from raw material unit processes are cut-off due to time limit and lack of data from the supply chain. This cut-off is also justified with the fact that many of the product components are small components, such as screws, that do not assumably emerge significant emissions during the manufacturing process from raw material.

All of the material inputs are included in this study. However, when defining the material inputs for the component that has multiple low EF materials and the component mass is under 100 grams, some calculation rules were set. If a majority (≥ 75 percent) of the mass is one material, the component/part is assumed to be only that material. This is the case, for example, with the copper cables that have thin layer of plastic around the copper. This calculation rule increases the efficiency of the calculations and is not considered to have a significant impact on results. If there is found component materials that have considerably high EF and could have a significant impact on results even in small quantities, this mass-based calculation rule does not apply.

Functional unit and reference flow

Functional unit according to PCR has to define the main function delivered to the product user, quantified magnitude of the performance to accomplish the main function and declare the reference service life (RSL) of the product (EN 50693:2018, 11-12). The functional unit for Satellite is to provide 133 kWh of power per day with 99,9% efficiency, over twelve-year RSL with 365 days of operation per year. The functional unit for Power Unit is to provide 391 kWh of power per day with 94% efficiency, over twelve-year RSL with 365 days of operation per year.

The reference flow, or in this case reference product, shall include the quantitative amount of product to fulfill the declared functional unit and it should also include the intermediate flows during the life cycle, like packaging (EN 50693:2018, 12). For the Satellite, the reference product is one Kempower Satellite model STC5ESC0 delivered to the user, its packaging, use including the spare parts over RSL, and end-of-life treatment. For the Power Unit, the reference product is one Kempower Power Unit model C501P160ND4C0 delivered to the user, its packaging, use including the spare parts over RSL, and end-of-life treatment.

Data and data quality requirements

In this study, site-specific primary data, primary data sources, and average secondary data for different unit processes and flows are used. Site-specific primary data is provided by Kempower and applied whenever possible. The site-specific primary data from Kempower is mainly from 2023, which is the representative production year. In the downstream processes where the collection of primary data is not applicable, for instance, energy production mix and diesel production, secondary or generic data are used.

Generally, for data used, data sets should have been updated in the past ten years or the past five years for site-specific data, as EN 50693:2018 (18) states. To improve data quality, the data collection is focused on processes that are considered to have a significant impact on results. The technological coverage of the study is fulfilled by using primary data for the technology-related processes, like the assembly and use stage. Geographical coverage is tried to reach by aligning the data used with the operational reality of the different life cycle stages. For example, if a steel bolt is manufactured in China, EFs for Chinese steel are used.

Allocation, assumptions, assurance

Allocation is avoided by process subdivision. If allocating is unavoidable, physical property-based allocation is used. Whenever the allocation based on physical properties is not possible or considered as the best method, an allocation procedure based on other properties is used. For recycling allocation, closed-loop allocation is used for recyclable materials that do not undergo significant changes in inherent properties during recycling. The energy obtained from the energy recovery of combustible materials is assumed to substitute energy production. For these recyclable and recoverable materials, quantities of credit obtained from the virgin material displacement and energy production substitution are calculated in $kgCO_2e$ and reported separately. Since assumptions are life cycle stage-specific, they are introduced in corresponding subchapters in the LCI chapter. The assurance of the study is not included.

4.3 Life cycle inventory analysis

The life cycle inventory analysis presents the data and data collection, quantifies all the relevant inputs and outputs within the system boundaries, and the calculation methods behind the quantification. This information is organized into subchapters, each corresponding to different stages in the product life cycle. These subchapters are further divided into themes, such as transportation, packaging, and individual components.

4.3.1 Component manufacturing

The Satellite and Power Unit are composed of multiple components, which of many are made of variation of materials. The products are compliant to the substance restrictions in the EU RoHS directive (2011/65/EU), which sets boundaries of certain substance use in materials. All components, parts, or subassemblies come from domestic or foreigner suppliers. The Satellite composes roughly of aluminum casing, plastic base and hat, copper cables, LCD screen, and electronic components. The main components of Power Unit are the steel frame, casing, and the electronics inside of it.

For component manufacturing phase data collection, technical data sheets and bills of material (BoM) obtained from Kempower's internal database Teamcenter was used. Excel-based part lists for the products were obtained from New Product Introduction -team. These part lists were then supplemented with the mass and material information gathered from BoMs and technical data sheets.

After the masses and materials were filled to the part lists, the material EFs were fulfilled. The EFs for materials were collected from literature sources based on geographical pertinence. The whole list of used material EFs can be found from Appendix 1. Under the following headlines is described how the corresponding components or part's environmental impact, i.e., EF or CF, was determined.

Printed circuit board assemblies (PCBAs)

In this study, the printed circuit board assemblies (PCBA) were not broken down to different materials, due to limited timeline. They were considered as individual components with one EF. The EF for PCBAs is an average from Yung et al. (2018) and Liu et al. (2015) studies. In paper by Young et al. (2018) the CF of PCBA manufactured in China. The result from that study was 282,93 $kgCO_2e/m^2$ of PCBA and by dividing that with mass of the PCBA in the study (4,2725 kg/m^2), we got an EF of 66,22 $kgCO_2e/kg$ PCBA (Yung et al. 2018). The study by Liu et al. (2015) defined carbon footprint of a 14-inch HP brand laptop manufactured in China. In that study, one of the main components of the laptop is motherboard and its emissions were 25 $kgCO_2e$ (Liu et al. 2015). According to Amazon (2023) which sells motherboards for HP's 14-inch laptop, mass of the motherboard is 1 pound which converts to about 0,4536 kilograms, from which we get EF of 55,11 $kgCO_2e$ per PCBA. As a result from these two studies, average EF of 60,67 $kgCO_2e/kg$ PCBA was acquired, which was used in this study.

LCD screen

As EF, or in this case as CF, for the LCD screen of Satellite, average of 113,75 $kgCO_2e/m^2$ of screen was used. This CF was acquired as an average of EPA's (2016) study, which covered GHG emissions of flat panel display suppliers and of VHK's (2005) paper, which reviewed methodology for European Commission's Eco-design tool. The EPA's study's (2016, 34) CF refers to Taiwanese company Innolux's products and VHK's (2005, 88) CF for Japanese producer. This geographical pertinence was considered to be accurate enough since the Satellite's screen is produced in China. According to the technical data sheet of the LCD screen, the screen is about 0,0134 m^2 and has roughly 100 grams of different kinds of PCBA's, like a panel driver and a driver circuit chip.

Fuses

The cartridge and ferrule fuses were considered to be fully copper, because the total mass of them in products was calculated to be relatively small, under 100 grams. Truthfully, cartridge fuses consist of also quartz sand and ceramics, but environmental impacts for these materials are very small compared to coppers about 4 $kgCO_2e/kg$. For one metric ton of quartz sand, the impact is about 50-90 $kgCO_2e$ (Heidari & Anctil 2022, 6-7; IFRB 2021).

Component transportation

The purchasing team provided the components'/parts' countries of origin and supplier locations. The transportation distances for land carriage were calculated using Google Maps (2023) and for marine freight with Searates (2023). Transportation route for components that are produced overseas, had two route options depending on the supplier: from the country of origin to Helsinki, Finland, then to the supplier, and to Lahti HQ, or straight from the country of origin to Helsinki, and to Lahti HQ. This is because for some suppliers Kempower pays the transportation from the manufacturer straight to Lahti HQ. If the component was made in Finland, it was assumed that the transportation route was from the supplier straight to Lahti HQ.

According to Tulli (eng. Finnish Customs) (2023) 91,1 percent of Finland's import transports were shipped and therefore in this study the parts that come from foreign countries are assumed to be transported by marine freight when applicable. The marine transportation distances for foreign components were calculated from the most used harbor of the country of origin to Helsinki. For inland foreign component countries of origin, like Hungary, the distance was calculated from the middle of the country to Helsinki/supplier/Lahti HQ by the shortest land route, while considering which route reflects reality the best way possible. In reality, these would presumably be transported partly via sea route to Finland. Therefore, this calculation method for inland foreign countries might be a slight overestimate. For all transportation distances, marine and land, an additional 5 percent distance was added to cover the possible errors in definitions of the distances.

The land carriage was assumed to happen with diesel powered semitrucks, a maximum weight of 40 tons, with an 80 percent load rate. This is due to the fact that in 2018, about 80 percent of the land carriage happened with heavy, under 48-ton weight trucks in Finland (VTT 2021). In addition, according to Lehtilä et al. (2021, 35), the share of diesel engines is around 95 percent in heavy traffic field, and the number is assumed to not drop under 90 percent by the end of 2030. The EFs for the land transport were adapted from CO2data's (2022) Kuljetukset -report. The CO2data is an EF database that is based mostly on EPDs and scientific reports. It is maintained by the Finnish Environmental Institute. The EFs for land transport in that report are presented individually for different maximum weight diesel trucks, by the load rate, and by type of driving, urban or highway. The EFs are in unit of gCO_2e/tkm, where ‘tkm’ stands for ton-kilometer and describes the transportation of one ton of cargo over one kilometer. Since these land transport EFs are only tank-to-wheels values, which means they do not include the production of diesel, the production EF for diesel had to be calculated. EF for diesel production, i.e., well-to-tank EF, on average in Europe is about 18,857 gCO_2e/MJ_{diesel} (Prussi et al. 2020, 201). To change this value to unit of gCO_2e/l_{diesel}, a density of 0,803 kg/l_{diesel} and a lower heating value of 42,9 MJ/kg_{diesel} was used (STAT 2023). By multiplying these three values, the EF for diesel production was received, 649,56 gCO_2e/l_{diesel}. By dividing the diesel production value of 649,56 gCO_2e/l_{diesel} with the diesel mix combustion value of 3051,72 gCO_2e/l_{diesel}, which has been used to calculate the transportation in the Kuljetukset -report (2022), we got a fraction of 0,27 (= 27,773%). This adjustment factor describes, how much had to be added to the Kuljetukset -report values to get the well-to-wheel (WTW) EFs for land transportation, including the production and combustion of diesel fuel. For example, for the 40-ton semi-truck with an 80 percent load rate, driving on a highway, the WTW EF is the following:

$$EF_{WTW} - semitruck\ (40\ t), load\ rate\ 80\%, HW = 57{,}71\frac{gCO_2e}{tkm} \times (1 + 27{,}773)$$
$$= 73{,}7\frac{gCO_2e}{tkm}$$

An average container ship was assumed to be used for all the marine freight in this study. The EFs were adapted from Clean Cargo’s (2023) study 2022 Global Ocean Container Greenhouse Gas Emission Intensities. This report is based on data that describes about 85 percent of global ocean container freight capacity by volume, and it considers the full life cycle from fuel production to combustion. The Clean Cargo’s (2023) data has also gone through a third-party verification. The used EFs in this study are for a 70 percent load rate, for non-refrigerated containers and the values are in unit of gCO_2e/TEU-km. TEU stands for a twenty-foot-equivalent unit, which refers to a shipping container that is twenty feet long. Therefore, TEU-km is one twenty-foot container transported for one kilometer. The weight capacity of one TEU is 28 200 kilograms and the empty weight is 2 280 kilograms, from which the fully laden weight calculated is 30 480 kilograms (Marineinsight.com 2022). Since the EFs in Clean Cargo’s (2023) report were for a 70 percent load rate, this means about 0,70 * 30 480 kg = 21 336 kilograms of load per container, or 21,336 t/TEU. With this information the marine cargo EFs can be converted from unit of gCO_2e/TEU-km to gCO_2e/tkm, to ease down the calculations. In Table 5, EFs for marine and land transportation used in this component manufacturing stage are presented.

Table 5. Emission factors (EF) used for different transportation modes in component manufacturing life cycle stage (CO2data 2022; Clean Cargo 2023).

Route/Geographical representativeness	EF [gCO_2e/TEUkm]	EF [gCO_2e/tkm]
Land transportation		
Semitruck (max weight 40 t), load rate 80%, highway driving (EUR)	-	73,7
Marine transportation – 'Container ship (TEU), load rate 70%'		
North Europe to-from Asia	39,6	1,86
North Europe to-from North America East Coast	88,9	4,17
North Europe internal	140,3	6,58
North Europe to-from Mediterranean/Black Sea	73,1	3,43
North Europe to-from South or Central America	81,6	3,82
North Europe to-from Oceania (via Suez)	81,9	3,84
North Europe to-from Middle East/India	63,2	2,96

After the transportation distances and transportation mode EFs were determined, they were fulfilled to the list with component country of origins and supplier locations. Thus, receiving the GHG emissions of transportation in the component manufacturing life cycle stage.

4.3.2 Assembly

In the Lahti HQ, the different components and possible subassemblies are assembled into one product. The Power Unit's Power Module assembly is under Kempower's control, and they are assembled in Kempower's second manufacturing facility, Lahti 3. All the other components and subassemblies come from suppliers. The assembly of products and Power Modules happens in a staged assembly line. After the product is assembled, it is tested for any faults and then packed. All of these mentioned stages are manpowered and carried out using cordless tools and computers. The energy usage in the testing and assembly stages is considered negligible, since they are about couple kilowatt-hours combined per product assembled, according to the production engineers. In addition, the chemical usage is negligibly small and therefore left out of the study. In the assembly stage of the products, minimal material losses occur, due to optimized design and use of all components. Thus, the impact of material losses is also assumed insignificant.

Product packaging

The CFs of the packaging's materials and transportation were defined the same way as individual components in the component manufacturing stage. The same transportation types and principles for defining the transportation distances and routes were used. Satellite's packaging consists of a custom-size pallet (2150 x 600 x 119 mm), a plywood box with metal supports in corners and on the lid, and zip ties and screws. The Power Unit is packed on a EUR-pallet (800 x 1200 mm), fixed on with metal brackets, and covered with a plywood sheet, some cardboard, and plastic film. Since, most of the packaging is wood, the biogenic uptake, i.e., removals, was also included in this study. EFs and biogenic uptakes for the wooden materials were mostly taken from VTT's (2013, 22-116) report that defined the carbon footprints of building materials. The rest of the EFs were adapted from the same sources as in the component manufacturing chapter and can be found in Appendix 1.

4.3.3 Distribution

The distribution stage begins after the products are packed and ends when the product is delivered to the customer. All of the products assembled and packaged in Lahti HQ are loaded onto trucks with electric and diesel forklifts. The consumption of electricity and diesel of the forklifts are considered negligible per product because the conveyance distances are hundreds of meters. From HQ the products are delivered to the customers mainly with full-trailer trucks.

The distribution route and distance naturally vary by customer location. Therefore, for distribution, four distribution options were formed. The distribution options were formed using the Kempower (2023c, 8) 2023 half-year financial report's revenue numbers by geographical regions. The transportation distances were evaluated with Searates (2023) and Google Maps (2023). The distribution option descriptions, transportation distances and shares of revenue are presented below.

Nordics

- 500 km marine transport from Helsinki to Stockholm & 700 km of land transport within Nordics
- Includes sales to Finland, Sweden, Norway, Denmark, and Iceland
- Presents 40 percent of the Kempower's revenue (Kempower 2023a, 8).

Rest of the Europe (RoE)

- 1 200 km of marine transport form Helsinki to Lübeck & 2 500 km of land transport within Europe
- Includes sales to rest of the continental Europe than Nordics, excluding Russia
- Presents 51 percent of the Kempower's revenue (Kempower 2023a, 8).

North America (NA)

- 7 600 km of marine transport from Helsinki to New York & 4 500 km of land transport within Nort-America
- Includes sales to United States and Canada
- Presents 2 percent of the Kempower's revenue (Kempower 2023a, 8).

Rest of the World (RoW)

- 23 000 km of marine transport & 2 000 km of land transport
- Presents 7 percent of the Kempower's revenue (Kempower 2023a, 8).

For modelling the land transportation diesel-powered full-trailer truck, with maximum weight of 60 tons and 80 percent load rate, was used. The EF for this vehicle type is 57,8 gCO_2e/tkm. For the marine transportation of the products, a container ship with 70 percent load rate was assumed to be used. Marine transportation EFs for respective routes can be found from Table 5.

For marine distribution, the allocation of emissions per TEU transported to the product transported, volume-based allocation was used instead of mass-based allocation. This was due to size of the packed products. The interior dimensions of a TEU are 5,898 meters long, 2,352 meters wide, and 2,393 meters high (iContainers 2013). By using the packaging information and products' dimensions, number of 27 Satellites per TEU was obtained. For Power Unit, respective number was 11.

After the transportation distances, used EFs, and GHG emissions for each distribution option were determined, a revenue share based weighted average (equation 3) of the distribution option GHG emissions was calculated.

$$Distribution\ stage\ GHG\ emissions = \sum_{i=1}^{n} (\% - share\ of\ revenue)_i \times (GHG\ emissions\ of\ transportation)_i \quad (3)$$

where i is a varying distribution option [Nordics, RoE, NA, RoW].

The revenue-based weighted average of transportation GHG emissions was calculated to get one number that represents the whole distribution stage CF. Additionally, this number is used in the maintenance life cycle stage as spare part transportation distance.

4.3.4 Use

The use stage of the products consisted of GHG emissions of dissipated energy due to power losses during charging and of energy consumption in standby state. This is due to the fact that the products work as distributors and converters of the input energy, not as end-users. The distribution options, that were introduced in the previous chapter, were used to provide transportation distances for the spare parts and to form a revenue share-based energy model. The energy model in this context is a revenue share-based weighted average electricity production EF of the geographical areas where the products are used.

Energy dissipated during use and consumed in standby state

The dissipated energy in operation during the product reference service life (RSL), E_{DIS}, was evaluated with the equation (4):

$$E_{DIS} = \left(\frac{E_{out}}{\eta} - E_{out}\right) \times RSL \times 365\frac{d}{a} \tag{4}$$

where, E_{DIS} is dissipated energy in operation during the product reference service life [Wh], E_{out} is average energy provided per day [Wh/d], η is the efficiency of the product [-], and RSL is reference service life [a].

The energy consumed in standby state during product RSL, E_{sbs}, was calculated with equation 5:

$$E_{sbs} = P_{sbs} \times t_{sbs} \times RSL \times 365\frac{d}{a} \tag{5}$$

where, E_{sbs} is energy consumed in standby state during product reference service life [Wh], P_{sbs} is power consumed in standby state [W], and t_{sbs} is average hours in standby state per day [h/d].

The efficiency of Power Unit according to the Kempower's research, development, and innovation (RDI) department is about 94 percent. The power losses of Satellite are nearly insignificant compared to Power Unit, but since the efficiency cannot be 100 percent, 99,9 percent efficiency for the Satellite is used in this study. The powers provided per day and average hours in standby state per day were obtained from product management team, based on usage data of the product models under observation in this study. The powers consumed in standby state were obtained from technical datasheets of the products (Kempower 2023b; Kempower 2023c). These abovementioned parameters and the calculated E_{DIS} and E_{sbs} using equations 4 and 5 for both products can be found in Appendix 3 table 1.

Energy model formation

To get the dissipated and consumed energy numbers converted to emission flows, an energy model was formed. The energy model was formed with the shares of the revenue (chapter 4.3.3) and electricity production mix EFs of the continental areas of the aforementioned distribution options. For RoE-option the EF of EU-27 electricity was used because no EF for not including Nordics were found. For the RoW-option, an average of electricity EFs of roughly 200 nations around the world was used. The NA-option's electricity EF was formed by taking an average of the United States (US) and Canada's electricity EFs. The electricity EF of Nordics was created by averaging the electricity EFs of Finland, Sweden, Norway, Denmark, and Iceland. All of the used EFs in determining the energy model EF are presented in Table 6.

Table 6. Breakdown of used the energy model in the assembly stage. EF stands for emission factor. The emission factors include only the direct emission of electricity production.

Area	Electricity EF [gCO_2e/kWh]	Share of the revenue	Electricity EF description and source
RoW	435	7%	Taken as average from Carbon Footprint's (2023) country-specific electricity GHG emission factors 2021 and 2022
RoE	223	51%	EU-27 GHG emission intensity of electricity production 2021 (EEA 2023).
NA	250	2%	As an average of US and Canada
US	389		US average electricity emission factor (EPA 2023).
Canada	110		GHGs emitted in the generation of Canada's electric power (CER 2023).
Nordics	49	40%	As an average of the countries below
Finland	55		Emission factor for electricity production in Finland 2022 (Fingrid 2023).
Sweden	28		Sweden's average emissions of electricity production in 2022 (Nowtricity 2023a).
Norway	30		Norway's average emissions of electricity production in 2022 (Nowtricity 2023b).
Denmark	123		Denmark GHG emission intensity of electricity production 2021 (EEA 2023).
Iceland	8,6		CO2 intensity of electricity produced & distributed (Reykjavik Energy 2020).
Energy model EF			169 gCO_2e/kWh (= kgCO_2e/MWh)

With the energy model EF of 169 kgCO_2e/MWh, the consequential GHG emissions from energy dissipation in operation, E_{DIS}, and energy consumption in standby state, E_{sbs}, were received.

4.3.5 Maintenance

The maintenance of the products is occasional part replacement. To simplify calculations, it was assumed that the spare parts come from the Lahti HQ to the product use site. For transportation the distance, the revenue-based weighted average of the distribution option distances was used.

The distribution distance used was 1785 kilometers of land transport and 2574 kilometers of marine freight. For transportation the following transportation types were used; for land transportation diesel-powered large truck, a maximum weight of 15 tons, with an 80 percent load rate and for marine transportation global average of a container ship with a 70 percent load rate. The EFs for these land and marine transportation methods are 98,4 gCO_2e/tkm and 3,31 gCO_2e/tkm, respectively. The amounts of spare parts needed in the RSLs of the products were acquired from the Life Cycle Services-team. The manufacturing GHG emissions for each part were retrieved from the manufacturing stage.

The installation of spare parts is carried out using power tools and manual tools, and therefore the GHG emissions of installation were assumed insignificant. Additionally, the packaging of the spare parts consists mainly of cardboard and thus the impacts of them were assumed insignificant.

4.3.6 End-of-life

For end-of-life (EoL) stage, European model and data were considered to be the most representative for EoL treatment of the products. This is due to the fact that Kempower's actions take place mostly on European area referring to the revenue shares. In Europe, the European directive on waste electrical and electronic equipment (WEEE) (2012/19/EU) (referred to as WEEE directive) sets boundaries for the treatment of electrical and electronic equipment (EEE). The WEEE directive falls under the scope of extended producer responsibility legislation. Kempower as a manufacturer of EEE, has to implement the requirements set by WEEE directive. The purpose of WEEE directive is to reduce amount of WEEE, improve the environmental performance of all the operators involved in the life cycle of EEE, and try to increase the retrieval of valuable secondary raw materials. (2012/19/EU, (6)-(7).) This is implemented through different kinds of targets, like minimum collection rates, as well as minimum recovery and recycling rates for the WEEE. The products of Kempower fall under the WEEE category "Large equipment (any external dimensions more than 50 cm)". For this category, the recovery rate should be 85% and an 80% rate for recycling or reusing the EEE component material should be achieved. (2012/19/EU, Annex III, Annex V.)

The end-of-life phase of the products starts from the collection and transportation of the EoL product, packaging, and spare parts to the waste management party. The whole EoL-phase is illustrated in Figure 13.

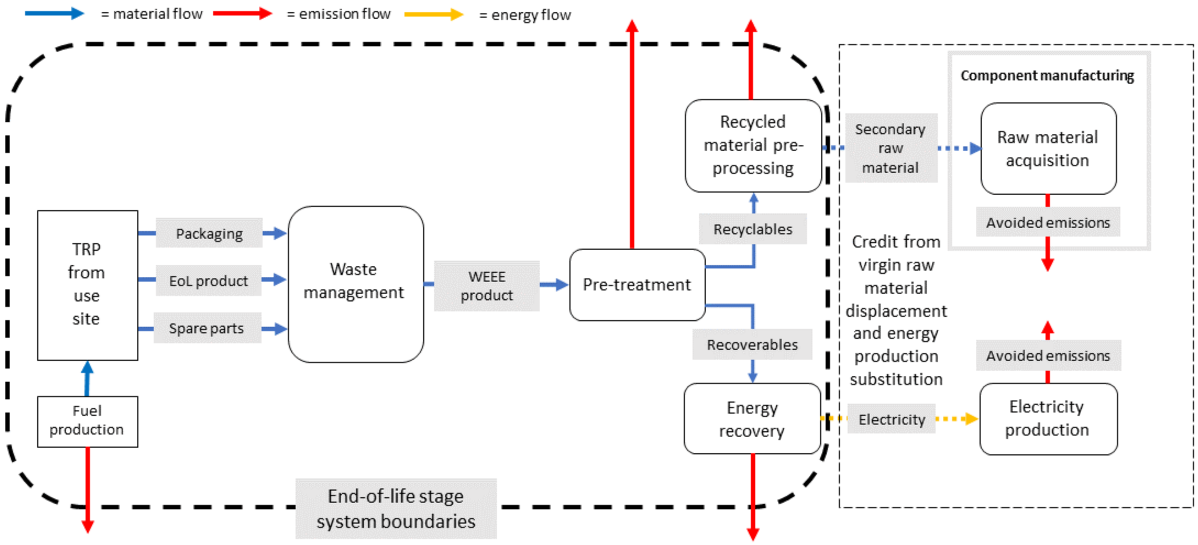

Figure 13. Product system of the end-of-life stage of the products. EoL stands for end-of-life and WEEE for waste electrical and electronic equipment. The avoided emissions refers to the credit obtained from secondary raw material displacing the virgin material input to the component manufacturing stage's raw material acquisition unit process and to credit obtained from energy recovery processes energy output substituting EU area's average electricity production (with emission factor of 223 gCO_2e/kWh).

Transportation from the use site to the waste management facility

For transportation, the revenue-based weighted average of the distribution option distances and the same vehicle types as in spare part distribution were used. To simplify the calculations, it was assumed that the product, packaging, and used spare parts (combined entity referred to as WEEE-product from now on) are all transported at the same time to waste management. The transportation types used for modeling the EoL-phase transportation were a diesel semitruck with a 40-ton maximum load (EF = 73,47 $kgCO_2e/tkm$) and an 80 percent load rate and a 70-percentile loaded container ship with a global route (EF = 3,31 $kgCO_2e/tkm$). As transportation distances, the aforementioned 1785 kilometers of land transport and 2574 of marine transport, were used. As an additional simplification, a collection rate of 100 percent was assumed for the products, meaning that the whole mass of the WEEE-product is transported to waste management without losses.

Pre-treatment, recycling, and energy recovery

In waste management center, or so-called treatment facility, the WEEE-product is first up mechanically and physically taken apart, then segregated, shredded, and sorted out into different materials (Brindhadevi et al. 2023, 2-3). For this pre-treatment, EF of 36 kgCO_2e/ton of WEEE was used, which was adapted from Dahlbo et al. study (2011). After the pre-treatment, different materials are treated with corresponding treatment processes. The WEEE-products' BoMs were based on the earlier calculation stages and categorized into recyclable and recoverable materials. The metals, PCBAs, and LCD-screen were considered to be recyclable. The rest of the materials were assumed to go energy recovery. Since all of Kempower's products are manufactured in accordance with the RoHS directive (2011/65/EU), no hazardous waste is produced, and normal recycling and recovery unit processes can be applied. The EFs for most of the recyclable material treatment processes were adapted from Y-HIILARI (2019), which is a calculation tool for company's carbon footprint definition. For material recovery from PCBAs and LCD screen, EF was adapted as an average of Turner et al. study (2015, 191) and WWF's (2018) climate change impact calculator datasheet. The EFs of recycling and recovery processes can be found in Appendix 2.

The recovery rate for the pre-treatment process was assumed 100%. For the recyclable material treatment processes the recovery rates, i.e., efficiencies, were adapted from PCR EN 50693:2019 since no specific data were found. For metals, used recovery rate was 70%, and for PCBAs' metals 50% (EN 50693:2019, 45). The energy recovery was assumed to happen with 20 percent efficiency. This assumption was based on ZeroWasteEurope's (2023) report which reviewed electricity and heat production numbers and efficiencies of waste combustion in Europe.

Credit obtained

As outputs from the recyclable material treatment processes, secondary raw material is received. This secondary raw material is assumed not to go through remarkable changes in inherent properties in recycling processes and to replace virgin material in the component manufacturing phase, in accordance with the closed-loop-allocation principles for recycling. The credits of the recycling or recovery activities were evaluated with equation 6 (EN 50693:2019, 44; GHG Protocol 2011, 72).

$$credit\ [kgCO_2e] = output\ of\ recycling\ or\ recovery\ activity\ [unit] \times average\ emissions\ from\ creditable\ process\ \left[\frac{kgCO_2e}{unit}\right] \quad (6)$$

The average emissions from the creditable process refers to emissions from the material manufacturing unit process. For example, in calculating the credit from metal recycling, the average emissions from creditable process were obtained by dividing the total GHG emissions emerging from metal material manufacturing processes by the summarized mass of metal material output of those processes. These total emissions and weight values were defined in the component manufacturing phase.

According to Kumar et al. (2018, 94-95), the PCBAs' composition is roughly 40% metals, 40% ceramics and glass, and 30% plastics. In this study, only the metal content was considered to be worth recycling and have some creditability. Since no studies for credit or avoided emissions from metal content recycling particularly of PCBAs were found, it was considered feasible to use numbers that cover the credit of metal recycling of small WEEE, since they usually contain circuit boards. In Dahlbo et al. (2011) study that covered different GHG emissions of handling and recycling of different waste types, the credit was 1,969 $kgCO_2e$/kilogram of WEEE metal waste. The study by Turner et al. (2015) reviewed emissions and credits of different source-segregated waste material recycling. The result and credit of that paper was 1,812 $kgCO_2e$/kilogram of small domestic appliances (Turner et al. 2015, 186-191). In this study, the average of these two studies was used, 1,891 $kgCO_2e$/kilogram of PCBA metals. The creditability of the LCD screen was considered insignificant due to the small size of the screen.

The materials that go to energy recovery, are assumed to substitute electricity production. Because of using European processes, the creditable electricity is average European electricity with EF of 223 gCO_2e/kWh (Table 6). In general, the fossil GHG emissions from combustion processes and LHVs were adopted from Tilastokeskus (2023) analysis that reviewed average GHG emissions and properties of different kinds of fuel combustion processes. The used energy recovery EFs and LHVs are presented in Appendix 2.

Biogenic emissions

According to ISO 14067:2018 (51), the biogenic emissions should be equal to the biogenic removals when the biomass-derived material is combusted. Therefore, the biogenic emissions and removals in this study have net zero contribution to the results.

4.4 Life cycle impact assessment

As a characterization model in this study, the IPCC's fifth assessment report's baseline model of global warming potential over 100 years (GWP_{100}) was used. The GWP_{100}-values for each GHG were introduced in Table 2. Due to the nature of the calculations and used EFs, the LCI stage results were already in unit of kilograms of CO_2 per functional unit, and no characterization was needed.

5 Results

This chapter presents the interpretation phase of the conducted PCF study. The 5.1 chapter interprets the LCIA phase results and identifies the significant contributors to these results. The chapter 5.2 interprets the results more thoroughly by life cycle stage, considers how the made assumptions and limitations have affected the results, examines the quality of used data, and carries out sensitivity analyses. The sensitivity analyses focus on the hotspots regarding the products' life cycles and parameters impacting on the hotspots. The recommendations based on this results chapter can be found in chapter 6.1.

5.1 Identification of significant contributors to the results

The CF of Kempower Satellite was calculated to be about 922 kgCO_2e per functional unit of providing 133 kWh of power per day with 99,9% efficiency, over twelve-year RSL with 365 days of operation per year. The reference product was one Kempower Satellite model STC5ESC0 delivered to the user, its packaging, use including spare parts over RSL, and end-of-life treatment. The cradle-to-gate CF was 439 kgCO_2e/FU. The biogenic CO_2 emissions were 75 kgCO_2e/FU due to packaging bio-based material combustion and biogenic CO_2 removals -75 kgCO_2e/FU resulting from packaging material carbon sequestration. As Figure 14 shows, the most contributing life cycle stages were component manufacturing, use, maintenance, and end-of-life. A summary of Satellite's PCF study results can be found in Appendix 3 table 2.

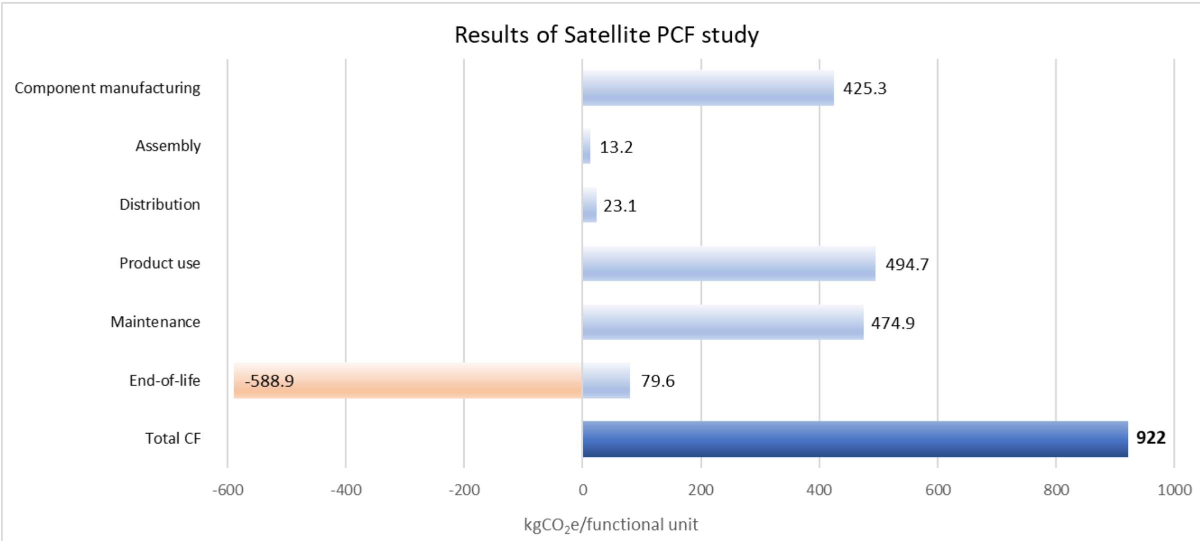

Figure 14. Results of the Satellite product carbon footprint (PCF) study by life cycle stage. The net CF of the end-of-life stage is -509 $kgCO_2e$/functional unit.

Figure 15 illustrates the Satellite CF by unit process, excluding the processes with the negative contribution.

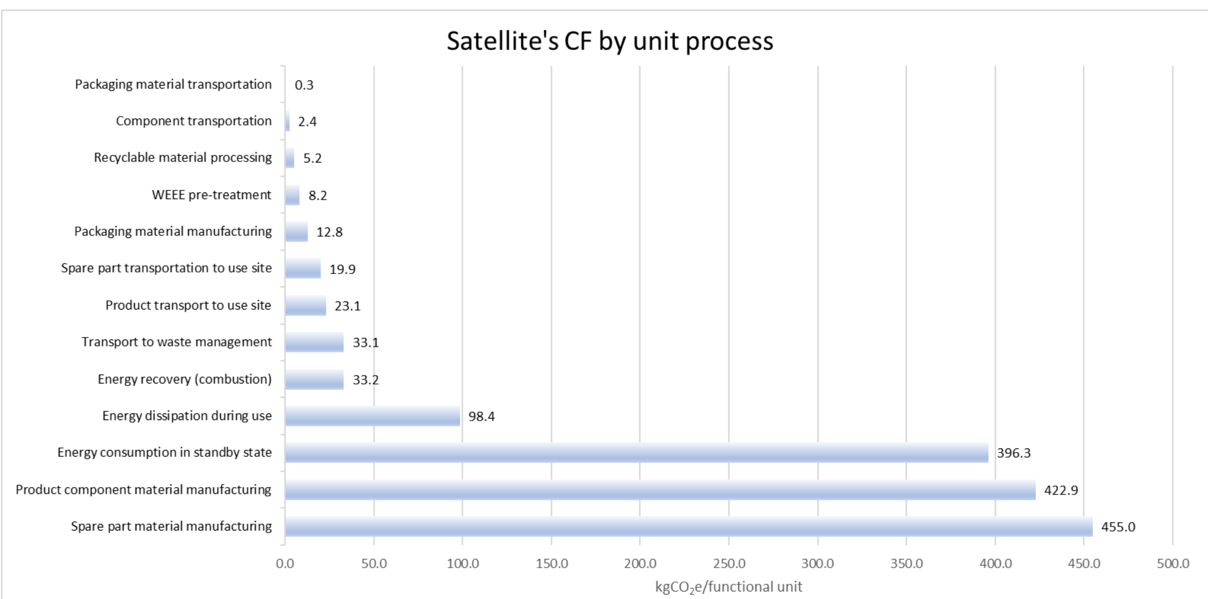

Figure 15. Satellite's CF by unit process. In ascending order by contribution. The unit processes credit from energy production substitution (-10,7 $kgCO_2e$) and credit from virgin material displacement (-578,1 $kgCO_2e$) were left out from the figure to achieve clearer layout.

Based on calculations, five significantly contributing (relative contribution of over five percent) unit processes of Satellite's CF were found. They are in descending order by absolute contribution: credit from virgin material displacement, spare part material manufacturing, component material manufacturing, energy consumption in standby state, and energy dissipation during use.

The defined CF of Power Unit was 27047 kgCO_2e per functional unit of providing 391 kWh of power per day with 94% efficiency, over twelve-year RSL with 365 days of operation per year. For Power Unit, the reference product was one Kempower Power Unit model C501P160ND4C0 delivered to the user, its packaging, use including spare parts during RSL, and end-of-life treatment. The cradle-to-gate CF was 4086 kgCO_2e/FU. The biogenic CO_2 emissions were 43,5 kgCO_2e/FU and corresponding removals -43,5 kgCO_2e/FU. The Power Unit's most contributing life cycle stages are component manufacturing, product use, and maintenance, of which product use is the most contributing by a huge margin (Figure 16). A summary of Power Unit's PCF study results can be found in Appendix 3 table 2.

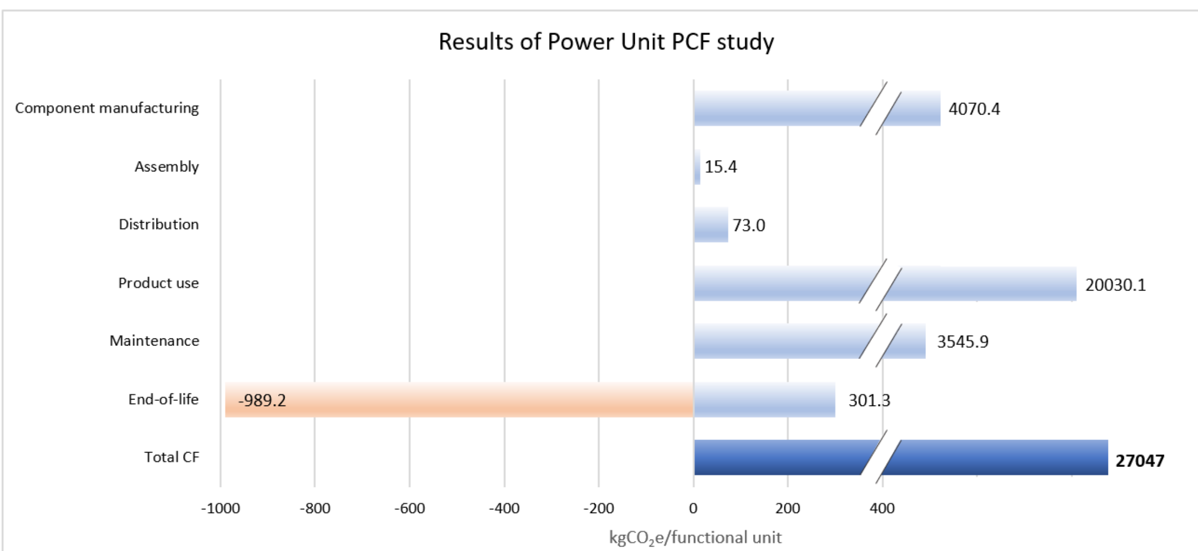

Figure 16. Results of the Power Unit product carbon footprint (PCF) study by life cycle stage. The net CF of the end-of-life stage is -688 kgCO_2e/functional unit.

Figure 17 illustrates the total Power Unit CF by unit process, excluding the processes with the negative contribution.

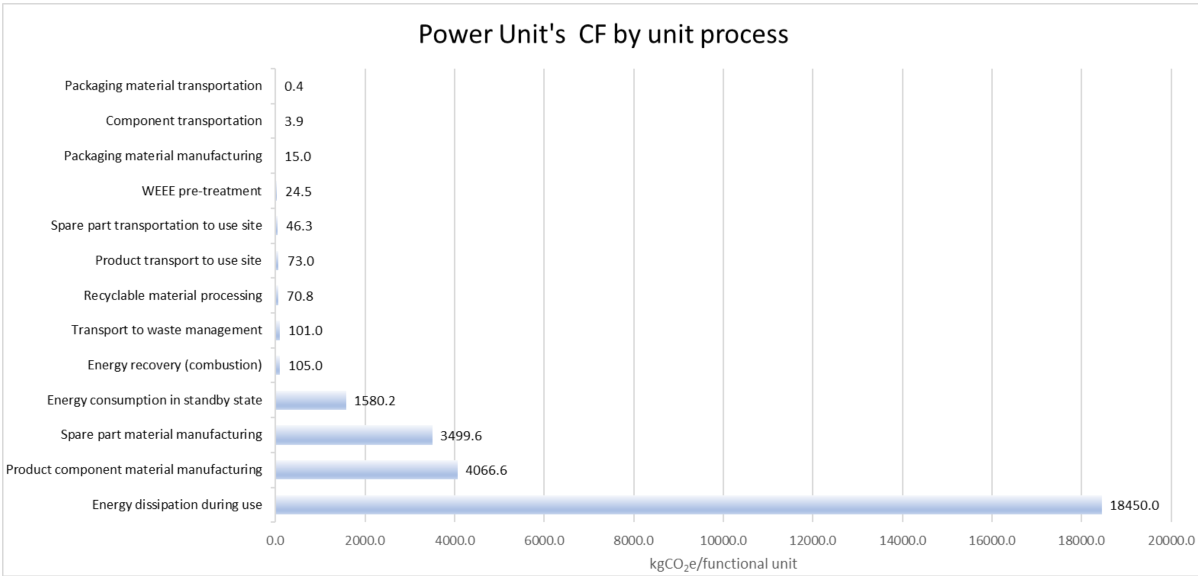

Figure 17. Power Unit's CF by unit process. In ascending order by contribution. The unit processes credit from energy production substitution (-21,1 kgCO_2e) and credit from virgin material displacement (-968,1 kgCO_2e) were left out from the figure to achieve clearer layout.

The significantly contributing unit processes follow pretty same path as Satellite. There were found four significant processes which of the energy dissipation during use was remarkably the most contributing with relative contribution of 68 percent of total CF of Power Unit. The other three significant contributors in descending order were product component material manufacturing, spare part material manufacturing, and energy consumption in standby state.

5.2 Result interpretation by life cycle stage

This chapter will interpret the results by life cycle stage, whilst considering the effect of used assumptions, cut-offs, and limitations to them. The focus of this chapter is on life cycle stages that include unit processes which are considered significant contributors to total CFs of the products. Results of both products are interpreted under same chapter since the life cycle structure for both products were identical.

5.2.1 Component manufacturing

As expected, the component, i.e., material manufacturing was one of the most contributing unit processes in product CFs. The material compositions of both products follow the same path; roughly same relative level of metals, and rest of the composition builds up from plastics and other materials. But when investigating the emissions emerging from the material manufacturing, the results differ remarkably. The whole list of materials, material weights, and corresponding GHG emissions for the Satellite can be found in Appendix 3 table 3 and for the Power Unit in Appendix 3 table 4. Appendix 3 figure 1 presents the material compositions for both products and the Appendix 3 figure 2 illustrates the emerging GHG emissions from the material manufacturing of both products.

Satellite's aluminium composition

Most of the Satellite's aluminium composition consists of the back, front, and cover profiles. In the calculation of emissions from these profiles' aluminium production, EF of 10,90 kgCO_2e/kg (EPD 2021a) was used. However, the same aluminium producer also provides EFs for aluminium produced from secondary material, i.e., aluminium scrap. For anodized and extruded aluminium made from secondary material, the EF is 2,36 kgCO_2e/kg (EPD 2021b). If this latterly mentioned EF had been used, the relative CF of component manufacturing stage would have dropped roughly 27% percent. However, the choice of using primary material-based EF was due to the chosen recycling allocation method. In closed-loop allocation, the product manufacturing stage is modeled by using particularly virgin material-based EFs, and the recycling benefit is obtained when calculating the virgin material displacement credit.

Power Unit's PCBA composition

With the Power Unit, the PCBA production seems to be a remarkable contributor to the material manufacturing CF. The used EF was an average of Young et al. (2018) and Liu et al. (2015) studies. In the study by Young et al. (2018), the electricity consumption in PCBA production contributes 27 percent of the total EF. By calculating the emerging GHG emissions of the electricity consumption in that study, a factor of 922,3 gCO_2/kWh was received. If Young et al. (2018) study's result is calculated with an electricity EF of Finland (55 gCO_2e/kWh), since the

PCBAs are manufactured in Finland, their study's result would drop from 66,22 to 48,61 kgCO_2e/kg PCBA. To analyze the effect of the alternative options of PCBA EF on the material acquisition results of Power Unit, a chart was made. Figure 18 presents material acquisition and total CF with altering PCBA EF of 30 to 110 kgCO_2e/kg PCBA. The chosen upper limit (110 kgCO_2e/kg of PCBA) was based on PCBA EF that appeared in the Clément et al. (2020) study.

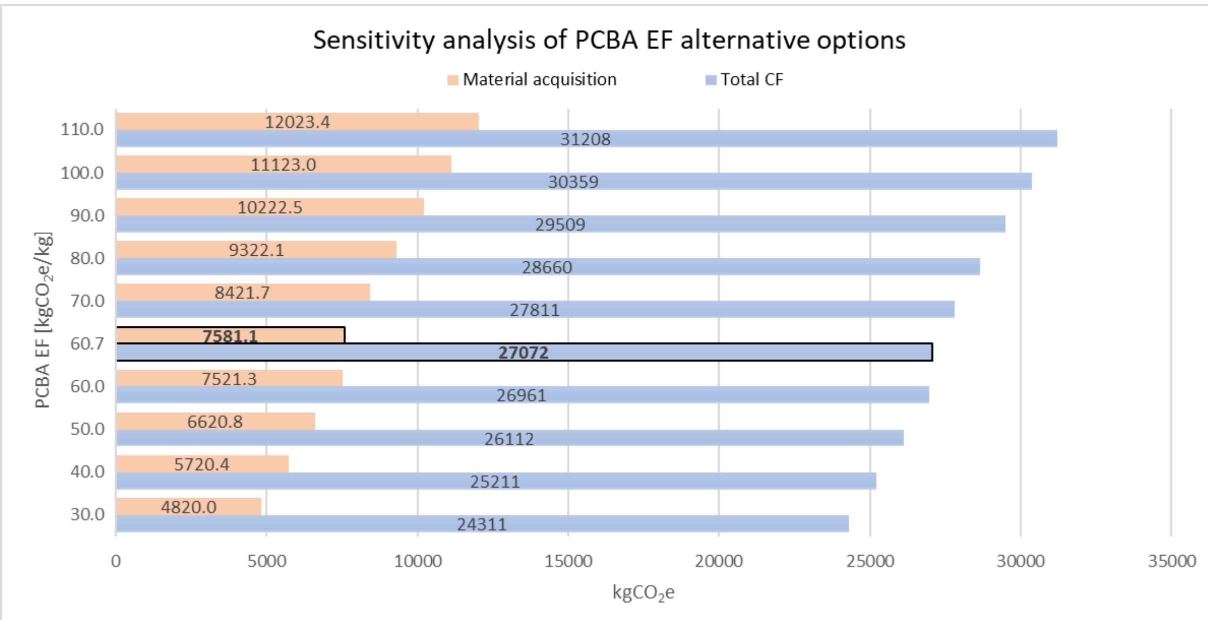

Figure 18. Effect of altering printed circuit board assembly (PCBA) emission factor (EF) to the Power Unit's material acquisition carbon footprint (CF) and total CF. The material acquisition refers to the combined CF of the product component manufacturing processes and spare part manufacturing processes. The value 60,7 kgCO_2e/kg (bolded) was used for the results in this study.

As the Figure 18 shows, the emerging GHG emissions from material acquisition and the total emissions of the Power Unit are directly proportional to the used PCBA EF. A unit variation of ten in PCBA EF has an absolute change of 900 kgCO_2e in material acquisition CF.

Used emission factors

The reduction in total CF emerging from using more environmentally friendly, i.e., lower EF materials, is also an interesting parameter under analysis since the manufacturing GHG emissions are directly proportional to the used EF values. The analysis is done by decreasing the material EFs. From materials, the metal is picked as only individual material category under analysis. The results of material EF reduction are summarized in Table 7.

Table 7. Results of the material emission factor sensitivity analysis. The relative change column shows how much the alternations affect to the material manufacturing and total, i.e., cradle-to-grave CFs of the products.

Parameter	Alternation	Relative change in results % (new CF $kgCO_2e/FU$)			
		Material manufacturing		Total CF	
		Satellite	Power Unit	Satellite	Power Unit
All material EFs	times 0,95	-4,9% (847)	-4,9% (7210)	-1,7% (907)	-1,3% (26698)
	times 0,90	-9,9% (803)	-9,9% (6831)	-3,3% (892)	-2,6% (26349)
	times 0,75	-24,7% (671)	-24,8% (5701)	-8,2% (846)	-6,5% (25301)
	times 0,50	-49,4% (451)	-49,8% (3806)	-16,4% (771)	-12,9% (23555)
Metals' EFs	times 0,95	-4,3% (852)	-0,8% (7518)	-1,1% (912)	-0,2% (26984)
	times 0,90	-8,7% (813)	-1,7% (7455)	-2,1% (902)	-0,5% (26921)
	times 0,75	-21,7% (697)	-4,2% (7265)	-5,3% (873)	-1,2% (26731)
	times 0,50	-43,4% (504)	-8,3% (6950)	-10,6% (824)	-2,3% (26415)

As the results from material EF sensitivity analysis show, the reduction of the Satellite's all material EFs has a pattern-like effect on the total CF. For the Power Unit the EF reduction does not have as significant impact as for Satellite since the material manufacturing's relative share from total CF is smaller. Surprisingly, by lowering the metals' EFs, the Satellite's material manufacturing CF goes nearly hand in hand with the EF reduction. The increment of the EF by the same amount as reduced leads to the same size, but positive, relative changes in products' material manufacturing and total CFs.

Component transportation

The CF of component transportation was surprisingly small for both products, with a contribution of 2,4 $kgCO_2e$ and 3,9 $kgCO_2e$ for Satellite and Power Unit, correspondingly. The result is validated when examining the made assumptions, limitations, and used data's overall quality. The low impact is explainable with the high shares of domestic suppliers in Kempower's actions.

Assumptions

From the component manufacturing life cycle stage, the component manufacturing energy use, e.g., casting, and the component packaging including the downstream emissions, were mostly left out of the study due to lack of data from the supply chain. Only for the PCBAs and for the Satellite's LCD-screen, these exclusions were not considered, and the emerging GHG emissions were included in their EFs. Considering the small sizes and mass production characteristics of most components, such as bolts, nuts, and zip ties, the emissions allocated per component from component manufacturing energy use were justifiably assumed insignificant.

5.2.2 Assembly

The magnitude of the assembly life cycle stage results is as expected since there are no carbon-intensive or high-energy consuming processes included. The emissions emerging from the physical assembly, testing, and packing were assumed insignificant since the energy use of those processes was negligible. Therefore, the only unit processes emerging GHG emissions were packaging material acquisition and packaging transportation to the Lahti HQ (Appendix 3 table 5). The combined CF of these two processes was 13,1 kgCO_2e for Satellite and 15,3 kgCO_2e for Power Unit. Additionally, the biogenic uptakes from packaging material production, such as wood, plywood, and corrugated board, were also assessed. Biogenic uptakes were -75,03 and -43,52 kgCO_2e of Satellite packaging and Power Unit packaging, respectively. The most contributing component of the product's packaging, in terms of GHG emissions, is the plywood walls (4,91 kgCO_2e) for the Satellite and the metal pallet fixing brackets (4,45 kgCO_2e) for the Power Unit.

5.2.3 Distribution

The products' distribution-stage consisted of the marine and land transportation of the packed product from Lahti HQ to the use site. For defining the distribution distances and the GHG emissions, revenue share-based distribution options were formed since Kempower distributes its products all over the world. The total impact from the distribution stage was 23,06 and 72,99

$kgCO_2e$ for Satellite and Power Unit, accordingly. The breakdown of formed distribution options with revenue-based weighted average numbers, i.e., distribution stage CFs, is illustrated in Figure 19. The data on which is Figure 19 based, can be found in Appendix 3 table 6.

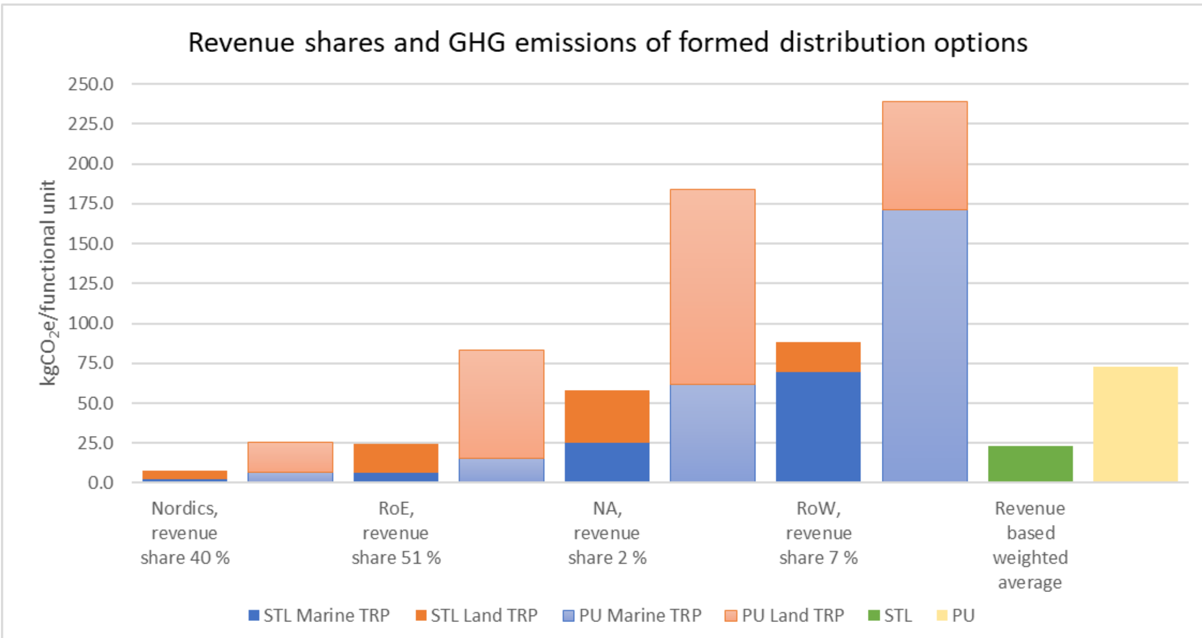

Figure 19. The distribution stage greenhouse gas (GHG) emissions breakdown by the distribution option. The columns with bright colors present Satellite (STL) and the pale ones Power Unit (PU). TRP stands for transportation, RoE for Rest of the Europe, NA for North America, and RoW for Rest of the World.

As the Figure 19 shows, the revenue-based weighted average stays rather low, because the revenue shares of the RoW- (2 percent) and NA-options (7 percent) are small. What comes to European-area distributions, land transportation naturally plays a significant role, since marine transportation distances to Europe from Finland are shortish, and cargo-specific emissions low in marine transport. The NA-scenario's land transport share is explainable with the size of the NA-continent, even though the used marine transportation distance is also significant, circa 7600 kilometers.

Allocation method

For the marine distribution of the packed products, a volume-based method was used instead of mass-based since it was considered the most representative allocation method in that stage. If mass-based method would have been used in the allocation of marine transportation capacities, the emerging GHG emissions from marine transportation to use site unit process would have been 53 percent smaller for Satellite and 32 percent smaller to Power Unit, compared to the used volume-based method. In terms of absolute value, that difference would have been 8,0 $kgCO_2e$ and 17,7 $kgCO_2e$ for Satellite and Power Unit, respectively.

Assumptions

A process exclude was made by leaving the installation stage of the life cycle completely out of the study, because it was considered too site-specific. The products can be retrofitted to the charging site when no major construction work is needed or a whole new charging site can be built. However, there are some similar infrastructural requirements for both of these installation options; the Satellite and Power Unit require firm base under it (usually some reinforced concrete where the product is bolted on) and the power distribution cable between Power Unit and Satellite(s) has to be dug down on earth and covered, which requires some excavator work and perhaps resurfacing. Apart from these facts, the power distribution cable has to be manufactured and transported to the use site, which would also contribute to the product CF. Study by Lucas et al. (2012) concerned LCA of energy supply infrastructure for EVs, with geographical coverage of Portugal. In that study, the impacts of construction and installation, as well as the impact of required materials were taken into account. The total impact per charger was 2500 $kgCO_2e$ (Lucas et al. 2012, 540). Considering the facts that study by Lucas et al. (2012) was a LCA for newly built site option, and study based on primary data, the above-mentioned the number could be used as a conservative estimate of product installation on new site option in this study. If estimating a CF for the retrofitting option, including the emissions emerging from power distribution cable manufacturing and reinforced concrete manufacturing, and assuming other emissions negligibly small, a number of 200 $kgCO_2e$ can be assumed. In fact, that should be allocated to both products since only one cable is needed between the Power Unit and the Satellite. All in all, just like assumed in this study, the CF of the installation phase is very site-specific. A scenario-based estimate could have been calculated if data from customers about their charging sites had been available. Taking into account the time resources of this study, data collection about installation would not have been feasible and the assumption about leaving the installation stage out of the study was justified.

5.2.4 Use

The use stage considered the product's energy dissipation during use and energy consumption in standby state. Both of these processes were defined as significant for both products' total CF. For Satellite the energy dissipation emerged 396,3 $kgCO_2e$ and energy consumption in standby state caused GHG emissions of 98,4 $kgCO_2e$. For Power Unit the numbers in respective order were 18450 $kgCO_2e$ and 1580 $kgCO_2e$.

Energy dissipation during use

The energy dissipation during use was directly proportional to the energy provided per day and to the efficiency. The energies provided per day were based on site-specific primary data and the efficiencies obtained from the RDI-team and technical datasheets. Since the Satellite's efficiency was assumed to be 99,9 percent, the CF of energy dissipation during use is rather small compared to the Power Unit's. The Power Unit's efficiency, however, was determined to be 94 percent, and the emerging GHG emissions from the energy dissipation during use are the most contributing factor to the Power Unit's total CF. In Figure 20, the effect of altering Power Unit efficiency on the amount of energy dissipated during RSL and the emerging GHG emissions of energy dissipation during use is studied.

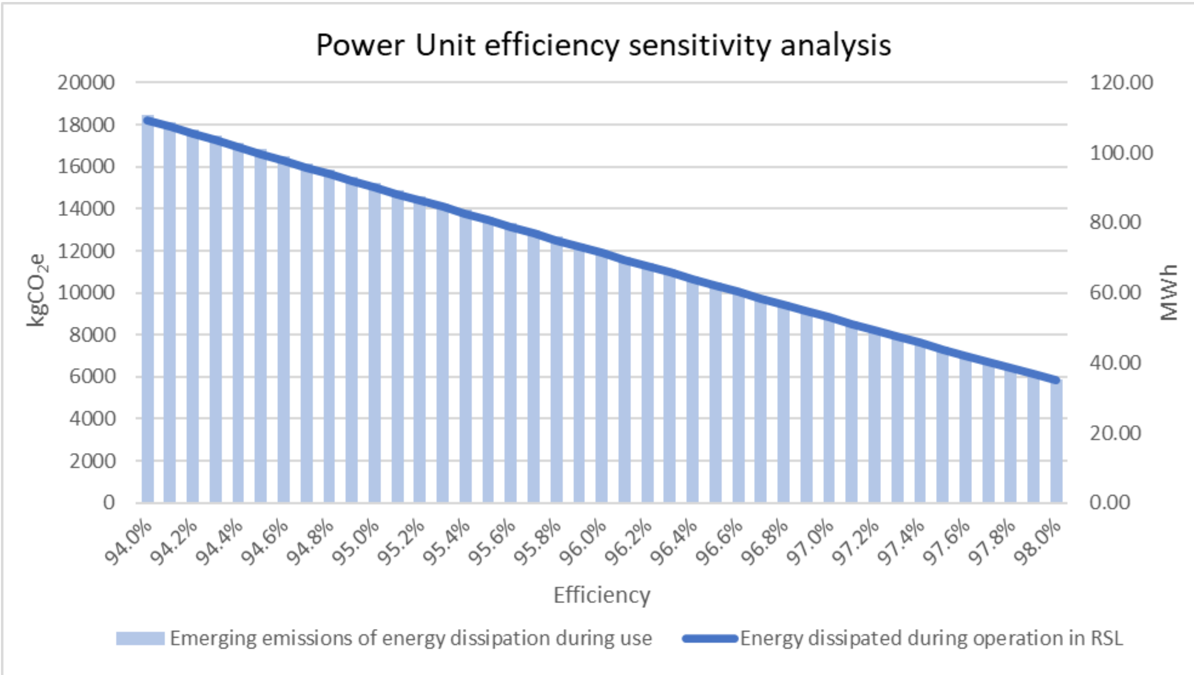

Figure 20. Power Unit's altering efficiency effect on the energy dissipated during reference service life and to the emerging greenhouse gas emissions of energy dissipated during use. An electricity emission factor of 169 kgCO_2e/MWh was used in the calculus.

As the Figure 20 shows, a 0,2 percent variation in efficiency changes the emerging emissions of roughly 650 kgCO_2e. For a one percent improvement in efficiency, this means about 3200 kgCO_2e decrease, which is a noteworthy change in Power Unit's total CF. A one percent improvement in efficiency would mean approximately a reduction comparable to emerging emissions of manufacturing a Power Unit.

Energy consumption in standby state

The energy consumed in standby state is the fourth most contributing unit process in Satellite's total CF and use stage CF. For Power Unit this process is GHG intensive (1580,2 kgCO_2e), even though the relative contribution to total CF seems low (5,6%). Table 8 illustrates the effect of alternative standby state power consumption parameters on the total CF.

Table 8. Results of the standby state power sensitivity analysis. The relative change column shows how much the results have changed compared to the total carbon footprint (CF).

Product	Alternation in standby state power	Relative change in results % (new total CF $kgCO_2e$/FU)
Satellite	25 → 24W	-1,7% (906)
	25 → 20W	-8,6% (843)
	25 → 12,5W	-21,5% (724)
Power Unit	150 → 135W	-0,6% (26889)
	150 → 75W	-2,9% (26257)
	150 → 50W	-3,9% (25993)

A one watt change in Satellite's standby state power has nearly two percent decrease in the Satellite's total CF. By taking a one-fifth off from the standby state power, a decrease of 8,6 percent is achieved, and by halving the standby state power, the total CF would decrease by a bit over fifth. On behalf of the Power Unit, the relative changes seem to be minor. By reducing the standby power by one-tenth, the total CF decreases by 0,6 percent. But when investigating this decrease in light of absolute value, the decrease in total CF is roughly 160 $kgCO_2e$.

Energy model

The main variable in the calculation of GHG emissions emerging from the use stage was the used energy model, i.e., used electricity EF. In this study, the energy model was formed using average electricity EFs of four different geographical options and the company's revenue shares to these areas. With the formed energy model, an electricity EF of 169 $kgCO_2e$/MWh was obtained. Table 9 illustrates the results if alternative energy models were used. Under comparison were chosen the US and Finnish average electricity EFs (Table 6), and a zero-carbon electricity EF option.

Table 9. Satellite and Power unit use-stage and total carbon footprints (CFs) with alternative energy models. The basic model refers to the number used in this study. The percentage number after total CF indicates the relative change to basic model. EF stands for emission factor.

Energy model [EF of electricity]	Satellite			Power Unit		
	Energy dissipated during use [$kgCO_2e$]	Energy consumed in standby state [$kgCO_2e$]	Total CF [$kgCO_2e$]	Energy dissipated during use [$kgCO_2e$]	Energy consumed in standby state [$kgCO_2e$]	Total CF [$kgCO_2e$]
Basic model [169 $kgCO_2$/MWh]	98,4	396,3	922 (0%)	18 450,0	1 580,2	27 047 (0%)
US average [389 $kgCO_2$/MWh]	226,8	913,3	1 567 (+70%)	42 523,0	3 641,9	53 182 (+97%)
Finnish average [55 $kgCO_2$/MWh]	32,1	129,1	588 (-36%)	6 012,2	514,9	13 544 (-50%)
Zero-carbon [0 $kgCO_2$/MWh]	0,0	0,0	427 (-54%)	0,0	0,0	7 017 (-74%)

The Table 9 confirms the above-introduced claim that the used electricity EF is the main variable in use stage result calculations. As we can see, with the US average electricity EF of 389 $kgCO_2e$/MWh, the total CF of Power Unit increases by 97 percent and Satellite's total CF by 70 percent. By using the Finnish average electricity EF, which is about one-third of the basic scenario, the total CF drops down by 50 and 36 percent for Power Unit and Satellite, respectively. Theoretically, if the products would use electricity with an EF of zero $kgCO_2e$/MWh, the total CF could drop by 74 percent for Power Unit and 54 percent for Satellite. This table also backs up the fact that the used energy model reflects the product use-stage reality rather well.

The used energy model did not consider the effect of possibly decreasing electricity production EF during the product reference service life. This could have affected the use stage results since the RSL of both products is rather long, 12 years. To achieve more reality-like results, an additional aspect of progressively reducing electricity production direct GHG emissions should be considered to be added to the energy model.

5.2.5 Maintenance

Maintenance life cycle stage consisted of spare part manufacturing and spare part transportation to use site unit processes. The impacts of installation of and packaging's of the spare parts were assumed insignificant. The maintenance stage CF breakdowns for both products are illustrated in Appendix 3 figure 3.

The spare part transportation to use site has a very minor contribution to the total CF of both products. It was assumed that the spare parts were transported to the use site from the Lahti HQ. In reality, some of the spare parts come from local suppliers and the total spare part transportation distance might be over-estimated. The exclusion of the spare part packaging unit process from this study had most likely an insignificant impact on the results, referring to the impact of the component packaging manufacturing unit process, which was also assumed insignificant.

For Satellite, the spare part manufacturing unit process was the biggest contributor to the total CF. The amount of replaced spare parts could have been also calculated using the number of product uses, i.e., charging sessions, instead of using the number on the regular maintenance plan. By basing the Satellite's maintenance stage impact calculations on the number of charging sessions, the relative decrease in the Satellite's total CF could be up to 20,0 percent. On the other hand, by basing the spare part need on charging session quantity, the model does not describe the average maintenance need that well, since it is more use site-specific parameter. Thus, the charging session-based calculation method was not used in this study, but if precise product use data is available, it should be considered.

What comes to Power Unit spare part manufacturing, the made assumptions were the same as for the Satellite and had a minor impact on the results. The spare part amounts reflect the reality relatively well, even though the climate conditions, especially on dusty sites, might have an impact on the filter replacement pace.

5.2.6 End-of-life

The end-of-life stage of the products began with the transportation of the end-of-life product, the packaging, and the used spare parts to the waste management center. In the waste management center, the above-mentioned items are pre-treated as recyclables and recoverables. The recyclables were assumed to substitute virgin material in the product component manufacturing unit process and the recoverables were assumed to be combusted and substitute energy production. The whole end-of-life stage was modelled by using European processes since it was considered the most representative based on Kempower's global revenue shares. Figure 21 shows the emerging emissions from the EoL-stage. More precise results for the Satellite can be found in Appendix 3 table 8 and for the Power Unit in Appendix 3 table 9.

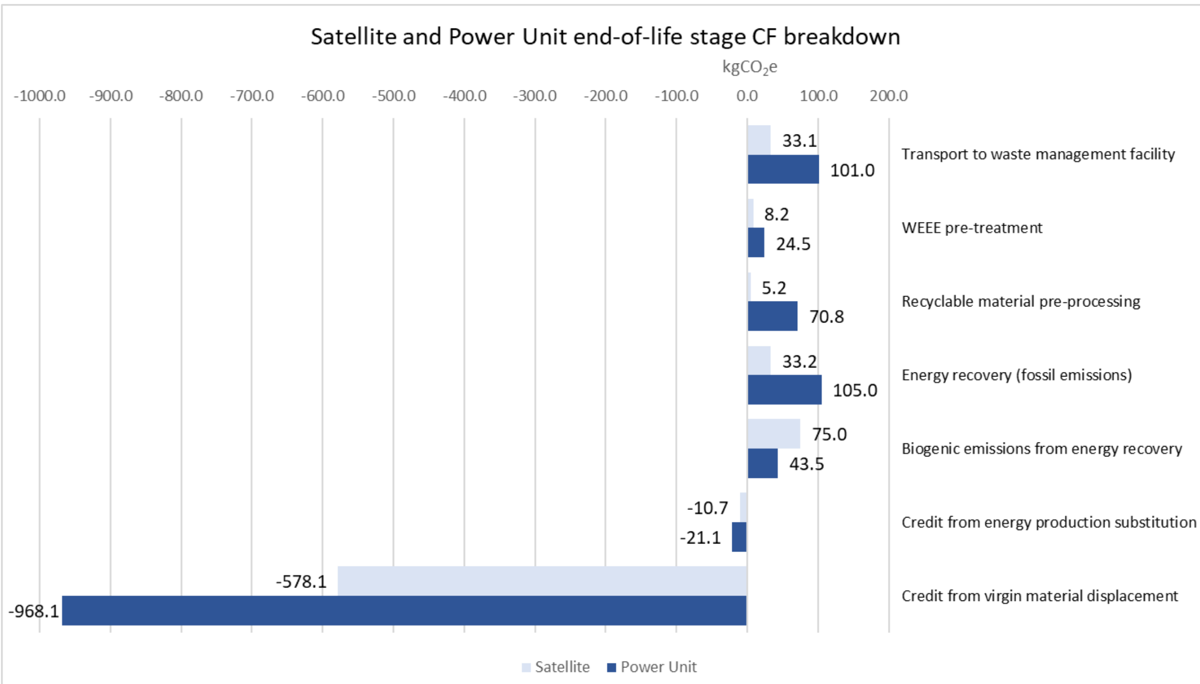

Figure 21. End-of-life stage carbon footprint (CF) breakdown of both products. The recyclables included metal materials and metals of printed circuit boards, and the LCD-screen. The other materials were considered energy recoverable. The energy recovery refers to combustion.

The relatively high CF of transportation unit process is explainable with the mass and transportation distance of transported items to waste management center. The weight of these items included the product, spare parts and packing. As transportation distance, average of distribution option distances was used, which led to 1785 kilometers of road transport and 2574 kilometers of marine transport. This seemed to be bit overestimate but was used since there were no statement about it in product category rules. The biogenic emissions emerging from combustion of the bio-based packaging materials are equal to the biogenic removals. Pre-treatment, recyclable material pre-processing, and credit unit processes had several assumptions made according the used parameters, and therefore the effects of those are picked under analysis in the following chapters. The results from these analyses are gathered in Table 10 at the end of the chapter.

First up, the collection rate of 100 percent was used to ease down the study calculus-wise, since no primary data for this number was found, and the used standards did not mention anything about it. In reality, the 100 percent collection rate would not be truthful. According to the Baldé et al. (2022, 4), an average collection rate of WEEE in Europe in 2021 was 54 percent. But since the followed standards did not mention anything about taking the collection rate into the account, the assumption of 100 percent collection rate is considered justified. The effect of decreasing the collection rate from 100 to 54 percent is shown in Table 10. When calculating the effect of decreasing the collection rate to 54 percent, the input values to the unit process of transport to waste management facility are multiplied with value 0,54 and the remaining fraction of 46 percent is assumed not to have any effect to the total CF.

The credits from the virgin material displacement of both products consist roughly about 98 percent of credit of metal recycling. The metal recycling credit itself is highly dependable on used material recovery rates. The material recovery rates for recyclable materials were adapted from the product category rules (EN 50693:2019) since there was no primary data available. The used metal material recovery rate was 70 percent. According to several studies (Bigum et al. 2012; Chancerel et al. 2008), that somewhat consider metal recycling in Europe region, the 70 percent is a reality-reflecting average between different metals that the products under study contain. To be more precise, the material recovery rate is a bit higher for ferrous metals, like steel, and a bit lower than 70 percent for metals such as copper and aluminum (Bigum et al. 2012, 11; Chancerel et al. 2008, 43-44). To see the effect of varying the recovery rate of metals to the total CF, alternative values of 0, 80, and 100 percent are included in the sensitivity analysis in Table 10.

Assumptions were made when categorizing the end-of-life materials into recyclables and recoverables. The metals, PCBAs' metal content, and Satellite's LCD screen were considered recyclable. The other materials, such as plastics, packaging wood, rubber, and suchlike, were considered to go energy recovery. The categorizing was based on the principles of the closed-loop allocation method stating that recycled materials cannot go through remarkable changes in inherent properties during recycling. If ignoring the principles of the closed-loop allocation method, and basin the categorizing to be more real life like, the plastics and packaging wood would be, at least partially, recycled. To see the effect of recycling also the plastics and wood materials, are chosen for analysis. According to Eurostat (2022), averagely 38 percent of plastic waste generated in Europe was recycled in 2020. For calculating the GHG impact of the plastic recycling process, an EF of 365,87 kgCO_2e/ton of recycled plastic (Appendix 2) and a recycling efficiency of 70 percent were used (Lase et al. 2022, 250). The rest of the 38 percent is assumed to be energy recovered. The recycling rate of wood picked under analysis is based on the EU's Waste Framework Directive (2008/98/EC), which states that 25 percent of wood packaging must be recycled in 2025. The wood recycling rate change is modelled by assuming a scenario where the wood is reused in subsequent product system and the emerging fossil emissions are only insignificant transportation emissions. Same as with the plastic, the rest (75 percent) of the wood is still assumed to be energy recovered. Additionally, besides the above-mentioned recycling rates, scenarios with a 100 percent recycling rate of plastic and wood are included in the sensitivity analysis in Table 10.

Table 10. Results of the end-of-life stage sensitivity analysis. The relative change column shows how much the results have changed compared to the product's original CF and the new CF after parameter alternation.

Parameter	Alternation	Relative change in results % (new total CF kgCO_2e/FU)	
		Satellite	Power Unit
Collection rate	100 → 54%	+25,6% (1158)	+1,1% (27351)
Metal recovery rate	70 → 0%	+63,8% (1508)	+3,4% (27979)
	70 → 80%	-8,1% (847)	-0,5% (26915)
	70 → 100%	-26,0% (682)	-1,5% (26649)
Plastic recycling rate	0 → 38%	-2,2% (902)	-0,3% (26967)
	0 → 100%	-6,9% (858)	-0,8% (26835)
Wood recycling rate	0 → 25%	+0,1% (923)	+0,1% (27071)
	0 → 100%	+0,2% (924)	+0,1% (27069)

As the Table 10 shows, the relative changes in Power Unit's CF are very minor since the total CF is already substantial compared to changes emerging from the parameter alternation. The collection rate and metal recovery rate decreases had major impacts on the Satellite's CF. Both of these are explainable by the fact that the obtained credit from virgin material displacement dropped enormously. At the same time, the metal recovery rate increment had a relatively big effect, since credits increased approximately hand to hand with it. By recycling the plastics, instead of combusting them, a small reduction in total CF is achieved. The recycling process of plastic is less GHG intensive than the combustion process, and the obtained credit from virgin material displacement is higher than the credit from energy production substitution. Nevertheless, the reduction in total CF is minor since the plastic compositions of the products are relatively low. Surprisingly, by recycling or reusing the wood material instead of combusting it, the change is more or less zero. This is explainable by the low fossil emissions of wood-based material production, so the obtainable virgin material displacement credit remains low with the closed-loop calculation method. The ISO 14067:2018 (51), additionally states that by reusing or recycling the bio-based materials to subsequent product system, the biogenic emissions are still the same as the removals, thus the biogenic emissions do not change.

6 Discussion and recommendations

This chapter contemplates the ways to reduce the CF hotspots associated with the life cycles of the products, compare received results to the other studies in the field, and extend the received CF to evaluate the CF of European public charging infrastructure. The ways for CF reduction are evaluated also from economic feasibility and implementation realism points of view, besides CF reduction potential.

6.1 Proposals for optimization of the PCFs

Based on the results, the most significant potentials for CF optimization, i.e., reduction for both products are in the product and spare part component manufacturing processes and in energy consumption in standby state. For Power Unit, the energy dissipation during use is by far the most dominant process with a 65,8 percent contribution to the CF. Therefore, the action proposals for CF reduction concentrate on these CF hotspots.

Table 11 shows the recommended action proposals to reduce the CFs of Satellite and Power Unit. All of the proposals are then discussed and evaluated by their economic feasibility and implementation realism.

Table 11. Proposals for reducing the product CFs. The percent values after the absolute reduction values indicate the relative reduction in total CF.

Action proposal	Reduction in CF [$kgCO_2e$]	Notes
Satellite		
Using components made out of climate-friendly (i.e., lower EF) materials in manufacturing	15 (1,7%) / -5% in material EFs	
Paying attention to using climate-friendly metals, particularly, in manufacturing	38 (4,3%) / -5% in metals' EFs	
Decreasing the standby power	16 (1,7%) / Watt decreased	Reduction potential dependent on the site's activity
Power Unit		
Increasing electrical efficiency of the product (current 94%)	650 (2,4%) / 0,2% efficiency	Reduction potential dependent on the site's activity
Using components made out of climate-friendly materials in manufacturing	349 (1,3%) / -5% in material EFs	
Paying attention to using climate-friendly PCBAs, particularly, in manufacturing	90 / -1 $kgCO_2e$/kg of PCBA EF	
Decreasing the standby power	53 (0,2%) / 5 Watts decreased	Reduction potential dependent on the site's activity
Common for both products		
Product design with easy repair, reuse, and recyclability in mind	Hard to evaluate*	*Perhaps increase the service life, ease down the end-of-life treatment, and decrease the product component manufacturing CF

Material choices

As the result interpretation showed, attention should be paid to the material choices. For Satellite, the material manufacturing contributes 59 percent of the total fossil GHG emissions during the product's life cycle. Therefore, just a five percent reduction in material EFs would decrease the Satellite's total CF by 1,7 percent or 15 $kgCO_2e$. For the Power Unit, a similar five percent reduction would lead to a 1,3 percent or 349 $kgCO_2e$ reduction in total CF. Particularly, the Satellite's metal composition contains the potential for CF reduction. A reduction of 4,3 percent or roughly 38 $kgCO_2e$ can be achieved when deducting five percent from metal EFs of Satellite by better material choices. For Satellite, special attention should be paid especially to components that are made out of aluminium and steel. If possible, profiles made of secondary aluminium should be ordered from the manufacturer of the Satellite's profiles. This would lead to about 130 kgCO_2e (14 percent) smaller Satellite cradle-to-gate CF.

Similarly, to the Satellite's metal EF enhancing, the Power Unit has the potential for CF reduction in PCBAs. The emerging emissions from PCBA manufacturing for Power Unit were roughly 75 percent of Power Unit's manufacturing emissions. Thus, a one kgCO_2e/kg reduction in PCBA EF (60,7 kgCO_2e/kg used in calculations) would reduce the Power Unit's CF by 90 kgCO_2e. The commercially available biobased PCBs are still restrictively available, but alternative options for the circuit board material and the conductive material have been studied (Ogunseitan et al. 2022, 750). Bio-based options such as PET, polylactic acid / glass fiber composite, and paper, are proposed to be the substitutes for the current popular material of circuit boards, fiber-glass-reinforced brominated epoxy resin. For conventional copper as a conductive material, the environmental problem is the etching in the manufacturing process. This could be substituted, for instance, with a mix of silver nanoparticles and resin, which can be printed to the circuit board without chemicals involved. (Nassajfar et al. 2021, 1-4.) According to the result of Nassajfar et al. (2021, 7) study, by combining these alternative options, the GWP-potential could be decreased down to 14 percent of that of the conventional PCB made out of fiber-glass-reinforced brominated epoxy resin and copper.

From economic feasibility and implementation realism points of view, the option of using more climate-friendly components is doable. However, the components made out of materials that are climate-friendly and from certified origin may be a bit more expensive than currently used. Problems might also arise during the procurement if no domestic suppliers for the components is found since Kempower promotes local sourcing in its actions.

Efficiency enhancement of Power Unit

Looking at economic feasibility, one potentially costly yet highly impactful way to reduce CF of Power Unit is improving its efficiency. By improving the Power Unit's electrical efficiency by one percent from the current 94 percent, a reduction of circa 3200 kgCO_2e is achieved in total CF. This reduction is comparable to CF of manufacturing a Power Unit. From economic feasibility and implementation realism point of view, efficiency improvement requires a lot of work, and technical constraints may prove to be a problem. Additionally, the calculated reduction potential is dependent on the site's activity since the emerging emissions of production of energy dissipated during use are also dependent on that. Hence, on more active sites the reduction potential can be even more substantial.

Standby power improvement

By decreasing the standby power of the products, reductions of 16 kgCO_2e per watt for Satellite and 53 kgCO_2e per five watts for the Power Unit, can be achieved. From the economic viewpoint, standby power reduction is categorized as the same as efficiency improvement; expensive, since requires a lot of work. Implementation realism-wise, the standby power reduction is possible with hardware updates, such as a more energy-efficient screen for the Satellite.

Enhancements in product repair, reuse, and recyclability

Lastly, a proposal common for both products would be to design the products with easy repair, reuse, and recyclability in mind. The easy repair should be kept in mind, since it would assumably increase the service life of the product, thus decreasing the overall GHG impacts of the products in the long run. By increasing the reusability of the products, some of the product components could perhaps be used again in similar products, for example. Therefore, the reused part's GHG emissions would comprise mainly from the transportation to the assembly site and possible processes of preparing for reuse, which would be nearly insignificant in comparison with the GHG emissions of manufacturing a new one. By designing the products with recyclability in mind, the possible effect of action would be seen especially in the end-of-life stage of the product. More components would end up recycled and less in energy recovery, thus increasing the recycling credit obtained, and such. The economic feasibility and implementation realism would need further examination.

6.2 Comparison of the results to other studies

For comparison, five electric vehicle charger-related LCA studies were reviewed. These studies had a lot of variation between them due to made assumptions and limitations. Additionally, the functional units varied in every study, which is a consequence of a lack of uniform product specific rules. The only somehow commonly made stage in the reviewed studies was usually the manufacturing stage, and therefore, the focus in this chapter is only to compare the cradle-to-gate CFs.

A relatively old study by Nansai et al. (2001) reviewed the life cycle of public charging sites in Japan. The study included 14000 charging sites around Japan. One site comprised a charger, a charger stand, and a battery storage unit. The manufacturing of a charger unit emerged roughly 3500 kgCO_2e. (Nansai et al. 2001, 258-260.)

Zhao et al. (2021) study evaluated and calculated the emerging GHG emissions from the implementation of electric bus charging stations into existing bus depots. As a modelled charging station in that study, they used Tritium's DC fast charger, in which the composition was evaluated and material emission intensity calculated. Since, this Tritium's charger can be divided into a power providing unit, a control unit, and a user unit, this study was from the product's similarity perspective the best one. The emerged emissions from the manufacturing were 2154 kgCO_2e, 315 kgCO_2e, and 922 kgCO_2e for the power providing unit, the user unit, and the control unit, respectively. (Zhao et al. 2021, 8.) If the manufacturing GHG emissions of power providing unit and control unit are combined, as Kempower's Power Unit has them in same product, the result is 3076 kgCO_2e.

A master's thesis conducted by Dahlberg & Rodriquez (2023) modelled the life cycle of an electric truck charging site. Their study used Kempower's Satellite and Power Unit as the visual models for the charger outlet and power providing unit. In addition, the thesis considered the compact secondary substation and infrastructure of the charging site. The manufacturing emissions of the products were based only on evaluated BoMs and had a lot of assumptions and mistakes when reflected in the material breakdowns of this study. The received results from Dahlberg's and Rodriquez' (2023, 26-27) master's thesis were for manufacturing the charger outlet 0,558 kgCO_2e/MWh provided and for the power providing unit 2,58 kgCO_2e/MWh provided. After converting these with the functional unit used in their study, the above-mentioned results are 109 kgCO_2e and 1344 kgCO_2e, correspondingly.

Additionally, a couple of studies were found where the results could not be converted to numerically comparable units. Zhang et al. (2019) made an environmental assessment of four main types of electric vehicles and related infrastructure in China. The manufacturing stage in that study was based on assumable composition of a public DC charge. From these authors, the result for manufacturing a public DC charger was 111,02 gCO_2e/kWh charged. (Zhang et al. 2011, 935.) The earlier mentioned (chapter 5.2.3) study by Lucas et al. (2012) conducted LCA of home, normal, and fast charging infrastructure in Portugal. The result from that study for manufacturing one fast charger was roughly 5,3 gCO_2e per driven kilometer with EV.

After reviewing cradle-to-gate CFs of five studies, three of those were comparable to the results of this study and two were incomparable due to the functional unit in those studies. The manufacturing, i.e., cradle-to-gate, GHG emissions of this study were 439 $kgCO_2e$ for the Satellite and 4086 $kgCO_2e$ for the Power Unit. The outcome of the comparison is summarized in Table 12.

Table 12. Results from comparison of the received results of this study to other studies. The Result 1-column refers to the user unit which is considered comparable to Kempower Satellite. The Result 2-column refers with the same principle to Kempower Power Unit and Result 3 to an imaginary combination of Kempower Satellite and Power Unit. The percent value after the result indicates the difference to this study.

Reference	Result 1 [$kgCO_2e$]	Result 2 [$kgCO_2e$]	Result 3 [$kgCO_2e$]	Notes [FU = functional unit, (+) = pro, (-) = con]
This study	438 (-)	4086 (-)	4524* (-)	*Sum of Result 1 and Result 2
Nansai et al. (2001)	-	-	3500 (-21,6%)	FU: one public charging station produced in Japan + BoMs determined by weighting the products - Reviewed technology from the early 2000's
Zhao et al. (2021)	315 (-27,1%)	3076 (-23,7%)	-	FU: one bus charging station produced in Australian conditions + Used Tritium's fast charger as a base for product modelling - BoMs roughly estimated
Dahlberg & Rodriquez (2023)	109 (-74,1%)	1344 (-66,1%)	-	FU: 1 kWh of delivered energy to an electric truck with an average power of 150 kW + Product models based on Kempower's Satellite and Power Unit's pictures and datasheets - The BoMs were evaluated with several assumptions and were inaccurate

As the comparison indicates, the received results of this study were a bit higher than the reviewed comparative results. The difference could be explainable by the fact that Dahlbergs' and

Rodriquez' (2023) study determined the PCBAs as notable contributors to the results but determined the impacts of those differently and with another kind of emission factor. Additionally, in Zhao et al. (2021) and Nansai et al. (2001) studies, the BoMs were not defined nearly as accurately as in this work. Although, as said, the results of the studies are hard to compare since the functional units, assumptions, and other factors differ remarkably between all published studies. Some of the differences are also explicable with used EFs in the studies, as the results from this study pointed out the importance of them.

6.3 Extending carbon footprint analysis to European public charging infrastructure

The purpose of this chapter is to extend the findings this CF study to broader context of the entire public charging infrastructure in Europe. This analysis focuses on calculating the CF of the EU member states' LDEV public charging infrastructure basing on European Commissions (2023b) estimate of 442 000 charging points at end of year 2022. The CF of the charging infrastructure is outlined to include only the cradle-to-gate GHG emissions.

To extend the cradle-to-gate CFs of Satellite and Power Unit to concern the whole public charging infrastructure, some assumptions is made. First up, assuming that a one Power Unit and four Satellites forms a one charging pool with four charging points. Additionally, it is assumed the CF of the Satellite is roughly similar to other public charger types. Despite the fact that the fast DC charger category, which Satellite is characterized in, only represented 4 percent of the total charging points in 2022 (EAFO 2023).

By using these aforementioned assumptions, the allocated CF of one charging point is 1460 kgCO_2e. For the whole EU public charging point fleet, the CF would be then 0,647 MtCO_2e (million tons of CO_2 equivalents). To get a perspective of this result's magnitude, the estimated manufacturing GHG emissions of EU's passenger BEV fleet of three million in 2022 (EAFO 2023) would be around 30 MtCO_2e, by using an average CF of 10 tCO_2e/BEV (IEA 2021; Kawamoto et al. 2019). Therefore, it can be said that the indirect emissions of the public LDEV charging infrastructure is relatively low compared to other road transport sector's indirect emissions, such as the EV fleet itself.

7 Conclusions

The first part of this master's thesis reviewed the state of public charging infrastructure in the EU area and possible environmental benefits of public charging infrastructure uptake. Despite lacking legislative pressure on low EV-adopting nations to expand charging networks, the EU is rapidly advancing toward a comprehensive public charging network. This transition holds a wide range of environmental benefits over the current, fossil-based fueling infrastructure.

The second part defined the CFs and GHG emission hotspots of Kempower Satellite and Kempower Power Unit. The CF of Satellite was determined to be 922 kgCO_2e and of Power Unit 27 047 kgCO_2e. The GHG emission hotspots were found from component manufacturing, use, and maintenance life cycle stages. The product component material manufacturing, spare part material manufacturing, energy dissipation during use, and energy consumption in standby state were the most contributing unit processes GHG emission-wise. Conclusively, some of these hotspots could be reduced by decreasing the standby power and using components made from more environmentally friendly materials, emphasizing particularly the metal choices of Satellite and printed circuit board assembly choices of Power Unit. For the Power Unit, remarkable CF reduction can be achieved through improvements in its electrical efficiency. Before incorporating these CF reduction suggestions, it is essential to conduct additional studies on technological and quality constraints, alongside assessing their time- and cost-effectiveness.

In possible future CF assessments for Kempower, the PCBAs should be characterized separately as the printed circuit board and the components populating it. Additionally, the use of LCA modelling software with according database and gathering primary data of components' manufacturing GHG emissions from the suppliers is highly recommended. These actions would elaborate the results and enable easier updating of the study.

Furthermore, the significance of such studies becomes more pronounced as societal environmental awareness progressively grows. Studies like this, providing publicly accessible data about environmental impacts from the operational manufacturers of the sector in particular, are vital for the development of the sector.

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Appendix 1. Emission factors of certain material manufacturing

Material:	Geographical coverage	EF [kgCO_2e/kg]	CO_2 uptake [gCO_2/kg]	Source:
Plastics				
plastic (ABS)	EUR	3.100		(PlasticsEurope 2015)
plastic (LDPE)	EUR	1.870		(PlasticsEurope 2014a)
plastic (HDPE)	EUR	1.800		(PlasticsEurope 2014a)
plastic (PVC)	EUR	2.070		(PlasticsEurope & ECVM 2022)
plastic (VCM)	EUR	1.760		(PlasticsEurope & ECVM 2022)
plastic (PMMA sheet)	EUR	4.580		(Cefic 2015)
plastic (PU/PUR foam, moulded)	EUR	3.660		(EURO-MOULDERS 2021)
plastic (PU/PUR, rigid)	EUR	4.200		(I Boustead & PlasticsEurope 2005a)
plastic (PC)	EUR	3.400		(PlasticsEurope 2019)
plastic (PA6/nylon 6)	EUR	4.520		(PlasticsEurope 2022a)
plastic (PA66/nylon 6.6)	EUR	6.400		(PlasticsEurope 2014b)
plastic (POM)	EUR	3.200		(PlasticsEurope 2014c)
plastic (PET)	EUR	2.190		(PlasticsEurope 2017)
plastic (acrylonitrile)	EUR	3.253		(PlasticsEurope 2005)
plastic (PP)	EUR	1.630		(PlasticsEurope 2014c)
polyester (clothing fabric)	GLO	12.700		(Openco2.net 2019)
Metals				
aluminium PM (extruded), PURSO	EUR	10.700		(EPD 2021a)
aluminium PM (extruded, anodized), PURS	EUR	10.900		(EPD 2021a)
aluminium PM (extruded, painted), PURSO	EUR	10.900		(EPD 2021a)
aluminium SM (extruded), PURSO	EUR	2.170		(EPD 2021b)
aluminium SM (extruded, anodized), PURS	EUR	2.360		(EPD 2021b)
aluminium SM (extruded, painted), PURSO	EUR	2.310		(EPD 2021b)
aluminium	GLO	4.476		(International aluminium 2022)
aluminium	EUR	2.165		(International aluminium 2022)
aluminium	CHI	2.398		(International aluminium 2022)
steel sheet/coil PM (hot rolled), SSAB	FIN,SWE,EUR	2.783		(EPD 2020a)
steel sheet/coil PM (cold rolled), SSAB	FIN,SWE,EUR	2.342		(EPD 2020b)
steel coil, hot rolled	GLO	2.340		(World Steel Association 2020)
steel galvanized	GLO	2.670		(World Steel Association 2020)
steel (rolled)	CHI	4.400		(Chen et al. 2022)
stainless steel (hot rolled)	SWE, EUR	2.910		(EPD 2021c)
stainless steel (cold rolled)	SWE, EUR	3.590		(EPD 2021c)
copper wire rod	GLO/SE	4.320		(EPD 2022b)
copper sheet	GLO/SE	4.360		(EPD 2022c)
copper sheet	EUR	1.981		(European Copper Institute 2012)
copper tube	EUR	2.385		(European Copper Institute 2012)
copper wire	EUR	4.238		(European Copper Institute 2012)
brass, PM	GLO	3.150		(Nakano et al. 2007)
brass, SM	GLO	0.770		(Nakano et al. 2007)
ferrite	GLO	2.213		(Gómez et al. 2018)
Others				
rubber, synthetic (silicone based (PDMS))	EUR	6.580		(Brandt et al. 2012)
silicone fluid	GLO	6.310		(Brandt et al. 2012)
cellular rubber, EPDM	GLO	3.000		(Malcolm Pirnie 2007)
glass fibre	EUR	1.440		(PwC 2023)
corrugated board	EUR	0.182		(CCB & FEFCO 2021)
plywood (birch)	FIN, EUR	0.718	1188	(VTT 2013)
plywood (conifer)	FIN, EUR	0.605	1708	(VTT 2013)
plywood	SWE, EUR	0.229	1731	(VTT 2013)
timber (dried)	FIN, EUR	0.068	1835	(VTT 2013)
timber (shipping dry)	SWE, EUR	0.013	1502	(VTT 2013)
fibreboard (porous)	FIN, EUR	0.425	1531	(VTT 2013)
glass wool	EUR	3.148		(VTT 2013)
styrene	EUR	2.090		(PlasticsEurope 2022b)
polystyrene (EPS)	EUR	3.300		(VTT 2013)
glass (float glass)	EUR	1.230		(VTT 2013)
PCBA	GLO	60.665		Average of (Young et al. 2018) and (Liu et al. 2015)
resin (epoxy)	EUR	5.459		(I Boustead & PlasticsEurope 2005b)
LCD screen/m^2	ASIA	113.750		Average of (EPA 2016) and (VHK 2005)
polyvinyl acetate	EUR	1.400		(EPDLA 2021)

Appendix 2. Emission factors of certain material recycling and combustion

Recyclables				
Material	**EF [$kgCO_2e/t$]**	**Process description**	**Credit [$kgCO_2e/t$]**	**Source**
Metals	24.64	sorting and pressing iron scrap		(Y-HIILARI 2019)
Plastics	365.87	treatment of waste polyethylene for recycling, unsorted		(Y-HIILARI 2019)
WEEE (pretreatment)	36	mechanical dismantling, shedding and sorting		(Dahlbo et al. 2011)
WEEE (material recovery)	592	metal recovery & processing from pretreated-WEEE	1890.5	EF avg. of (WWF 2018) & (Turner et al. 2015) Credit avg. of (Dahlbo et al. 2011) & (Turner et al. 2015)

Recoverables					
	Emissions				
Combustible waste	**Fossil [$kgCO_2/t$]**	**Biogenic [$kgCO_2/t$]**	**LHV [MJ/kg]**	**Notes**	**Source**
SRF (former REF)	572.4	858.6	18.0	assumed bio-share 60 %	(Tilastokeskus 2023)
MSW/mixed waste	400.0	400.0	10.0	assumed bio-share 50 %	(Tilastokeskus 2023)
Other mixed waste	1000.0	111.1	10.0	assumed bio-share 10 %	(Tilastokeskus 2023)
Wood	142.5	1282.5	12.5	assumed bio-share 90 %	(Tilastokeskus 2023)
Treated wood	136.8	1231.2	12.0	assumed bio-share 90 %	(Tilastokeskus 2023)
Rubber waste	1904.0	634.7	28.0	assumed bio-share 25 %	(Tilastokeskus 2023)
Plastic	1852.0		25.0		(Tilastokeskus 2023)
Hazardous waste	1170.0		10.0		(Tilastokeskus 2023)
Other waste	1125.0		15.0		(Tilastokeskus 2023)

Appendix 3. Confidential material

The content of this appendix may be accessed by contacting Kempower.