Model for Generating the Climate Impact of Prefabricated Power Systems

Master's thesis in Sustainable Energy Systems

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Abstract

With the ever-rising emissions, reaching the temperature below 2 degrees climate change goal is becoming more far-fetched. The current focus is on accurately calculating, modelling and finding ways to reduce carbon emissions which is escalating yet necessary for achieving sustainable solutions. This study will focus on the climate impact within the power transmission system, providing a comprehensive model for its evaluation for an electrical substation.

This study integrates Life cycle Assessment, its methodologies and the stages involved in an LCA study. Furthermore, performing an analysis of the components including the materials and working of the substation, evaluation and quantification through sensitivity analysis. A life cycle assessment (LCA) is conducted from cradle-to-grave to quantify the emissions. Real-world data are collected from various suppliers and available databases, literature reviews are conducted to enhance the model's accuracy and validation to assess the climate impact. The results and findings highlight in detail the contributing factors behind carbon emissions. Further stressing the type of energy source, materials, production, and power losses affect the outcome for the environment. The model provides comprehensive insight and acts as a tool for stakeholders and producers a step towards reducing their carbon footprint for these systems and adopting more sustainable energy practices.

Keywords: Life Cycle Assessment, Substations, Climate Impact, Carbon Footprint, cradle-to-grave.

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Ashwin Balaji and Joseph Lianminthang Naulak, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

AIS	Air-insulated Switchgear
CO_2eq	Carbon Dioxide equivalent
CML-IA	Centrum voor Milieuwetenschappen Leiden-Impact Assessment
EAF	Electric Arc Furnace
EoL	End of life
EPD	Environmental Product Declaration
EPDM	Ethylene Propylene Diene Monomer
eq	equivalent
GGBS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GIS	Gas Insulated Switchgear
GJ	GigaJoules
GWP	Global Warming Potential
HC	Hydrocarbon
HMIC(C)	Holtab Modular Indoor Concept (C)
HV	High Voltage
ISO	International Standard Organisation
kg	kilogram(s)
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LF	Load Factor
LV	Low Voltage
MCCB	Molded Cast Circuit Breaker
MCM	Multi-Compact Modules
MJ	Mega Joules
Mt	Metric tonne
MV	Medium Voltage
N_2	Nitrogen gas
NOx	Nitrogen Oxide gas
NR	Non-renewable
NS	Network Station
O_2	Oxygen gas
PF	Power Factor

PM	Particulate Matter
PN	Particle Number
R	Renewable
ReCiPe	Relevance, Endpoint and Damage Orientation
RMU	Ring Main Unit
SBR	Styrene Butadiene Rubber
SF_6	Sulfur Hexafluoride gas
t	tonne(s)
tCO_2	Tonnes Carbon Dioxide gas

Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

Parameters

P_{Fe}	Iron power loss
P_{Cu}	Copper power loss
P_{ad}	Additional power loss
T	Operating time
V	Total volume
P_r	Rated pressure
E_{em}	Emissions from material extraction
E_{fa}	Emission factor for assembly
E_{fp}	Emission factor for production stage
E_{fo}	Emission factor for operation
E_{feol}	Emission factor for end of life
E_{fs}	Emission factor for energy source
E_{ec}	Carbon Emission from energy consumption
E_{SF6}	Carbon Emission from SF_6 emission
E_f	Emission factor
E_{ft}	Emission factor for transportation
U_a	Unite assembled
E_a	Emissions from assembly
E_{ep}	Emissions from production
E_t	Emissions from transportation
E_o	Emissions from operation
E_{eol}	Emissions from end of life

L_{lf}	Load loss factor
k	Hoebel coefficient
T_l	Transformer loss
E_{ot}	Operation Emission from transformer
E_{SF_6}	Emission from SF_6 leakage
P	Power or Copper loss
L_f	Loss factor

Variables

E_{fm}	Emissions from material extraction
W_{tf}	Total loss of all transformers
F_y	Relative annual leakage rate
F	Leakage rate over a period of time
M_{leak}	Total mass of SF6 leaked
M	Rated mass of SF6 leaked
E_{total}	Total carbon emission
E_c	Energy consumption
T_d	Transportation distance
T	Time taken
P_o	No-load loss
P_k	Load loss
L_s	Lifespan
E_{fs}	Emission factor for energy source
t	Operating time
I	Current
R	Resistance
Ac_f	Actual Power loss
A_p	Apparent Power
ρ	Resistivity
L	Length
A	Cross-sectional Area

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1

Introduction

The rise in greenhouse gas emissions has seen an unprecedented effect on the world leading to climate change. With the rise in population, the rise of emissions continues to grow and ultimately the demand for energy also grows. According to the International Energy Agency [1], electricity and heat generation contribute to around 41% of the CO_2 emissions. This sparks the need for a rapid transition to adopting more efficient, innovative and sustainable means of technologies and industries and companies are pushing towards adopting a cleaner source of energy.

Prefabricated systems are production methods that offer advantages by increasing productivity and offering energy savings as the components are integrated to minimise energy consumption and reduce waste[2]. It also improves the process efficiency in terms of faster assembly time as the products come as modular units for quicker assembly as well as more efficiency in energy use with an overall reduction in energy use thereby lesser emissions [3]. Taking into consideration this transition, Holtab is at the forefront of producing and developing prefabricated power systems which are modular units that can be installed efficiently and easily to power grids [4]. These systems offer a promising solution where the components are pre-assembled off-site and the components are carefully selected for offering energy savings, thus lowering energy consumption and reducing greenhouse gas emissions. They are designed to support a wide range of applications and power requirements with different substations. However, the production and use of these systems have an impact on the environment responsible for the emissions, energy consumption and resource use. It is significantly crucial to address these challenges and requires assessing and quantifying its environmental impact throughout its lifecycle both from the environment as well as Holtab's perspective which is to reduce the environmental impact from their products and to use environmentally friendly energy alternatives and meet customer's requirements.

To address these challenges, it is crucial to study the life cycle of the power systems and their impact which is done by the widely used life cycle assessment method defined as an important method that is used to calculate the environmental impact of products. In LCA, the environmental impact linked with the lifecycle of the system is assessed and evaluated based on the life cycle inventory data that includes the material flow, both input and output and also its emissions that are gathered through various sources such as EPD, company and supplier's data associated with the product or system in study [5]. The scope of LCA is broad which is useful and valuable in avoiding the issue of shifting the problem from one phase or region or environmental impact to another [6]. It provides a comprehensive evaluation of the environmental impact throughout its lifecycle and the results can help interpret and identify the parameters that significantly contribute to climate impact.

This report presents the result of the developed model for generating the climate impact of prefabricated power systems using the LCA method. This model evaluates the life cycle of the product from the cradle to grave and a validation is carried out for stakeholders to make informed decisions about Holtab's products and it's associated impacts. The model would give producers and manufacturers an insight into their processes and provide them with opportunities for areas where improvement can be made through impact reduction recommendations concluded from this study by acknowledging the associated impacts from the products. This study also highlights the entire lifecycle processes involved during the lifetime of the products and processes that have a large impact on the environment. To facilitate a strategic informed decision and to fill in the knowledge gap for the transition towards developing a more sustainable method of production and use, this report presents an overall insight into the processes and impacts through an assessment of the prefabricated power systems.

1.1 Aim

The aim of this thesis is to calculate the environmental footprint of the power systems by analysing them into sub-components and the necessary criteria that would allow assessing their climate impact for each component effectively and efficiently. Using this, a model will be formulated based on the collected data from Holtab and suppliers that generate and measure the carbon footprint of the power systems by considering the product's life cycle from cradle to grave. The carbon footprint of the substation will be calculated and key parameters that influence the product's carbon footprint will be identified by analysing the material flow and their respective environmental performance parameters will be analysed by evaluating the impact over the lifetime from resource extraction to product disposal. Additionally, analysing the energy source would provide an understanding of the parameters that contribute the most to greenhouse gas emissions and would allow for assessing the loss utilization factor from the energy consumption of the components. Sensitivity analysis and evaluation will be carried out to validate the model through which recommendations will be made from the evaluation of the environmental impact outcome of the products. Furthermore, the project aims to provide schemes for reducing emissions through analysis of the product design and throughout its lifecycle

1.2 Objective

The goal of this project is to develop a model that would allow producers and stakeholders to provide information on the climate impact of their products. This would allow them to assess a comprehensive tool that generates the environmental impacts giving an insight into the processes that have a significant contribution towards carbon footprint. By identifying areas for improvement in the product design process involved in resource extraction, manufacturing and transportation operation and end-of-life handling, the model can provide informed decisions on developing more innovative and sustainable products. Under this study, an analysis of the cradle-to-grave and its impact will be carried out. However, an economic evaluation will not be taken into account and the scope of this study will be limited to greenhouse gas emissions only and other factors are not considered.

The questions to be investigated and studied are developed based on the goal of this project:

1. Which main factors in the processes contribute to the carbon footprint of the systems and ways to quantify them?
2. How does the type of energy source or production process have an impact on the environment and how sensitive is the model's output with the input and how can they be improved?
3. What measure can be adopted to handle the power losses arising from the use of prefabricated power systems and ways to reduce them?
4. How can the model be used by manufacturers and other interested stakeholders so as to ensure efficiency in the processes?

2

Theory

In this chapter, a literature study is undertaken based on the findings from different scientific papers and reports and other case studies. The process and the use of products are carefully studied and act as a support for further research purposes for the model. The prefabricated substations come as modular units which are assembled with ease. It consists of transformers, switchgear, sheet metal, concrete, insulators and other components. These power systems are used for generating and distributing electricity and the emission arising from these units are used for evaluating its impact by the use of data sets but there often can be inconsistencies among the LCI data sets for electrical technologies with similar configuration [5].

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool that calculates the impact of a certain product or process on the environment [7]. This analysis may be done till the production part of the product or till the waste management process. If it is done till the production part then it is called as cradle to gate analysis and if it is till the waste management then it is considered as cradle to gate analysis. The LCA is done according to ISO 14040 [8] and 14044 standards [9]. Different input parameters (energy and material) and desired and acquired output needs to be considered at each stage of the LCA.

For performing a study and analysing of the impact of the prefabricated power systems, the following stages are considered:

- **Sourcing of Raw materials**: This is the initial step which requires extraction of raw materials which is used for the production of components or products.

- **Production**: After the initial stage of sourcing the raw materials, they are obtained to produce each of the components. These raw materials go through different processes in this stage to get the desired components of the product.

- **Assembly**: Once the required components are produced, they are assembled and fabricated at the assembly site where the components are assembled together to produce the finished product.

- **Operation**: This stage covers several aspects of the product during its lifetime. The energy consumption by the product is considered which includes electricity consumed and heat generated. Also, the waste generated during its lifetime could be losses arising from the use of the system and can be both direct or indirect waste. Additionally, during its lifetime, the utilisation factor is an important criterion in determining the efficiency of the product to calculate if the product is being utilised to its required capacity.

- **End-of-life**: This stage is the decommissioning stage where the product has served its purpose up to its service life and its performance does not perform to its full capacity and is called the product has reached its end-of-life stage. The parts of the components are dissembled and are either incinerated, disposed or recycled. Incineration and disposal are less favoured due to environmental concerns. Recycling is most favoured due to less need for extraction of raw materials as some of the materials can be reused for new products and reduces the burden on the environment.

The method for carrying out LCA as defined by the ISO standards [8][9] involves the following phases:

- **Goal and Scope definition**

In this step, the main objective and purpose of the study are established which involves setting up various system boundaries such as geographical boundaries and Temporal boundaries. One essential aspect to consider in an LCA study is the functional unit, where the quantity of a product is determined with respect to its performance, which is also defined in this step.

- **Life cycle Inventory**

In this step all the required data are gathered based on the energy demand of the various processes, the materials used and emissions of the various processes involved in the above-mentioned stages. These data can be sourced from the available databases like ecoinvent, literature reviews and EPDs (Environmental product declaration).

- **Impact assessment**

All the data gathered from the inventory analysis is used to calculate the environmental impact of the product. These impacts are assessed across various categories like Global warming potential, ozone layer depletion, eutrophication, etc. Impact assessment methods like ReCipe and CML-IA are used for the assessment.

- **Interpretation of results**

This step involves a thorough analysis of the results from the impact assessment. The results are summarized and the issues from the study are highlighted. The accuracy of the results and the completeness of the study is validated and verified.

- **Improvement strategies**

The main purpose of LCA is to analyse and evaluate the total emissions of the product throughout its lifetime and to identify solutions for reducing the emissions. So in this step, the results and their interpretation are used to unearth areas and processes where the product has the potential to be more sustainable, reducing the overall environmental impact of the product.

2.2 Substation

A substation is a component that provides the distribution of electricity. There are numerous components like transformers, circuit breakers, busbars and among others playing a crucial role in the transformation of power [10]. According to literature from Sun et al.[11], carbon footprint analysis is used which is an analysis method that mainly includes the input-output method, emission factor method and LCA method with the latter being the most widely adopted method of calculating the carbon footprint [10], while in another literature study Lenzen [12] used process analysis method which is used to calculate the emission of substations. The process analysis is a bottom-up approach that considers the environmental footprint of products throughout their lifecycle taking into account the various stages and processes involved in it [13]. However, it does not establish a deep analysis of carbon emission mechanism or carbon measurement models for substations [10].

Establishing a carbon measurement model requires a deeper analysis of the substation such as losses, power consumption and other aspects to be considered and carefully studied. In the literature [14], a hierarchy process has been established for creating an energy efficiency index in substations and does not establish a correlation between the substation's energy consumption and carbon emission data and in the literature of He et al.[10], the carbon emission mechanism by using a 500kV gas-insulated substation for conducting a practical carbon measurement model with an in-depth analysis of the carbon emissions arising from the substations is taken into account.

Two mechanisms namely Carbon emissions from Energy consumption of substations and Emissions of Sulphur Hexafluoride Gas are identified and analysed in [10] which are the main carbon emissions components. Leakages from SF_6 gas are considered relatively small however, the effect resulting from the emissions cannot be disregarded [10]. The literatures studied have also concluded that although the use phase has the highest environmental impact, the associated environmental impact per unit time during resource extraction and production has a greater significant impact [15][16].

2.2.1 Transformers

Transformers are the main component in a substation and its efficiency is characterised by two factors namely no-load and load losses [17]. According to the European Union, the operational efficiency of transformers is on average 98.38% during its service life which is around 30-40 years [18]. Also, transformers act as the core equipment and losses from transformers contribute the most to carbon emissions [10]. No-load losses occur due to changes in the magnetic flux by the core which requires energy to keep it constant while load losses also known as copper losses [10] occur in the conducting materials of the windings due to resistance losses [19]. The resistance of the copper wire and its associated copper loss ultimately increases due to the presence of skin and proximity effect. The secondary side current of the transformer is dictated by the load and is known as load losses while stray losses occurring in wires and shells are linked to the load, in practical applications, their magnitude is small and is usually disregarded [10]. It is important that there is an evenly distributed load among the phases to prevent voltage imbalances as a result of which can affect the efficiency and cause damage to the system this is why a balanced distribution of loads prevents one phase from getting overloaded adding to more losses [20].

According to [21], the losses contributed by the total electricity flowing through the transformers is less than 1% but have a significant contribution over its lifetime where load losses are responsible for 66% and no-load losses to 16% of GWP100. According to [10], the total loss in a transformer is given by:

$$W_{tf} = (P_{Fe} + P_{Cu} + P_{ad}) * T \tag{2.1}$$

where:
W_{tf} = Total loss of all transformers in the substation
P_{Fe} = Iron power loss of transformer
P_{Cu} = Copper power loss of transformer
P_{ad} = Additional power loss of transformer
T = Selected operating time
It should be noted that this equation is only valid under constant loading conditions which is not always the case in real-world scenarios as the system is often subjected to variable loads.

2.2.2 Switchgears

Switchgears are another important part of the substation that functions as a switch by breaking the current flow. There are mainly two types of Switchgears: Air-insulated and Gas Insulated Switchgears (GIS). The most widely used switchgears are GIS due to their compact size and operation [22]. GIS are equipped with Sulfur hexafluoride (SF_6) gas due to their excellent electrical insulation properties and performance [23]. Even though it is considered good, they are also a destructive greenhouse gas with a global warming potential of 23,900 times more than carbon dioxide and a long life cycle of around 3,200 years [10].

The gas is mostly used in equipments requiring high tightness, however, there are emissions and leakages always involved due to aging of sealants, poor gas tightness, improper installation of equipments [24][10]. According to [10], the leakage from SF_6 is can be estimated as shown here:

$$\begin{cases} F_y = \frac{F*31.6*10^6}{V*(p_r+0.1)} \times 100\% \\ M_{leak} = M * F_y \end{cases} \tag{2.2}$$

where:
F_y is relative annual SF_6 leakage rate;
F is the SF_6 leakage rate over a period of time obtained in the gas leakage inspection test (MPa*m3/s);
V is the total volume of the closed gas container (m3);
p_r is the rated pressure of the SF_6 in the equipment (MPa);
M_{leak} is the total mass of the SF_6 leaked by the SF_6 electrical equipment in the substation;
M is the rated mass of the SF_6 in the SF_6 electrical equipment

In the report [25], development for a free SF_6 gas GIS was described by using dry air as the insulation gas. Since SF_6 gas is a greenhouse gas having a long atmospheric lifetime, three activities are undertaken: 1) minimizing the utilisation of SF_6 gas; 2) mitigating the gas released from SF_6 through recycling; 3) adopting environmentally friendly alternative gases [26]. Efforts made for developing a more compact design have resulted in the lesser utilisation of the amount of SF_6 to less than 40% but due to its limitations on the design, it became challenging to further reduce the amount of SF_6 gas for GIS. The paper adopted dry air, N_2 and N_2/O_2 mix as an alternative for SF_6 gas and concluded that out of these three, dry air proved to be the most suitable [25].

2.3 Carbon Measurement Model

The study conducted by [10] represented a carbon emission model of substation given by

$$E_{total} = E_{ec} + E_{SF_6} \tag{2.3}$$

where:
E_{total} = Total carbon emission of substation
E_{ec} = Carbon emission from energy consumption of substation
E_{SF_6} = Equivalent carbon emission from SF_6 emission in the substation

According to [10], the carbon emission mechanism was analysed according to the composition of the substation whereby losses, emissions and energy consumption were first analysed and then models were established based on the data collected from the mechanism performed. This paper focuses on the research method for the development of a carbon measurement model through scenarios of emissions, however, it does not discuss the processes contributing the most to climate impact and solutions for reducing its impact.

In an LCA study made for GIS substation, two cases were made, one for a high load which operated at 40% of the time for 100% load and a reduced load operated at 60% of the time for 50% load. Based on these cases, it was observed that the construction phase has a higher impact in 10 out of the 15 categories but the impact increases to 13 out of 15 when the reduced load is studied [27]. Research for newer development for reducing SF_6 gas emissions is undertaken involving a more environmentally friendly mix of gases and technologies [28].

According to [27], an alternative solution was evaluated by replacing the double multi-compact function modules (MCM) with 3 single-bar MCMs that would reduce the total SF_6 gas to 57kg and a loss reduction from 71kg to 48kg during its 40 years of lifecycle and additionally 30% reduction of materials required for construction.

For calculating the carbon footprint of substation, the main data required is the materials and their emission factor. According to [29], the method of calculating the carbon footprint is given by:

$$E = \sum_{i=1}^{n} A_i F_i \tag{2.4}$$

where: E is the emission of substation;
n is the number of materials;
A_i is the quantity or intensity of the i^{th} material; F_i is the emission factor of the $i^t h$ material

2.4 Materials

Several types of materials are involved in the manufacturing of components for the substations. Even though the components come as prefabricated modular units, the materials involved during the manufacturing and production of components need to be taken into consideration. In analysing the lifecycle of products, the material used in the production is carefully analysed. Metal is the main material used in electrical equipment [29] and the process of material extraction and production involves a significant amount of emission. Steel, copper and aluminium have the largest share of metal material composition in substations.

2.4.1 Metals

Metals play an important role in the material composition of substations being an integral part of the electrical components that range from providing a support structure to electrical conductivity to protection of equipment and personnel. The primary production of metal consists of several steps of mining and concentrating the ore followed by smelting in a furnace and separating to obtain a refined metallic form [30][31]. Different literature has published the study on the production of metals and their associated environmental impact using the LCA method using different tools and analyses. A comprehensive assessment was made by Westfall et al. on the cradle-to-gate lifecycle of global manganese alloy production to provide insight into the environment and economic performance of these alloys [32]. It was also concluded in two other studies that the most driving factor for environmental impact is the utilisation of resources [33][34]. A thorough quantification and comprehension enable us to better understand the impacts of metal production and its associated resource use [35]. The conductor materials in the power cables rely on aluminium and copper as its primary metal and the support structure is primarily composed of steel in transformers and substations [36].

2.4.1.1 Copper

Copper is one of the key materials used in a substation. The main purpose of these copper parts is to provide earthing to the substations. There are a lot of processes involved in the production of coppers like mining, smelting and refining. Therefore, there is high energy demand to complete these processes. Global demand for copper production is around 600 million GJ of energy, which contributes to 0.21% of total GHG emissions from the metals [37]. Additionally, Copper production is energy intensive and has a large environmental impact with the depletion of resources [38]. According to UNEP, the primary production of copper being energy intensive requires about 30 MJ/kg to 90 MJ/kg with energy savings from the recycling process constituting about 84% to 88% [39].
Furthermore, it was reported that the energy required from secondary sources is between 6.3 MJ/kg [40] and 14.9 MJ/kg [35]. With this high energy-intensive, high CO_2 emissions are involved. It is significantly important to identify the potential benefits arising out of a reduction in energy consumption through increasing the recycling rate of copper materials and by implementing renewable sources for its production that could drastically reduce the environmental impact.

2.4.1.2 Aluminium

Aluminium is another conductor material that is used due to its lightweight and good electrical conductivity. However, to carry the same current as that of copper, a much larger conductor of aluminium is required [41] meaning as compared to copper, aluminium has a lower electrical conductivity. In addition, the production of aluminium is energy intensive and the energy required for the production is around 200-220 GJ/t [42] making it higher than the production of copper. According to T. Peng et al.[43], the energy consumption associated with the primary production of one ton of aluminium is 144612 MJ resulting in about 14772.72 kgCO_2eq. A study conducted by Dimos Paraskevas et al.[44] selected 29 different countries and stated that the primary emissions are contributed by indirect emissions that account for 65% evolving from electricity production giving a view that the overall environmental impact is dependent on the energy mix used in the production of Aluminium. Since no specific data for the consumption of electricity mix is made available, so an average of national electricity production is taken and analysed [44]. The International Aluminium Institute stated the energy required for primary aluminium production is on average 66 MJ per kg in 2012 with the Hall-Héroult process [45]. The study made by Dimos Paraskevas et al.[44] concluded that the emissions from the aluminium industry were responsible for the emissions of 861 Mt of CO_2eq. in 2012 and China was the highest country producer accounting for 56% of total CO_2eq. emissions and 54% of global impact and the energy mix is the driving factor in its impacts which could be overcome by cleaner sources and more efficient energy use [44].

2.4.1.3 Steel

Steel is the major material component in the substation and is produced extensively in many parts of the world. Blast furnace technology is still the most dominating technology used to produce steel from iron ore. For every tonne of steel produced, 1.89 tonnes of CO_2 is released in the atmosphere [46]. The substation is always exposed to the environment and to protect the steel from corrosion there is usually a layer of alloy coating. Metallic-coated steels are steel substrates that are coated with alloys mainly with zinc, aluminium and magnesium and have several technological, economical and environmental performances over other types of alloys and these metallic coatings are mainly produced by two types: The hot dip coating process where the steel is dipped and immersed in a molten metal bath and electrodeposition where metal is deposited electrolytically on the cold steel [47]. From an environmental perspective, the production process takes into great consideration the environmental impact throughout the production process. According to Arcelor Mittal's brochure [47], targets for improving efficiency and reducing water consumption are made and the products are lead-free. Reduced material coating from excess coating with improved consistency is also achieved.

2.4.1.3.1 Hot-dipped galvanised steel

Hot-dipped galvanised steel is is another important material used in the substation. The galvanised coating has an outer layer of pure zinc and multiple inner layers of an intermetallic alloy layer of zinc and iron [48]. When dipped in a hot molten bath of zinc, the thickness of the zinc-iron alloy layer decreases by reducing the solubility of iron in zinc and enhancing the ductility of the coating [49]. It has the advantage of self-healing capability which offers a corrosion resistance property and along with the coating provides dual protection thereby increasing its lifespan and this dual protection offers unique features with the first layer formed by creating a barrier between the metal and the external environment and the second protective layer arises from the formation of a galvanic element when the metal is exposed to moisture [50][51].

2.4.1.3.2 Specially coated steel

This coated steel is a carbon steel that is coated with zinc, magnesium and aluminium as alloys and has exceptional corrosion resistance properties even in the most hostile environments. It has a unique composition that provides a durable layer and stability giving it more effective corrosion protection than other metals with lower aluminium and magnesium content. There is a significant argument and dispute between the traditional zinc-coated products and these new emerging alloys asserting better performance and improvements in these alloys exhibiting enhanced corrosion resistance [52].

2.4.2 Insulation materials

Insulation materials are used in the substation for insulation that provides protection and prevention of leakages of current [53] highlighting the importance of possessing properties that have high electrical insulation resistance, a high mechanical strength-to-weight ratio, high thermal conductivity, easy moulding and lower maintenance cost [54] [55].

Porcelain and glass have been used in the past [56] but their complexity of maintenance due to their bulkiness becomes a challenge [57]. As an alternative to this, polymers and plastics offer promising solutions and greater benefits due to their chemical composition and ease of fabrication for complex designs [53]. Their lightweight nature, compact design and ability to mitigate and prevent consecutive failures offer several advantages [58] [59]. Epoxy resins and ethylene propylene diene monomer also known as EPDM are the commonly used materials for insulation. These polymers have a low thermal conductivity and are affected by high temperatures leading to their degradation [53]. However, they can be enhanced by using an intrinsic thermal conductive polymer offering high thermal conductivity [60] and by making a polymer composite with a filler that has high conductivity however, both have different disadvantages with the former being high cost and complex manufacturing process and the latter with difficulty in comparing its thermal conductivity due to variations in the filler properties. Under this literature, the difference in the relative permeability and the electrical conductivity of the filler and the polymer needs to be small to help obtain a higher dielectric strength [53].

Furthermore, the contamination in the insulation materials also poses a risk during the operation of the systems especially in coastal areas and in industrial and agricultural zones from pollutants such as salts, dust, feces, etc [61] [62]

2.4.3 Sulphur Hexafluoride gas insulation vs Air insulation

SF_6 gas is known to be the most effective insulator and has been used for many years now. The main reason is its dielectric property, making it better than air insulation [63]. However, it is a Greenhouse gas with long-term effects on the environment and alternative options can't be ignored whilst keeping sustainability in mind.

There are many advantages for using SF_6 as an insulator.

1. It does not require a lot of space therefore a more compact design of the switchgear can be implemented.

2. It has lower noise pollution levels.
3. Most importantly, it is a much safer option as it is less likely to be a fire hazard.

These factors make it possible for the substations to be installed in populated areas and harsher environments without worrying about fire accidents [63].

2.5 End of Life

End of Life stage of a product is when the product can no longer be used by the consumer and the product will either be recycled, processed as waste or a combination of both. The emissions from different EoL methods would be different, with Recycling being the most environmentally friendly.

2.5.1 Recycling

After the use phase of the substation, the unit is completely deconstructed and all the components go through different end-of-life treatments.

2.5.1.1 Steel

Steel has a very high recycling potential which ends up saving a lot of energy when it comes to the production of steel from the extraction of raw materials [64].
Unlike the primary production process of steel which uses raw materials like Iron ore and limestone, the secondary production process uses steel scrap which is processed in an electric arc furnace [65].
The primary production process also uses coal which results in higher environmental impact whereas secondary production uses an electric arc furnace which runs on electricity and requires no coal. Therefore, in theory, if the electricity supply to the EAF is from renewable sources it will be more environmentally friendly compared to blast furnaces.
Steel can be recycled as many times as desired, which not only reduces carbon emissions but also reduces the waste in landfills and saves natural resources like iron ore, coal and water [66]. As the steel goes through multiple cycles of recycling, out of all steel produced to date, 70% is still being used [66].

2.5.1.2 Copper

It is important to maximize the recycling of copper as it has double the emission compared to steel per metric tonne [67]. There is no degradation of quality when recycling copper. However, the process of recycling copper is much less energy intensive compared to producing copper using raw materials. From 2009 to 2018, 32% of the copper used across the globe was from recycling [68]. That being said, the copper demand is increasing day by day and it is not possible to meet this demand only through recycling and primary production processes have to be used. Additionally, the copper scrap might have impurities that make it difficult to maintain the conductive properties. So, additional purifying processes might have to be used, which will increase the energy consumption [69].

As recycling copper can reduce the environmental impact and reduce the need for extraction of virgin materials and their associated emissions and save energy and to better understand the end-of-life handling process of copper, the following steps are carried out when recycling copper [70]:

1. The first step is to separate copper from any other material, for example, an insulative material like plastic.

2. After separating the copper from other materials, it is segregated according to the grade. If the copper has a lower grade, then there will be additional treatment processes to improve the quality. Whereas, if the copper is already of a higher grade, then it doesn't need any treatment and can be melted directly.

3. After the sorting, there will be a quality check where the metal is once more checked for impurities.

4. Finally, the copper is melted in a furnace at a temperature of 1084°C[70]. This melted metal can be cast into any required shape.

2.5.1.3 Sulphur Hexafluoride Gas

Components like switch gears in a substation use SF_6 as insulation and it is important to recycle this gas has global warming potential on the higher side [71]. The GWP of 1 kg of SF_6 has the same greenhouse effect of 22,800 tonnes times more than tonnes of CO_2 [72] according to the Fourth Assessment Report of Greenhouse Gas Protocol which was further changed to 23,500 in the Fifth Assessment Report [73]. SF_6 gas in itself is not harmful but if the used equipment has decomposed solid SF_6, it is toxic and corrosive. Therefore, the transportation and processing should be carried out carefully.

The switchgear is first dismantled and all the metals are separated and sent for recycling separately. The casing of the SF_6 gas with the gas itself is handled separately with care to prevent any leakage. Then the SF_6 casing is connected to a pump, where the gas is extracted in separate bottles suitable for storing SF_6. These bottles are then sent for purification of the gas (Excess moisture and decomposed SF_6). The recycled SF_6 is reused in other electrical equipment [72].

2.5.2 Waste Management

Not everything can be recycled and reused. When it cannot be recycled, it is then considered waste that needs to go through incineration or landfill.

2.5.2.1 Incineration

In this process, the waste is burned and converted into heat. This means that there will be levels of CO_2 emissions and negative effects on the climate. However, this process can be used to gain some benefits. For example, Sweden uses waste combustion to complement heating demand [74]. One more advantage of this process is that it does not occupy land space and there is not a lot of transportation of waste involved. Therefore, lesser transportation emissions.

2.5.2.2 Landfill

In a landfill, huge amounts of waste are dumped on empty land far from the human population. With a landfill, there is no burning of waste, so there is lesser emissions than Incineration. However, there are methane emissions which also have negative effects on the climate [74].

3

Methodology

3.1 Scope

Holtab specialises in two types of substations, HMICC and NS stations. Due to HMICC's complex design and considerable variabilities, the gathering of relevant data poses a challenge. So this study is limited to the NS substations. This thesis is focused on building an LCA model for the substation from cradle to grave with the stages from the extraction of raw materials and manufacturing of components to assembly including the transportation, operation and end-of-life stages. The geographical boundary for this study is confined to Europe with a particular focus on Sweden which aims to provide insights from the region's perspective. This would allow a particular focus and enhance its relevancy in the stated context. Further, it would also allow the findings to be interpreted and closely aligned with the sustainability practices of the region. The system boundary is defined from cradle to grave and includes all the emissions and environmental impact up to the end-of-life handling of the products. The functional unit of this study is one unit of substation over its lifetime.

3.2 Data Collection

Data collection is one of the most crucial steps within an LCA study as the accuracy of the study depends a lot on the quality of the data used and its outcomes. The data concerning the energy consumption for manufacturing each of the components of the substation have been sourced and collected from various suppliers of Holtab. The data for the energy mix used in the production of copper and steel are supplied by the concerned suppliers. This also allows us to differentiate the type of energy source whether it is renewable or non-renewable energy source giving a concrete idea of the process. For components like switch gears and transformers, the Environmental Product Declaration(EPD) are gathered for assessing the database. For the assembly phase at Holtab, the focus is on the electricity consumption used for assembling the parts into a finished product for assessing the carbon footprint. Transportation is heavily reliant on trucks (Lorry) and some ships (Ferries). When it comes to the use phase, the electricity losses are considered and the Swedish electricity mix is used for this study. The emission factor from resource use, energy mix, transportation and fuel consumption are sourced from the Ecoinvent database 3.8 [75][76] and analysis is performed in Mobius Ecochain software. The end-of-life management data for each component will be taken from the same EPDs taken for the manufacturing stage. Various data from the existing literature studies are used to account for any missing data, which will be referenced and cited throughout the report. All the data used in the model are aligned with the product lifecycle of 40 years with relevance to real-world scenarios.

3.3 Process flow

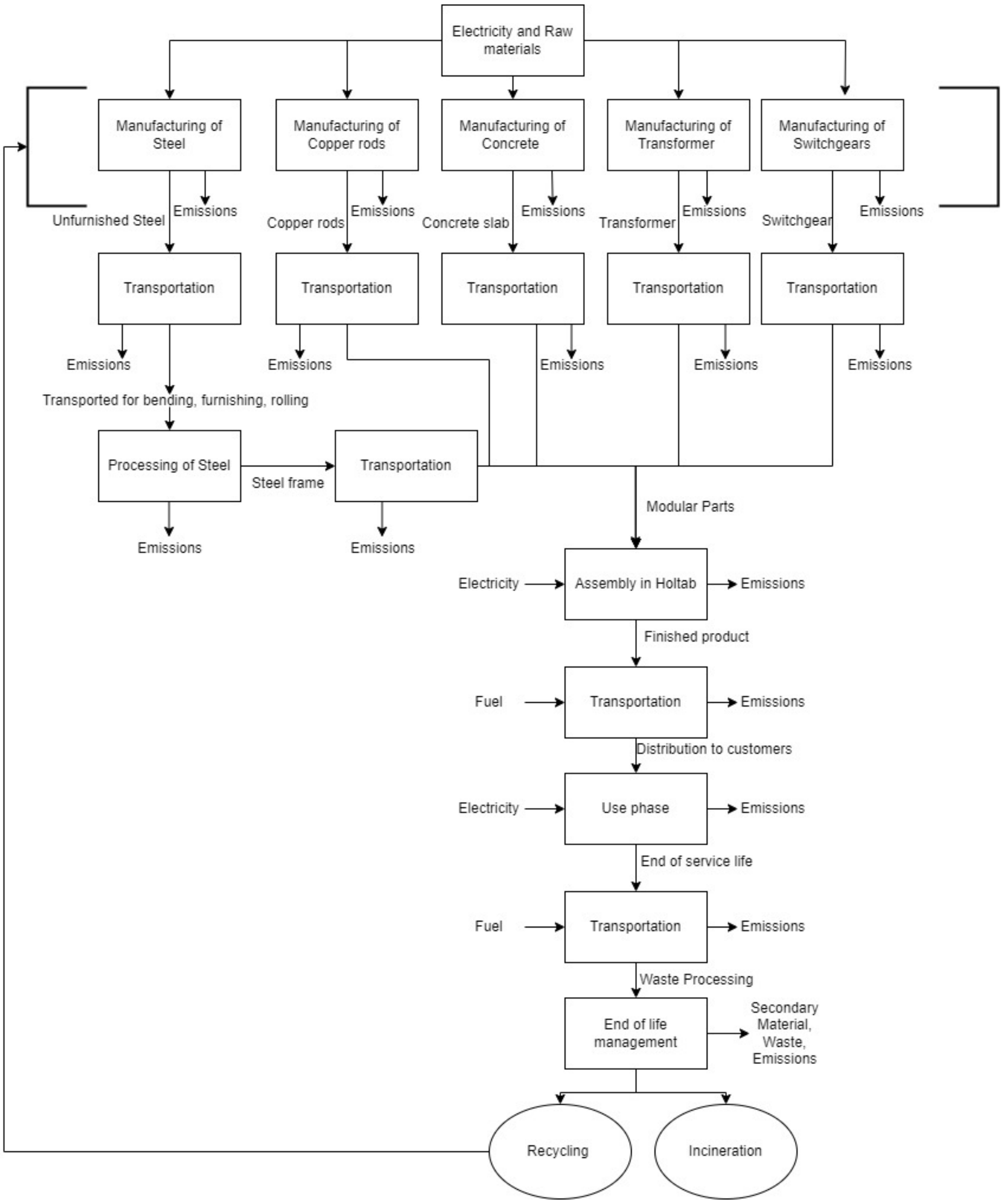

Figure 3.1: Flowchart for the lifecycle of prefabricated power systems

The flow process figure represents the process flow of the lifecycle of prefabricated power systems from the material extraction to the end of life i.e., cradle-to-grave emphasising the assessment is carried out beyond the assembly and distribution. It highlights the order in which the flow takes place and provides an understanding of the sequence for each process. Arrows represent the process and material flow and demonstrate that an impact in one stage can influence the next stage of the process which involves emissions and energy consumption implying the need for careful assessments for comprehensive planning and considerations to be undertaken for reducing the carbon emissions and sustainable planning. The labels at each stage provide information on what is occurring for each process and are used for conducting the study and actionable decision-making. The flowchart ends with two bubbles which demonstrate an action undertaken after the end-of-life whether the materials are recycled or incinerated.

To assess and analyse the climate impact of prefabricated power systems, a model is developed that incorporates the various factors and parameters involved during the product life cycle.

Components: This is the initial stage where the prefabricated system as a whole is broken down into smaller components and studied. In this study, the main components studied are transformers, switchgear, the substation frame and the concrete slab used as a foundation for the substation. The data for these main components are gathered from relevant sources and their impact is analysed as they have a large share in the substation composition and are considered to be the major contributors to the overall climate impact. The other smaller parts are not included in this study as the relevant data including the production processes are not available and their share in the total material composition is relatively small as compared to the other components and their impact contribution is assumed to be minor.

Emissions: The emissions consist of emissions arising from production, transportation, assembly, operation and end-of-life. The emissions associated with the Production include emissions from resource extraction, transportation of the materials and the manufacturing processes. These emissions arise from energy consumption during the three processes and the data are drawn from the available EPDs and other sources provided by the suppliers. The emission factor for each material associated with the production process such as smelting processes is also considered to provide more accurate results. Transportation-related emissions arise from the transportation of the various components to the assembling site. The mode of transportation is based on the considerations and industry needs which is mainly trucks(lorry) or Ferries(ship). The emission factor is represented by tonnes-km which is the distance travelled by the weight of each component and the emissions produced from it. The distance, type of fuel and weight of the component has an influencing factor on the emissions. Since the components come as modular units at the assembly site, the emissions generated during the assembly process are accounted for. This includes the energy consumption during the assembling together of the components, connections and type of equipment used. Further, the emissions arising from energy consumption and losses from operation and end-of-life are also carefully analysed.

Evaluation: Evaluation for the quantity and type of energy source used is essential in carrying out an evaluation for assessing the energy mix either as non-renewable or renewable energy sources and by considering their impact on energy use. The outcome is to have a comparison of the differences in the amount of emissions and the potential for improvement in energy efficiency. By analysing the emissions, considerations for weighing can be made against the background of cleaner sources of energy such as renewable energy giving us a better evaluation of the impact for mitigating and reducing emissions.

Calculation and Sensitivity analysis: A sensitivity analysis is important to understand the contributing factors by varying the key parameters involved such as energy consumption, type of material and its emission factor, type of transportation and distance, etc. By performing this analysis, the impact on the climate can be evaluated by comparing the different scenarios and identifying which factors contribute the most. Further, the study is also compared with different literature and data sources and identifying the key trends.

To quantify the emissions for the different processes, an equation is developed that can be used for calculations of the emissions. To quantify the related emissions during material extraction, an equation represented below is used to perform the calculation:

$$E_{em} = E_{fm} * W * E_c \tag{3.1}$$

where:
E_{em} is the emissions from material extraction
E_{fm} is the emission factor for material extraction
E_c is the energy consumption
W is the weight of the material

This equation 3.1 is used for calculating the emissions related to resource extraction by multiplying the weight of the material with the emission factor. Here, the emission factor is the emission associated with the extraction per unit of material. W is the weight of the material extracted to be used for production in kilograms. This equation provides an estimation of the emissions involved during the material extraction phase.
Data on the type of material and their corresponding quantity is collected from the suppliers and the emission factor for each specific material is taken from literature and other sources.

The parameters are analysed and varied based on factors such as transportation distance, emission factor, type of energy source used, etc. For some of the materials, transportation is carried out within the country from the resource extraction to the production site while some are imported from other countries and for some a lack of data for transportation is observed which includes the type of fuel used or the distance. However, an estimated data and emission factor are assumed. During the manufacturing stage, the type of energy used plays a major role in the outcome of the overall impact of the substations. The impact of the use of renewable energy integration is calculated and is then replaced by non-renewable energy. The two are

compared to analyse the impact of resource use. Considering the transportation, a baseline is set at 100 kms. A range is selected between 80 and 120 kms with each increment of 20 kms. The outcome of the emissions are calculated for each distance and recorded and evaluated.
Further, we analyse our calculations with that of the available LCIA carried by the suppliers.
For calculating the emissions during the production phase, the equation is represented by:

$$E_{ep} = E_{fp} * E_c \tag{3.2}$$

where:
E_{ep} is the Emissions from production or manufacturing
E_{fp} is the Emission factor for production stage
E_c is the energy consumption

This equation 3.2 is used for calculating the emissions during the manufacturing or production phase by multiplying the energy consumption during the process with the emission factor involved with the energy consumption. Energy consumption is the amount of energy consumed for the production of the components and the emission factor is the emissions from the sources such as using electricity or other sources. The source could either be fossil fuels or renewable fuels. The relevant data from what type of energy source is used and the consumption intensity.

Emissions from the assembly phase can be calculated by:

$$E_a = (U_a * E_c) * E_{fa} \tag{3.3}$$

where:
E_a is the emissions from the assembly of products
U_a is the unit assembled per unit time
E_c is the energy consumed
E_{fa} is the emission factor for assembly

After producing the materials, they are assembled at the assembling site. To calculate the emissions associated with the assembly stage, the time for assembling is multiplied by the emission rate. Assembly time is the time taken to assemble the components. The energy consumed here represents the emission generated when the energy is consumed during the assembly process and the company's estimate is used for this data.

Transportation also has emissions which can be represented by the equation:

$$E_t = (T_d) * E_{ft} \tag{3.4}$$

where:
E_t is the emissions from transportation
T_d is the transportation distance in tonnes-km

E_{ft} Emission factor for transportation
The emissions from transportation are calculated in tonnes-km by multiplying the distance covered or travelled with the weight of the material and the associated emissions stemming from the weight of the material from the transportation of the components to the customers. The mode of transportation carried out is mainly either by ship or truck. The weight of the components or materials influences the emissions from transportation.
Emissions from the operation or use phase are represented by the equation:

$$E_o = E_c * E_{fo} \tag{3.5}$$

where:
E_o is the emissions from operation
E_c is the energy consumption
E_{fo} is the emission factor for operation

Emissions from the end-of-life phase are represented by the equation:

$$E_{eol} = E_c * E_{feol} \tag{3.6}$$

where:
E_{eol} is the emissions from end of life
E_c is the energy consumption
E_{feol} is the emission factor for end of life

3.4 Substation

The housing is a steel structure with a concrete base and an assembled unit of corrosion-resistant sheet metal [77]. The substation has separate compartments for each of the components. High voltage compartment: This compartment is equipped with an SF_6 insulated switchgear of the range 12-24kV [78]. Low voltage compartment: This compartment is equipped with the low voltage unit which can be either an open distribution board with a busbar spanning along the length of the assembly or a metal-enclosed modular switchgear and switch fuses and MCCB can be used for switching devices [77]. Transformer compartment: The transformers are equipped between the HV and LV compartments. The transformer is connected by cables with the HV and LV components.

3.5 Components

3.5.1 Steel structure

The substation housing is made up of steel structure and in order to withstand harsh environmental conditions and to prevent corrosion the steel sheets are coated with a material that lasts for a long time. The input data for the steel is taken from the

EPDs provided by the suppliers. This EPD report covers all the processes involved in the extraction of raw material to the coating of the steel sheets. Additional data on transportation is also obtained which allows us to understand the emissions produced during transportation. The coated steel sheets are then sent for further processing such as cutting and bending according to the design of the substation.

3.5.2 Transformer

The transformer used for this study is a 100 kVA transformer taken from open access EPD [79]. The data was obtained from the company supplier and used for the upstream processes. This includes raw material extraction, treatment, fabrication and complete assembly of the transformer. To assess the impact of the transformers during operation, the losses from the transformers are considered. Here the losses arising from the transformers are calculated by the sum of the load losses and no-load losses, same as in [10]. Load losses occur when the transformer is in operation and no-load losses occur irrespective of whether the transformer is in operation or not. According to Statista [76], the emission factor of Sweden for the energy source is 0.045 kgCO_2/kWh. To calculate the emissions from the operation, the following formula is used:
Transformer losses:

$$T_l = P_o + P_k \tag{3.7}$$

where T_l is Total loss from the transformer
P_o is the no-load losses
P_k is the load losses

Operation Emissions:

$$E_{ot} = T_l * E_{co} * E_{fs} * t \tag{3.8}$$

where E_{ot} represents Operation Emissions from transformers
E_c is the energy consumed
E_{fs} is the emission factor for the energy source
t is the operating time assumed to be 8760 hours.
The total emissions are calculated by the sum of operation emissions and the emissions from energy consumption. Load loss factor [80]:

$$L_{lf} = LF^2 * k + (1 - k) * LF^2 \tag{3.9}$$

where:
L_{lf} is the load loss factor
LF is the load factor
k is the constant coefficient also known as Hoebel coefficient [81] and is taken as 0.2 for distribution transformers [82]

3.5.3 Switchgears

The data for switchgear used was based on the open-access database of the EPD available online. In this study, the switchgear used is high voltage switchgear. The functional unit is 1pc of Switchgear over its lifetime. The material composition does not include the packaging, however for the impact assessment, the packaging is included and some of the materials that have a small contribution to the composition and impact are omitted from this study as their contribution to the overall impact is very small and minute.

The specific type of materials under each category is identified to analyse the environmental impact contribution of each material. This switchgear has employed the use of SF_6 gas but the amount of SF_6 gas used is very small compared to the other materials. Each material is entered in an LCA software along with their respective weights. Under each material, their impact is assessed with a focus on the production from the Ecoinvent database and for our assessment, the European region is taken as the reference region. The EPD was easily accessible and gave us a comprehensive analysis of its impact. To assess the impact of the switchgear during the use phase, it is assumed that there is no leakage of SF_6 gas. The following expression is used for calculation:

$$E_o = E_{ce} * L_s * E_f \tag{3.10}$$

E_{ce} is the Emissions from energy consumption
E_f is the emission factor (Sweden)
E_o is the total emissions from operation
L_s is the lifespan of 40 years

3.5.4 Concrete slab

The concrete forms the base of the support structure for the substations. Portland cement and aggregates constitute the majority of the material used for the production of concrete. Aggregates such as gravel, sand and rock materials are used and constitute about 73% of their total weight. The manufacturing process consists of mining the aggregates at a quarry mine where they are later dumped in pockets to be passed onto a conveyor belt where the mixing takes place in the mixer. The additives are added and cement is later blown into silos. After a certain period of time when all the materials are mixed, they are directly transported into the truck and transported further to customers.

3.5.4.1 Flow Process

The process consists of 5 phases as shown in Fig.3.2. Module A1 consists of the manufacturing of raw materials which includes material extraction and material production, A2 is the transportation of materials to the production site. The materials are transported to the production facility where the materials are cast for the production of the concrete slab in A3. The concrete is then transported in A4 to the assembly site where the concrete base is used as the supporting structure for the substation in A5. The final product is then transported to the customers.

The concrete slab for this analysis is 1 cubic meter provided by the EPD from Holtab which is around 2500 kgs, a value slightly higher than the total material composi-

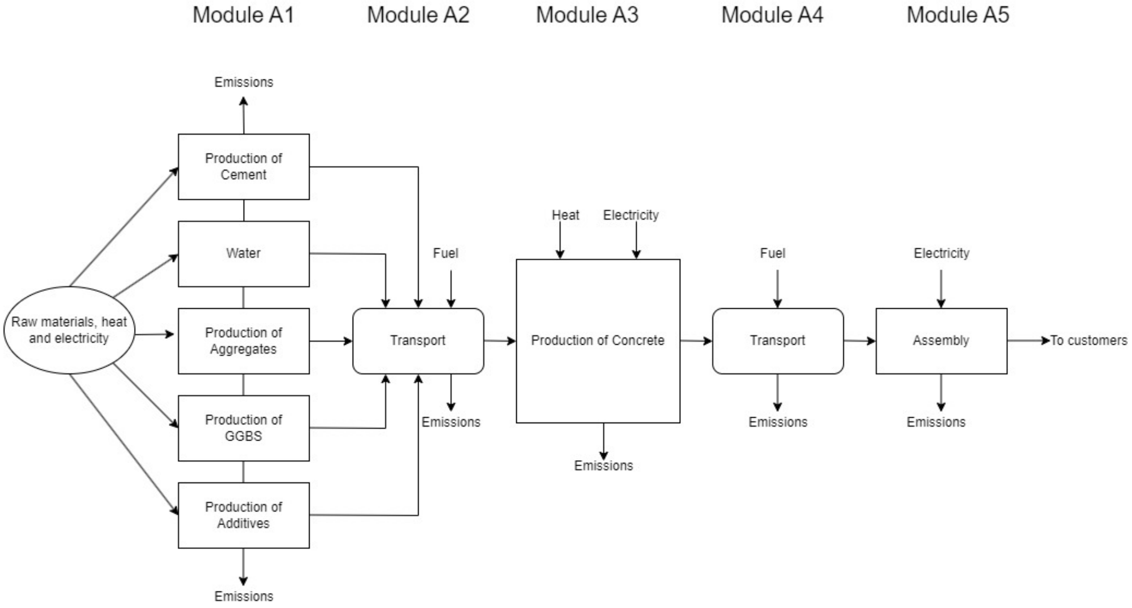

Figure 3.2: Process flow for the production of concrete [4]

tion. However, the total weight of the material used by Holtab is adjusted for this study amounting to a total of 2272 kgs and their associated emissions are calculated in Ecochain software. Additionally, the type of vehicle used for all transportation processes is assumed to be carried out by Lorry(Truck) and the total distance is assumed to be 140 kms.

3.5.5 Analysis and Quantifying emissions

To analyse the impact and quantify the emissions, it requires a thorough understanding of the greenhouse gases and data from consumption and production was required which were obtained from the company and also from reports from the suppliers. In cases where the relevant data was hard to obtain, environment reports were consulted and issued by the concerned companies that are closely in line with the components used by the company. Data from energy use during resource extraction, production, assembly and transportation was provided by the company. The emission factor for the electricity and heat produced was referenced in Sweden and Europe context. However, due to variations in the type of share of renewables between different countries, for our study, we referenced the electricity mix used from Sweden's perspective and their respective emission factor.

For each component based on the functional unit used, the material extraction, energy consumed, waste and emissions were analysed i.e. for the production of one unit of a component, the process input and output are quantified. The energy used is further classified into renewable and non-renewable energy sources. This is carried out throughout the lifecycle process. Emissions from the process including both direct and indirect emissions are also studied. The waste is either recycled or disposed and as far as concerned for this study, most of the products are recycled and the amount of energy and material savings made by recycling are studied.

For the transportation process, data on the type of transport (Ship or Truck) was gathered. The most common mode of transport is made by Truck/Lorry with respect to Euro 5. This is according to the European Emission standards for emissions of vehicles in the EU. The Euro 5 has a set of a limit of standards for diesel vehicle emissions such as NOx, HC, PM and PN. According to [83] for Euro 5 standards, the emissions for NOx limit is set at 0.18 g/km, Particulate Matter at 0.005 g/km, combination of (HC+NOx) at 0.23 g/km and Particle number at $6 * 10^{11}$ particles/km.

For the operation phase, the initial data sourced from the suppliers are used and for cases where there is unavailability of data for the use phase, calculations are made based on the analysis and sources from relevant sources are sourced online. Since the study is based in Sweden the electricity mix of Sweden is selected for the use phase. This is carried out while analysing the impact and the losses arising from the substations.

For each of the materials used in each component, relevant data are entered into the Ecochain software. This software allows us to enter the material and their amount under the category created under the substation unit. This also includes the energy consumption for each process. For each material data entered, the impact category is added and that automatically outputs the impact for the respective materials. Since there is no relevant data for the operation stage, estimated data for energy consumption by the substation is used as its emission factor.

3.5.6 Analysis of Product Design

An analysis of the product design is carried out and involves a structured approach by analysing the data and design process to allow us to evaluate the design needed to reduce the impact of the current design. Under this, the current product design with its components. For the substation operation, power factor and load conditions are taken as the parameters for this analysis. As mentioned in the objective, cost-related analysis and evaluation are not carried out due to the unavailability of data, however, a brief overview of the economic consequences related to the impact is carried out. A thorough analysis of the environmental impact of the current design is undertaken so as to identify areas in the product design with its potential reduction in emissions and its related advantages and disadvantages as a result of that. Under this, the life cycle stage that has the most impact is considered for assessing the product design and quantifying the greenhouse gas emissions. After gathering the data, hotspot analysis is made that identifies the areas having the highest impact within the lifecycle stage such as processes or materials that have an influencing factor in the overall climate impact. This analysis gave an insight into how altering the materials used, type of components and type of resource used would contribute to the potential reduction in CO_2 emissions with strategies to reduce the impact of the design.

3.6 Sensitivity Analysis

Sensitivity analysis is carried out to assess the output by understanding the input and what impact is observed by varying the parameters and how these parameters influence the outcome of the climate impact of prefabricated power systems and aimed at identifying the key parameter contributing to the climate impact. In this process, the key parameters such as energy source, transportation distance, SF6 leakage, operation parameters and emission factors are used.

Table 3.1: Parameters carried out for sensitivity analysis

Cases	Description
Energy Source	Type of Energy source used. Wind is used for renewables and nuclear for non-renewables. Varying from 20% to 80% share
SF6 leakage	Impact of emissions from SF6 leakage
Carbon intensity	Carbon intensity for the downstream for the selected countries
Transportation distance	The distance with which transportation takes place and includes it emissions
Operation Parameter	Factors that influence the operations such as losses, loads and power factor

The energy source represents the composition type of energy source used for the life-cycle of the components and its emissions. An assumption is made that the source for renewable is supplied by wind and hydropower for non-renewables, it is carried out by fossil fuels such as oil and natural gas. Further, the input source is varied by changing the parameters and assessing the difference in the output. This helps us to understand the impact of the use of varying sources of energy.

The SF_6 gas leakage is carried out to better understand its impact. SF_6 gas has a high environmental impact and according to the IPCC report [73], it has a greenhouse gas potential of 23500 times more than CO_2. For this sensitivity analysis study, it is assumed that the leakage is at the rate of 0.1% per year according to [21] and analyse its impact. Varying the emission factor for different countries accounts for the intensity of emissions between the different energy sources which arises from the use of these sources. The emissions from transportation distance arise from transporting the materials and products to each processing and distribution site. The longer the distance, the higher the emissions and different distances are selected for assessing the impact associated with transportation. The operation parameters include the loads where different loads are selected to reflect upon their emissions and their efficiency associated with the systems.
Through varying these parameters, we intend to capture the influence of the climate impact by these systems and carry out assessments with different input values.

The share of energy sources is varied between 40% to 80% using the baseline for the current share used according to the EPD of 52% and 48% renewables and non-renewables respectively. Four scenarios were made that allow us to assess their impact on energy consumption during their lifecycle. The share of energy source for various cases are shown in table 3.2. With a focus on renewable integration, the case for 30% only renewables is not carried out.

Table 3.2: Assessment for climate impact with various shares of energy mix

Cases	**Share of energy source**
Case 1	60% renewables, 40% non-renewables
Case 2	50% renewables, 50% non-renewables
Case 3	40% renewables, 60% non-renewables
Case 4	70% renewables, 30% non-renewables
Case 5	80% renewables, 20% non-renewables

The amount of energy consumed for renewables and non-renewables is first calculated for each share to be inputted into the software and their emission output given by the software is recorded allowing us to evaluate the climate impact and where reduction and a better choice for the selection of reducing emissions can be made.

The leakage rate for SF_6 is assumed as 0.1% per year for the baseline scenario. The cases are varied between leakage of SF_6 gas of 0.05% and 0.15% per year and assessed. The cases are shown in the table 3.3.

Table 3.3: Analysis for SF_6 leakage rate

Cases	**SF6 gas leak %**
Case 1	0.05
Case 2	0.1
Case 3	0.15

The following expression is used for the calculation of emissions from SF_6 gas:

$$E_{SF_6} = GWPofSF_6 * leakage \tag{3.11}$$

where: E_{SF_6} is the emissions from SF_6 gas leakage
leakage is the rate of leakage of SF_6 gas per year.

Sensitivity analysis for transportation distance is varied from 500 kms to 1500 kms with a baseline of 1000 kms. The type of transportation for this analysis is taken as Lorry (Truck) and Ferry based on Euro 5. This includes all transportation distance from cradle to grave i.e., from transportation of materials from the resource extraction site to transportation after the end of life. The distance is shown in table 3.4.

Table 3.4: Analysis for impact of transportation distance

Cases	Distance (kms)
Case 1	500
Case 2	1000
Case 3	1500

Keeping other parameters constant, different distances are selected for each iteration and recorded.
Since after the production, the location of the products is unknown, some countries are selected in Europe for this analysis to assess their emissions associated with their carbon intensity which is crucial in knowing the impact during the operation. For this study it was assumed that the products are exported to those countries and used with their respective emission factor for electricity grid sourced from [76]. This allows us to further analyse the impact of the use of the products at different locations. The countries selected and their carbon intensity are shown in table 3.5.

Table 3.5: Analysis of the emissions from different countries for operation

Cases	Carbon Intensity (kgCO2/kWh)
Sweden	0.045
Spain	0.21
Germany	0.38
Poland	0.63
Italy	0.37

For carrying out sensitivity analysis for operation for load variability and losses, the loads are selected from the range of 40% to 100% to see the impact of whether running at full load or partial load contributes significantly to the climate impact and adds to more losses to assess the efficiency of the system. The load scenarios are shown in table 3.6.

Table 3.6: Analysis for the operation parameters for loading and losses

Cases	Scenario
Loading	40% to 100%

This analysis is done by calculating with Excel using the appropriate data. The loading conditions represent the usage which overall affects the impact of the power systems which also connects the losses involved and affects the efficiency of the systems and their emissions and their respective loss factor and is also analysed.

The results are categorised and interpreted according to their level of impact where studies can be made for redesigning or improvement can be suggested. The final step is validating data based on real-world scenarios and performing further analysis to ensure the model is reliable.

4
Results

4.1 Concrete

An assessment is carried out for concrete that provides an insight into its share of resource use from production.

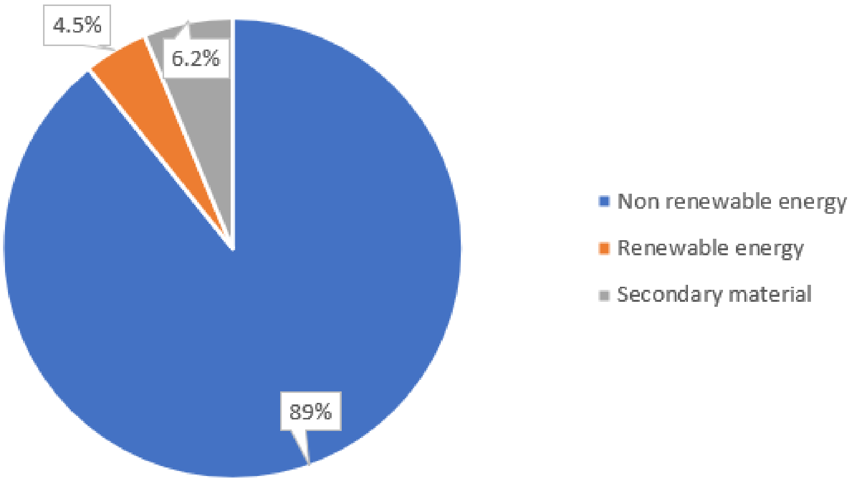

Figure 4.1: Share of Resource use from Production

Figure 4.1 illustrates the share of the impact of resource use on concrete production. From the figure, the impact is predominantly influenced by the use of non-renewable energy sources in the production stage constituting about 89% of the total impact. Other contributors come from the use of secondary materials and renewable energy sources each representing 6.2% and 4.5% respectively. Contribution from freshwater usage represents a relatively small percentage and hence is not included in the figure. The production stage is characterised by the extraction and transformation of raw materials into useful products requiring large amounts of energy consumption. Although secondary materials have an impact, it does not have a large magnitude of impact.

The materials are entered in the ecochain software with their weights and their associated emissions are extracted and represented in the table 4.1.

Table 4.1: Material composition and its related emissions

Concrete	**Weight (kg)**	**Emissions (kgCO2eq)**
Portland Cement	350	312
GGBS	78	34.83
Aggregates	1658	20.48
Water	181	0.09
Superplasticisers	6	7.54
Total	2273	374.94

The table 4.1 represents emissions arising from material extraction. As seen in the table, portland cement predominantly contributes to the largest impact signifies that it is a major source of CO_2 emissions. It arises mainly due to a chemical process called calcination where CO_2 is released as a byproduct. Although the amount of aggregates used is high, it does not have a large impact as compared to cement and along with superplasticisers, they still have a small impact. Emissions from water are relatively small and have negligible impacts.

A small sensitivity analysis for transportation distance is carried out to see the impact of the distance associated with its weight shown in the table 4.2.

Table 4.2: Impact of the transportation distance

Transportation Distance	**Emissions (kgCO2eq)**
Transport for 120 kms	29.87
Transport for 140 kms	34.84
Transport for 160 kms	39.82
Total	104.53

The table 4.2 illustrate the sensitivity analysis for the transportation of concrete. The range selected for the transportation is 120km to 160km with an average of 140km. The impact of emissions followed a direct trend with respect to their distance, longer distances have higher emissions. However, the overall impact from transportation is small due to transportation occurring within the country and due to the type of fuel used which is biodiesel.

The overall GWP impact of concrete is carried out and is represented in the table 4.3 to give an overview of its emissions.

Table 4.3: The share and contribution of the GWP of concrete production

Stages of Life	**Emissions (kgCO2eq)**
Manufacturing	400.79
Transportation	34.84
Total	435.64

The GWP of concrete production that includes the manufacturing and distribution is illustrated in the figure 4.2 in percentages to get a clearer view of its impact.

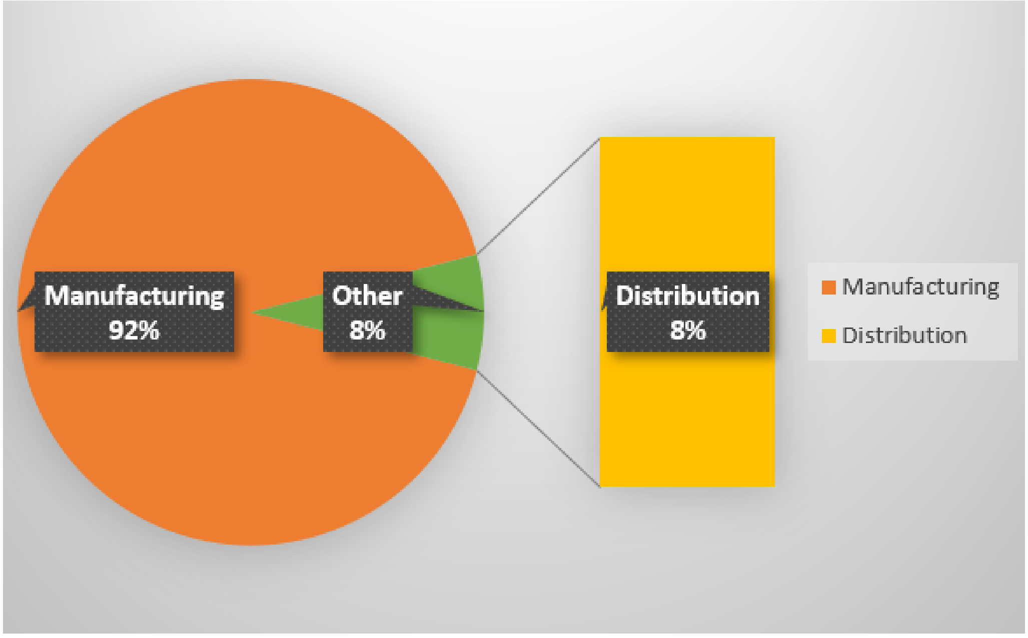

Figure 4.2: GWP of Concrete from production

Figure 4.2 illustrates the Global warming potential arising from the processes involved in concrete production. The manufacturing stage includes several processes, raw material extraction, transportation to the production site and the production process and these together result in the highest share of emissions. As evident from the graph, the manufacturing stage for concrete production has substantially a higher impact compared to the distribution stage. Under this, the emissions related to energy consumption for the whole manufacturing stage are considered.

4.2 Switchgears

The overall impact of switchgear from each product lifecycle is illustrated in figure 4.3 showing the associated emissions from cradle-to-grave.

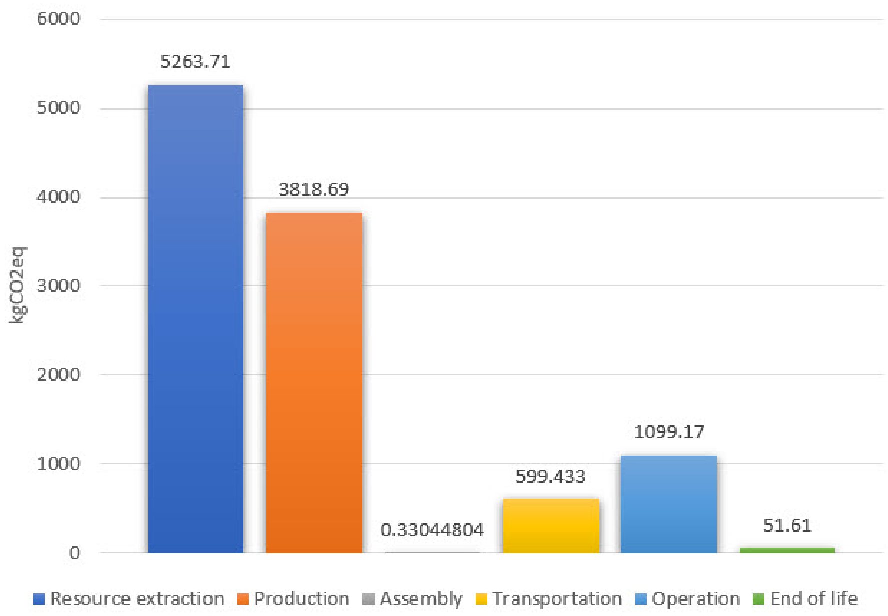

Figure 4.3: Emissions from the stages of switchgear

From figure 4.3, the impact from resource extraction to transportation to the customers i.e., cradle-to-grave is represented in the graph. Resource extraction and production have a large impact. Both these processes are energy-intensive and include the transportation carried out to the site for production and assembly site. Since switchgear is made up of various types of materials mainly metals and plastics, the extraction of these resources is energy intensive and has to undergo various processing and refining to be fit for use in production as reflected in the figure.

During the operation of the substation, we assumed that there was no leakage of SF_6 gas. After the operation period of the substation, the SF_6 is separated and recycled. The metals are also separated and recycled. The emissions from the assembling phase are relatively small since it comes as a modular units and does not consume much energy.

4.3 Transformers

In this section, we present figures and tables encapsulating the findings of our study of the impact of transformers during their lifespan. This provides a clear and concise understanding of the associated impact for the readers of our results highlighting the key contributors.

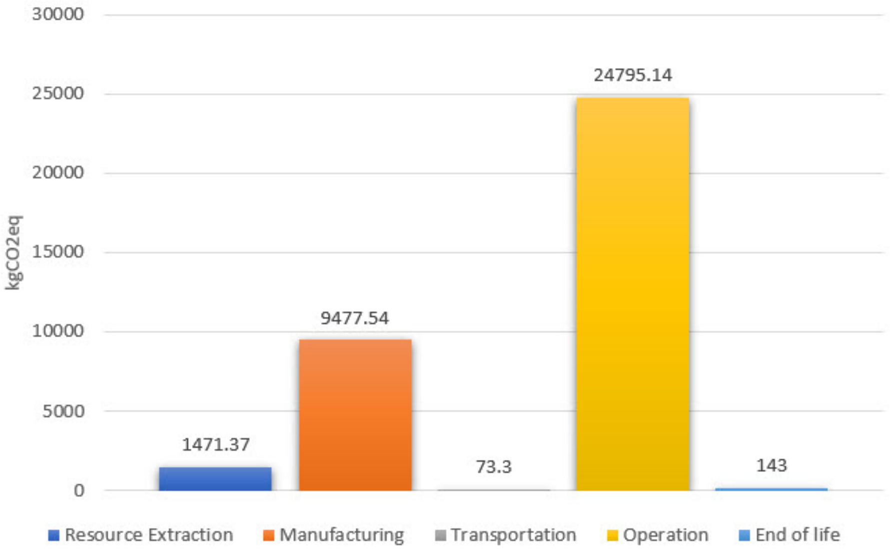

Figure 4.4: GWP from the lifecycle of transformers

The GWP from transformers is given in the figure 4.4. Analysing the lifecycle of the transformers yields the result that gave the operation process the highest emissions which significantly stems from the load losses during the use phase. The energy consumption during the use phase is taken as Swedish energy mix with renewable energy source as wind and non-renewable energy source as nuclear. The production includes the assembly phase as well and is second to operation in terms of emissions Resource extraction has an emission stemming from each material extracted for the production process. The impact of transportation and end-of-life are relatively small and do not contribute much to the overall impact.

An analysis is carried out in table 4.4 by varying the loads from 40% to 100% to assess their influence on load losses and emissions.

Table 4.4: Impact of transformer at operation stage for different loads at 0.8 PF

Load	**Load Losses (W)**	**Loss factor**	**Efficiency (%)**	**Emissions (kgCO2)**
40%	200	0.052	99.58	5282.28
45%	253.12	0.073	99.51	6119.95
50%	312.5	0.1	99.44	7056.18
55%	378.13	0.133	99.36	8090.95
60%	450	0.175	99.27	9224.28
65%	528.13	0.227	99.18	10456.15
70%	612.5	0.290	99.07	11786.58
75%	703.13	0.365	98.96	13215.55
80%	800	0.455	98.84	14743.08
85%	903.17	0.562	98.72	16369.15
90%	1012.5	0.687	98.58	18093.78
95%	1128.13	0.832	98.44	19916.95
100%	1250	1	98.29	21838.68

Table 4.4 shows the impact of the transformer during the use phase at different loads. The loss factor, efficiency, emissions and load losses are represented in this table. At lower loads, the efficiency is higher and lower load losses. 99% efficiency is achieved at lower loads due to lower losses which ultimately represents lower emissions.

To reduce the impact, it is crucial that the transformers operate at optimal loading conditions. From our study, lower loads have lower losses and lower emissions. Since the final location of the product is unknown after the assembling phase, some countries are selected for evaluating their emissions from the load at 40% so as to achieve higher efficiency and lower emissions.

The selected countries are shown in table 4.5 with their carbon intensity obtained from Statista [76].

Table 4.5: Countries with their carbon intensity and associated emissions at 40% load

Country	**Carbon Intensity (kgCO2/kWh)**	**Emissions (kgCO2eq)**
Sweden	0.045	5282.28
Spain	0.21	24650.64
Germany	0.38	44605.92
Poland	0.63	73951.92
Italy	0.37	43432.08

The results from the table show that Sweden has the lowest emissions mainly due to lower carbon intensity arising from the integration of more renewable energy in the electricity grid. Spain also has fairly low emissions but higher than Sweden as compared to other countries due to higher integration of renewables mainly solar in the grid. Poland has the highest emissions due to their high carbon intensity stemming from their heavy dependence on non-renewables such as coal.

4.4 Summary

This section provides a summary of the report findings and insights conducted in the study for researchers and decision-makers in addressing the climate impact of prefabricated power systems for improved sustainable solutions.

The summary of the key components and their emissions from cradle-to-grave is shown in table 4.6 which provides a clear overview for better understanding and facilitates a better insight into our study.

Table 4.6: Summary of the components from cradle-to-grave

Components	**Emissions (kgCO2eq)**
Concrete	537.66
Switchgears	10832.94
Transformer	35960.352
Substation Frame	3971.89

In table 4.6, emissions from the transformer have the highest impact and this includes the whole life cycle of the transformer during its lifespan. Switchgear is second to the transformer, while concrete and substation frames have lower emissions although they still represent some emissions and contribute to the overall impact.

The figure below represents the overall climate impact of prefabricated power systems and provides a visual overview of their lifecycle from cradle to grave through which we can explore the intricate carbon footprint.

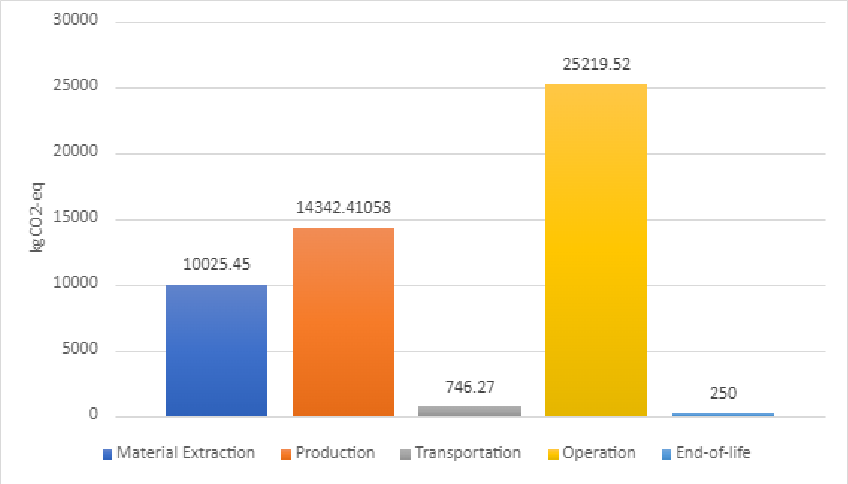

Figure 4.5: The total overall impact of prefabricated power systems from cradle-to-grave

In figure 4.5, the highest overall impact stems from the operation impacted by the losses arising during the use stage and energy consumption which includes the energy source during the operation stage with high contribution from emissions from non-renewable energy use. The impact of the assembly process is included in the production process. Emissions from material extraction are slightly lower than production. Transportation and end of life have the lowest overall impact with emissions from the former arising due to the distance and type of fuel used which is Diesel mix and the latter due to lower energy and material consumption for end-of-life handling.

The results of the energy source for sensitivity analysis with different shares and their associated emissions are summarised in the table 4.7 below.

Table 4.7: Energy sources and their emissions for downstream phase for the case of Sweden

Renewable Source (Wind)	Emissions (kgCO2eq)	Non-renewable energy source (Nuclear)	Emissions (kgCO2eq)
40%	3070	60%	2160
50%	3840	50%	1800
60%	4610	40%	1440
70%	5380	30%	1080
80%	6150	20%	719

Based on the results for the energy source from the table 4.7 for the downstream phase, the energy source is a significant contributor to the overall emissions. Since the upstream phase takes place outside Sweden, the energy source mix for Sweden does not have an influence on the upstream and the result is depicted only for the downstream phase with the energy source of Sweden. Taking the renewable source as wind, a larger share of renewable energy use has a higher impact than the non-renewable energy source with nuclear due to low greenhouse gas emissions associated with nuclear. The result depicts that the integration of more non-renewables in the system still has lower emissions than using renewable sources.

The results of the sensitivity analysis from the emissions resulting from varying the transportation distance for both types of transportation are shown in table 4.8.

Table 4.8: Comparison of emissions from type of transport and distance

Distance	**Lorry transport Emissions (kgCO2eq)**	**Ferry transport Emissions (kgCO2eq)**
500	268	233
1000	537	465
1500	805	698

The table 4.8 reveals that transportation distance has an impact on emissions. Weight is also a factor as heavier components require more fuel and energy for transportation. Minimising transportation distance is crucial in reducing the climate impact by selecting transportation modes that have lower emissions or locating the products closer to the production site.

The table 4.9 below represents the SF_6 leakage rate and their associated carbon emissions providing a clear overview of the impact.

Table 4.9: SF_6 gas leakage rate and their emissions

Rate of SF6 gas leakage	**Emissions (kgCO2eq)**
0.05%	1066
0.1%	2133.8
0.15%	3200.7

This table 4.9 shows how varying the leakage rate has an impact on the emissions. Since SF_6 has a high global warming potential, the higher the leakage rate, the higher the emissions. The results show the significance of minimising leakages to reduce the climate impact.

4.4.1 Analysis of product design

Analysis of the product design carried out shows the potential impact of each action undertaken and its related reduction in CO_2 emissions and their associated consequences highlighting its advantages and disadvantages to provide actionable insight for stakeholders. (+) depicts the impact advantages and (-) depicts the impact disadvantages as a result of this analysis.

Table 4.10: Product design analysis and impact reduction strategies

Strategies	**Potential kgCO2eq. emission reduction**	**Impacts**
Energy source Wind Nuclear	2.9-5.85% 0.76-2.3% (varies on the share of energy source)	Low operating and maintenance cost(+), high investment cost(-), Wind: reduce stress on the grid(+), intermittency and variable(-) Nuclear: continuous source of energy (baseload)(+), long operating life(+), safety concern and radioactive waste(-)
Optimise Logistics Lorry(truck)	0.5-1.6% (varies on distance and weight)	Faster, reliable transportation (+), improved efficiency, reduced fuel consumption(+), additional infrastructure investment(-),careful monitoring required(-)
Secondary metals Steel Aluminium Copper	6.06% 1.2% 0.36%	Reduced new material extraction (+), reduced energy consumption (+), lower material costs(+), quality concern, impurity contamination(-), limited supply, additional processing costs(-)
Concrete Ultra-high performance concrete [84]	1.1%	Higher tensile strength, longer life(+), reduced material use(+), higher material cost, limited availability(-), specialised equipment requirement(-)
Loading 40% 50% 75%	17% 20.5% 32.65%	Energy savings, lower losses at low loads and flexibility of operation(+), underutilised capacity, reduced cost savings(-), efficient utilisation of capacity at higher loads(+), reduced efficiency, higher energy consumption(-)
Power factor 0.8 0.9 0.95	20% 10% 5%	Reduced investment in capacitors at lower PF(+), higher losses and lower efficiency (-), higher efficiency at higher PF and lower losses (+), expensive equipment needed (-), risk of fault in equipment (-)
Switchgear Air-insulated	9.8%	No risk of leakage of gas and easy installation(+), lower investment cost (+), requires more land space(-), susceptible to pollution requiring more maintenance(-), poorer dielectric properties (-)
Amorphous metal core [85] 40% load 50% load 75% load	3.84% 4.8% 7.2%	Lower losses and higher efficiency at lower loads(+), higher material cost(-), lower reduction potential at higher loads than traditional metal core(+), heavier weight (-)

Table 4.10 shows the different strategies for reducing the climate impact and their consequences as a result of adopting the strategies. The main takeaways from this table are:

- Wind as an energy source can benefit from using secondary metals where these metals can be incorporated for manufacturing of tower, rotor blades, nacelle and other components of the wind turbine that would reduce the need for new materials incorporation in the construction of wind turbines and reduce investment cost and further reduce the environmental impact from new infrastructures from renewable sources.
- Incorporating concrete in the secondary metals can be beneficial for construction purposes especially where the equipments undergo continuous stress and pressure. The ultra high performance concrete itself has high tensile strength which would further enhance its properties by reinforcing with secondary metals in the form of fibres as fibre composites and offer superior quality and lifespan thus reducing the environmental impact. However, it can become challenging in regions where the supply of recycled metals are really limited and their quality should be properly assessed.
- Amorphous metal core distribution transformers have high efficiency and reduction in their environmental impact. These transformers have high efficiency at lower loads and can be incorporated in loading conditions where variations occur. While operating at optimised loads have higher efficiency and lower losses, the combination with amorphous metal could contribute to energy savings with reduced energy consumption and cost savings for the customers or users. Further, the lower reduction potential at higher loads for traditional transformers could significantly benefit from the incorporation of the amorphous metal. Although the higher material cost could lead to overall higher investment costs but the benefits associated with its long term lifespan can be taken into consideration by decision-makers.
- Operating transformers at its optimise loading ensures higher efficiency, energy savings, reducing the losses and ultimately lower emissions where loading conditions and power factor strategies could be combined to complement each other. Improving the power factor by installing capacitors reduces the current flow allowing higher loads and the electrical power is supplied effectively and efficiently reducing the losses and thereby reducing energy consumption and emissions. However, installing power factor correction capacitors might incur additional charges and also contribute to the carbon footprint and require careful monitoring and controlling.
- Switchgears controls, regulates and isolates the electrical equipment and this could be used in connection with the power factor and enhance their efficiency and emissions by benefitting from each other. By integrating power factor correction capacitors with switchgear, inductive loads in the system could be counteracted by the switchgear by switching on the capacitors and improving the power factor thereby minimising the losses associated with reactive power and with AIS lower investment cost, the combination would have better cost savings but requires more space for installing and this could limit in areas

where power factor correction capacitors need to be integrated.
- Incorporating secondary metals and optimising transportation could offer significant benefits in reducing the environmental impact. Optimising transportation by optimising the routes and delivery times carried out with lorry transportation that is quick and easy from collection to delivery of the secondary metals, emissions and their associated costs are greatly reduced where the materials are transported to their production site for processing through optimised transportation with reduced waste and energy consumption. Also, the synergy between wind energy as a source and transportation can also be highlighted where wind provides a clean source of energy consumption for powering transportation and due to lower operation costs of wind energy, offers cost savings and the optimised transportation system reduces the fuel consumption and overall reduction in climate impact.

These planned strategies provide an overview of the potential contribution to CO_2 emission reduction and actionable insight for stakeholders by considering the advantages and disadvantages of adopting a planned action for reducing the climate impact of prefabricated power systems.

5

Discussion

The main objective of this project was focused on assessing the lifecycle of prefabricated power systems from cradle to grave and their evaluation of their climate impact where a model would be developed and used as a tool for calculating the climate impact of power systems. The focus relied on the identification of key parameters influencing the carbon footprint through analysis of the material flow and their respective environmental performance parameters. This further involved analysing the energy source determining the contributors to greenhouse gas emissions and assessing the loss utilisation factor from energy consumption that derived strategies and recommendations from the impact assessment and suggestions to the product design and its lifecycle. The findings from the results are discussed and presented in this chapter.

This project on the climate impact of prefabricated power systems was a part of conducting the assessment and also gathering information from literature studies centering around the research done on reducing emissions and towards climate sustainability. By performing analysis and evaluation, there are certain findings that align with that of other literature but also differ from our research. Our analysis of the emissions and energy consumption from the lifecycle of the substations aligns with the type of energy source used particularly with the significance of renewable energy sources for the production of substations through energy efficiency. This concurs with the conclusion made by Li et al.[86] and Gou et al.[87] in energy-saving design of envelopes and optimisation. Further, our research question on change in the product design aligns with the conclusions drawn from Chen et al.[29] in the use of low carbon materials and environmentally friendly equipment that comes from a clean source which would lower the climate impact of the systems. These are some of the findings that resonate with our research questions to achieve our objectives.

Our research focused on the whole substation components from the emissions and energy consumption involved during the life cycle rather than each individual component setting us apart from other literature studies that enable us to explore and expand our assessment and provide a more integrated climate impact of the system. The main components to name a few include transformers, low voltage and high voltage switchgears, concrete and the substation casing. A study was carried out for each component separately and analysed their impact and evaluated them. For the cradle-to-gate process, the focus was emphasised on manufacturing and resource extraction which has the highest impact during the upstream phase but when the whole lifecycle from cradle-to-grave is carried out, emissions from operations surpass the emissions from manufacturing and resource extraction and contribute to the highest overall impact. The model revealed that for the manufacturing and resource extraction phase, a significant portion of the emissions stems from the energy used during production due to the energy-intensive nature of the process and the emission factor of the materials and this was used as one of the key parameters that have the most significant greenhouse gas emissions. Although both non-renewable and renewable energy sources are used for the production process, the use of non-renewable sources contributes to a higher share as compared to renewable sources which contributes to a higher climate impact. This highlighted the importance of carefully selecting the type of energy source that served as a key influencing factor for the emissions from the manufacturing and resource extraction phase.

A trend was observed in the emissions with the type of energy source used for the production of the components. A higher share of renewable sources showed lower emission levels compared to the production heavily reliant on non-renewable sources indicating that the integration of a larger percentage of renewable sources into the system can significantly reduce the carbon footprint. For the operation phase, even though there was higher consumption of non-renewable energy, the emissions were lower due to the use of nuclear as its source than renewable sources with wind, however, the majority of the emissions stemmed from the energy losses. Additionally, the type of materials used such as sustainable or recycled materials and adopting energy-efficient processes in the equipment to lower energy consumption can translate into reduced emissions. During the transportation phase, the emissions from the transportation of materials and equipment were influenced by the distance, mode of transportation, weight and the type of fuel used. In this study, biodiesel was used for the type of fuel and holds a lower emission factor, hence showing reduced emissions as compared to the other processes. However, this phase still contributed to the emissions and longer distances contribute to higher emissions.

Geographical location also plays an important factor. For the materials that were imported, the importing country might not have an influence on the type of transportation mode or fuel used which became an important aspect to consider when carrying out the entire life cycle of the products. The results might exhibit lower emissions when considering the production of products locally but emissions should be considered that stem from where the materials are sourced (geographically) and emissions from the transportation routes used from cradle-to-grave. The operational phase represents the highest overall impact and the emissions mainly stem from losses and efficiency of the systems throughout the lifespan. Losses mainly arise from the transformers under various loading which affects the efficiency of the systems and ultimately higher emissions as more losses in the system do not give the desired output and hence more energy consumption. Using high-efficiency components to minimise losses and maintenance checks to ensure that the system is optimised and operated at desirable loads for producing high efficiency would reduce the impact of the emissions. The end-of-life phase although does not have a high impact as most of the components are recycled in this study, designing and producing the components that are durable and do not need frequent maintenance or disposal and enhancing recycling techniques and methods could further negate the overall emissions. The sensitivity analysis carried out ensured that the model is flexible in incorporating new and improved data and changes in the system and making informed decisions for the stakeholders to have a thorough idea of the impact of their products.

5.1 Evaluation of Concrete

An evaluation of the concrete provided valuable insight into the share of resource use and their emissions from the materials for concrete production. The impact is largely dominated by the use of non-renewable resources for material extraction which is significantly concerning for the environment. This fosters the need for transitioning to a cleaner source of energy for production such as renewables like wind or solar. Even though secondary materials are more sustainable, the emissions involved with it is still considerable as the process is still energy intensive as it involves various processes for the product to be recycled. Further, there could be complexity in the processes involved and a lack of availability of data on the environmental impact.

5.1.1 Manufacturing and transportation

For the sensitivity analysis undertaken for the transportation of concrete, it was observed that there is a direct correlation between the transportation distance and its emissions. This could be due to the fact that the emissions increased due to more energy and fuel required for transporting longer distances. From these findings, it could be noted that to reduce emissions, there is a need to optimise transportation distance and logistics such as suppliers setting up their production units closer to the customers, sourcing materials locally to minimise the carbon footprint or investing in more fuel-efficient vehicles to transport their products. These insights could be used by stakeholders and decision-makers in reaching their sustainability targets.
Emissions from material extraction for concrete production have a high environmental impact. Materials such as GGBS, cement and aggregates such as sand and gravel require high amounts of energy including transportation for extraction and excavation. Portland cement due to the chemical process involved in the refining emits large amounts of gases which significantly contributes a large amount in the overall impact. According to [88] [89], the process involved in clinker production for cement emits large amounts of GHG gases. As a solution to combat this, implementing more efficient technologies and blending with other alternatives such as fly ash and carbon capture storage to capture the emissions produced during the production of cement are some of the strategies that can be adopted. By reducing the weight of the cement used, an analysis is carried out to see its impact. However, it still has a higher impact compared to other materials used. One reason could be that since the chemical process requires high temperatures and energy, the energy that is used is derived from fossil fuels which release more CO_2 emissions. Also, it is assumed during the use phase the concrete base does not require any maintenance

during the lifetime of the product which reduces the need for replacement and addition of new materials and energy consumption. Overall, for the GWP of concrete, it can be observed that the manufacturing stage has the highest climate impact. The weight of concrete is heavy and exporting it to other countries contributes a lot to the carbon footprint due to its fuel consumption, there is also a risk of the concrete breaking during transportation so it is recommended that if the concrete base is produced in the exporting country, it could contribute a lot less to the carbon footprint.

5.2 Transformers

The analysis highlighted the significance of using renewable sources of energy for manufacturing and operation as it has an overall lower impact on the lifecycle of substations. During the operation or use phase, the high environmental impact arose due to several factors. The impact arose from the losses occurring as a result of the resistance from the core and windings. Load losses also known as copper losses vary with the load and these losses even though seem small, accumulate over their service life and contribute to a large share of the overall impact. After the assembly phase, since there is no data for the final location of the product, it was assumed that the products would be exported to different countries to evaluate the impact. The different countries selected were within Europe with their respective carbon emission factor. Of the selected countries, Poland has the highest emissions mainly from the country's carbon intensity stemming from the use of non-renewable sources and emissions from Sweden were the lowest. The reason could be due to Sweden's high dependence on renewables according to Statista [76] at 68% such as wind and hydro with only 0.045 kgCO_2/kWh as compared to other countries.

The emissions and power losses are the lowest at 40% load, which is significant in evaluating the climate impact. Even though the emissions per year with different loading do not have a large impact, when considering the service life of the products, it has a large contribution to the climate impact. Further emphasizing efficiency plays an important role in handling the losses by adopting more energy-efficient equipment to minimise the losses and implement strategies for managing the load system. Further ensuring that the transformers are run at rated load as underutilised or overutilised capacity could have significant consequences on its performance and efficiency. Since the power losses depend on the square of the current square and the resistance, it is important to select materials like copper and aluminium that have low resistance and are important conductors widely used for minimising losses and improving efficiency. Although copper has superior properties than aluminium in terms of resistivity, aluminium has a larger cross-sectional area. Also, properly sizing the conductors could reduce the losses as larger conductors have larger cross-sectional areas and reduce resistance thereby reducing the losses. Due to resistance, the electrical energy flowing through the circuit often results in heat dissipation in the form of resistive losses which means if conductors with high resistivity are used then more heat is generated and the electricity energy is wasted as heat and the efficiency of the system is reduced. With conductors that have low resistance, the losses are reduced and minimised and this reduced loss improves the overall efficiency of the system. Larger conductors have higher heat dissipation properties by reducing the heat generated due to their lower resistance. When transformers run continuously on load, overheating can take place but with the use of larger conductors, overheating is prevented due to its ability to handle higher currents with lower resistance thereby reducing the degradation of insulation materials and extending the transformer's lifetime reducing maintenance requirements and its environmental impact. Further due to the long lifespan of transformers, it is important to properly size the conductors since efficiency also depends on the conductor size and an increase in efficiency over its lifetime can have a significant reduction in energy consumption. Additionally during operation, when transformers transfer electrical energy from primary to secondary winding, some amount of the energy is lost as heat in the conductors and the amount of electrical energy transferred in the secondary winding is low. With proper sizing of conductors, more electrical energy would be transferred to the secondary winding and enhance the overall efficiency of the overall system. So, it is important to take on scenarios that fit the best for reducing environmental impact and overall efficiency.

5.3 Switchgears

Looking at the impact of switchgear, the extraction of resources and production have a substantially higher impact than the other stages. The reason is due to the complexity of the product requiring high energy consumption needed for these stages and heavily relying on non-renewable sources and high demand for energy. As metals contribute to the largest share of the production of switchgear, the process involved could be the downside for the overall climate impact. In the operation stage, the use of SF_6 as an insulting medium is the influencing factor due to the high GWP of SF_6 gases. Although it is known for being an excellent insulator, any leakage could be disastrous for the climate. In this study, no leakage of SF_6 gas takes place during the lifecycle which could be the reason for lower emissions for the operation phase. Under the sensitivity analysis carried out, the assumption made for the gas leakage is between 0.05% to 0.15% per year and its emissions are small but due to its high GWP, the leakage emissions over the service life cannot be overlooked and this necessitates the need for having a compact design which further requires the need for more energy consumption. Additionally, proper check and maintenance are required during the use phase as any leakage could reduce its efficiency and contribute to loss of heat and electricity that would impact the climate. On the other hand, air-insulated switchgears are less risky as leakage would have a minor impact on the environment but poorer insulation. The choice of selection depends on the customers and the users but from an environmental perspective, the key influencing parameters to the climate impact need to be considered.

5.4 Analysis and Impact Reduction

Analysis of the product design carried out reveals strategies and opportunities for impact reduction during the product's lifecycle supported by several strategies for reduction in their CO_2 emissions. One key strategy in this analysis is the energy source for the lifecycle where the energy source is dominated by non-renewable sources in the upstream module mainly from oil and natural gas whereas for the case of Sweden, the downstream module is composed of non-renewable sources as nuclear and renewable source as wind. Transitioning the energy consumption during their lifecycle to rely on renewable sources shows that emissions could be significantly reduced which in the long-term future could provide a higher reduction in emissions and offer operational cost savings but this comes with a trade-off. Ensuring a continuous supply of energy from renewables such as wind or solar requires a storage system like batteries due to the intermittent nature of renewable sources and this comes with high upfront investment costs in infrastructure and technologies and also grid management system. Nuclear although considered non-renewable on the other hand has lower emissions than wind energy and can offer a continuous supply of energy and act as a baseload to meet the demand. This might sound favourable but it has a lot of issues regarding the handling of radioactive waste, safety and security concerns and political issues which in the long run might not be favourable.

Emissions from transportation are influenced by the type and amount of fuel used based on the weight of the product, distance and mode of transportation. The choice depends on the easiest the fastest factor for the suppliers however, depending on these factors might not be the most sustainable method requiring optimisation of transportation logistics that can minimise fuel consumption and cost savings from lower emissions. This however would require investment in newer infrastructure and careful planning and execution that might consume more time and is a question for the stakeholders whether they would want to invest in more technologies.

According to [85], distribution transformers both dry-type and oil-filled have a higher impact than using transformers with amorphous metal cores irrespective of the load offering advantages of lower losses emissions making it attractive from an environmentally friendly perspective. It might not be favourably and widely adopted by producers and suppliers due to their high investment cost and limited availability, however, the long-term impact reduction offers a promising solution.

From the analysis of the current design, the main metals mainly composed of steel, aluminium and copper are not widely incorporated in the production process as secondary or recycled metals and as a result, their impact is considerably large which could be reconsidered by incorporating more in the production process and this would significantly reduce the emissions arising from the extraction of resources. These secondary materials could mitigate reducing the need for the extraction of virgin materials and could offer cost savings. Even though it has added additional processing costs and there is no clear transparency of the durability of the recycled metals, careful selection of the type of material and enhancing recycling practices with standards could outweigh the challenges and enhance impact reduction.

Ensuring lower energy consumption by enhancing energy efficiency plays an important factor for the transformers since they operate throughout their lifespan. Introducing high-efficiency components to minimise losses such as one that has lower no-load and load losses during electricity generation and distribution could reduce the energy losses. From the analysis, at lower loads, the transformers have a higher efficiency and lower emissions and this could be considered by optimising the loading of the transformers to run at a rated load which is another challenge as load varies depending on the demand. Implementing control systems and voltage regulators that can monitor the load profile according to the demand would reduce losses and efficiency accordingly, thereby reducing energy consumption. The power factor of transformers varies between 0 and 1 with 1 being highly efficient. Incorporating power factor correctors such as capacitors can be introduced to eliminate reactive power and improve the efficiency of transformers which can be challenging since the load varies over time and determining the ideal level of correction might require continuous monitoring making the optimising process rather challenging and complex and would be an additional investment although a higher power factor has higher efficiency than lower power factor and lesser room for improvement. Further, the production of capacitors even though the impact might be small, would still contribute to the overall emissions.

Substitutes for concrete such as ultra-high performance concrete [84] offer a promising solution in reducing the impact due to their high tensile strength and lower emissions. Traditional concrete is brittle and their weight poses a challenge during transportation. Using materials that can be a substitute for concrete with lower emissions with higher tensile strength eliminates the need for maintenance costs during its service life and offers additional savings in recycling the used materials. However, the challenge is whether the mechanical properties of concrete are still the same as those of new products and might not offer a longer service life.

For the switchgear, the environmental impact of using SF_6 gas is immensely huge as it has a GWP of 23500 times more than CO_2 which makes it hazardous in case of leakage although it has excellent dielectric properties. Either preventing the leakage of SF_6 gas during its operation and end-of-life handling or minimising its use or alternatives such as air-insulted switchgear is ideal for reducing the impact but comes with the challenge of poorer dielectric insulation properties requiring higher maintenance during the lifespan. Another strategy would be reducing the percentage of SF_6 used and mixing it with other gases like nitrogen would reduce its environmental impact without affecting its dielectric performance [90].

5.5 Challenges

Like any LCA study, the results of the study might vary depending on various factors like the electricity mix of the country, losses from the transformer and the rate at which the SF_6 gas will leak. There are a few data that are missing from the study like the small plastic components used in low-voltage switchgear. Adding those data to the model would increase the accuracy of the results. The transportation data after the assembly part is difficult to obtain because Holtab's customers are in different parts of Sweden and Europe. Also, all the transportation taking place during the end-of-life stage is neglected for most of the components mainly because of the variability pertaining to those data. Although change in the product design is a strategy that can be undertaken arising from this study, there would always be a trade-off. As for renewable energy integration, it does not seem entirely possible to switch all energy-related involved to renewable sources. Since most of the materials are sourced from other countries, the importing country does not have an influence on the type of energy used for production or materials extraction or transportation. Even if the sourced materials are sustainable, factors such as specification, durability, temperature, stress, climatic conditions, customer needs, costs, etc. play a major role. Assuming that the product is fully sustainable, the emissions stemming from cradle-to-gate might be less environmentally friendly. However, in studying this LCA with the current design, the operation stage has the highest emissions and this is pinpointed to the fact that after the product is assembled, the final geographic location for the product is unknown which makes it challenging to have an influence on the process involved in gate-to-grave. Therefore, the components that majorly contribute must be evaluated and validated carefully with the standards and room for alternative processes needs to be considered.

5.6 Quality of Data

For each and every component of the material, data from a reliable or company-trusted source were used for the model. However, there were some adjustments and assumptions were made. For instance, the data used for the transformer was from a different transformer than Holtab uses but with the same power rating. This was done due to the lack of required data from the original transformer. Secondly, the energy consumption used in the model during the assembly of the substation is not only the energy used on the work floor but also includes the energy usage in the office areas. The sheet steel undergoes various additional processes like cutting and bending. Unfortunately, we could not acquire those data. Hence, we used the ecoinvent database to get the data and make the model as accurate as possible.

5.7 Holtab and Sustainability Goals

Holtab is continuously trying to make a positive impact on the environment. They aim to reduce their carbon footprint in every possible step and are making improvements with their technologies to do so. They also aim to reduce waste production and electricity consumption and try to find any possible environmental risks and take actions to prevent them [4]. By taking the above actions, Holtab is contributing to achieving the following United Nations Sustainability Goals, Goal 7 -Affordable and Clean Energy, Goal 9 - Industry Innovation and Infrastructure, Goal 11- Sustainable Cities and Communities, Goal 12- Responsible Consumption and Production and

Goal 13- Climate Action [91].
From this study, the primary contributors to climate impact are material extraction and manufacturing/production stage as they contribute the most to carbon emissions. Being the major source of carbon emissions for prefabricated power systems, the process needs to be optimised or streamlined and requires immediate intervention to reduce the impact. The assembly stage had a really low impact due to the prefabricated systems that come as modular units and do not require large amounts of energy for assembling. The emissions the transportation depend on the distance and the weight of the material. Higher distance and heavier weight consumes more energy thereby emitting more emissions as compared to shorter distances.
Varying the choice of material for this study was a complicated process as it required the data for each material which includes the amount, type of production and transportation distance. With the available data and EPDs, the materials used for each component were analysed carefully for each and every material. For example, the EPD provided by Holtab for SF_6 gas and SF_6 free gas comparison was made where emissions for the production of switchgear are lower for SF_6 free gas. The EPDs for different types of concrete are also provided.
The sensitivity of the model depends on the key variables which include the transportation distance, energy source and production process. By altering these variables, the relationship between the input and the output could be seen. Integrating more energy-efficient production processes, waste heat recovery and reusing them, integration of more recycled materials for the new product and shortening the transportation distance either by setting up the production unit closer to the material extraction site or production within the country could lead to a reduction in the carbon emissions. Finally, varying the type of energy source for the whole lifecycle could drastically reduce the overall emission and varying the different sources provided varying results which could be used by policymakers and manufacturers alike. This approach allows them to give an insight into the climate impact by allowing them to observe the areas or processes that have the highest impact. As carried out in the different scenarios, they could experiment with the different scenarios which could help them to strategise and adopt more sustainable practices. A higher production cost might lower emissions but from a sustainability perspective, it is important to carry out the long-term goal of reducing the carbon emissions. However, a higher investment cost might also lead to lower operation costs and in the long run that might be a mutually beneficial outcome so it is important to find a balance between them.

6

Conclusion

In conclusion, after the careful analysis and evaluation of key parameters that have a huge impact on the carbon footprint of the power systems, the study of the model for generating the climate impact of prefabricated power systems highlighted the most influencing parameters and provides an understanding of the knowledge gap between the products and their impact on the environment. The type of energy source plays a significant role in the way it impacts the environment and it also highlights the importance of careful analysis of the data with solutions to develop strategies and take action.

We took an approach that analysed the lifecycle of the products from cradle to grave and studied each and every material, energy, transportation and emission involved in the processes. We also delved deep into examining how the key parameters are sensitive to change and how much of an influence they exert on the products and the environment through sensitivity analysis. From this, it became evident that even a small difference in the composition of materials or the production process has a huge impact, implying the need for the integration of sustainable practices. Furthermore, our approach helps us to gain an understanding of the different sources and their impacts uncovering the problems that need to be addressed and emphasising the need for integration of more renewables into the system. There were not many alterations made with the choice of materials due to lack of data, however, the sources and the methods used for the manufacturing and operation of products play an important role in determining the impact of the systems. Overall, in analysing the lifecycle, the operation stage has the largest overall impact and the model is a tool for the study of the impact and with its outcome, it also acts as a guiding tool for policymakers to improve and develop strategies in stressing new decisions on the climate impact of prefabricated power systems.

6.1 Future recommendations

This study provides a comprehensive understanding of the lifecycle of power systems, however, there is still a need for further exploration and expanding the scope which would help in developing robust strategies. While this study is based only on one geographical context, expanding the study to different locations by using different data from various locations could provide valuable insight into how these products have an impact. Since this current study involves two different locations each for the upstream and downstream modules where only the downstream module is based in Sweden, incorporating the entire upstream module to be in Sweden in the future would definitely have a lower impact due to the country's lower carbon intensity as compared to other countries but considerations such as material sourcing and availability could pose a challenge even if the materials are recycled and reused. Expanding the study by conducting a comparative analysis with different types of systems could offer better insight for improvement. Renewable energy integration could be a promising opportunity although it might offer some economic trade-off, however, the long-term emission reduction should be taken into consideration and these could weigh out other factors such as investment costs. Additionally, engaging suppliers in adopting cleaner sources of energy could help influence the overall impact. Incorporating newer technologies and materials, for example, adopting green steel for its production process instead of the traditional production techniques could pave the path for predicting and solving the climate impact. Furthermore, conducting an LCA for certain periods of time could provide a better understanding of the impact such as incorporating changes in the share of energy mix or newer advanced technologies. The model could also benefit from incorporating more up-to-date data, information and methodologies which would help in carrying out the analysis better and assess the impact.

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A

Appendix 1

Table A.1: Load current and loss factor for varying loads

Load (%)	**Primary Load Current (A)**	**Loss factor**	**Secondary Load Current (A)**
40	2.31	0.002	55.64
45	2.59	0.0025	62.6
50	2.88	0.0031	69.56
55	3.17	0.0038	76.51
60	3.46	0.0045	83.47
65	3.75	0.0053	90.43
70	4.04	0.0061	97.38
75	4.33	0.0070	104.34
80	4.61	0.008	111.29
85	4.90	0.009	118.25
90	5.19	0.010	125.21
95	5.48	0.011	132.16
100	5.77	0.012	139.12

$$P = I^2 * R \tag{A.1}$$

where P is the Power loss/Copper loss
I is the current flowing through the conductor
R is the resistance

$$L_f = \frac{Ac_p}{A_p} \tag{A.2}$$

where L_f is the loss factor
Ac_p is the actual power loss
A_p is the apparent power

$$R = \rho * \frac{L}{A} \tag{A.3}$$

where R is the Resistance
ρ is the resistivity
L is the length
A is the cross-sectional area

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