Master’s Thesis – Master Sustainable Development

The Role of Power Electronics for the Raw Material Demand of the Energy Transition

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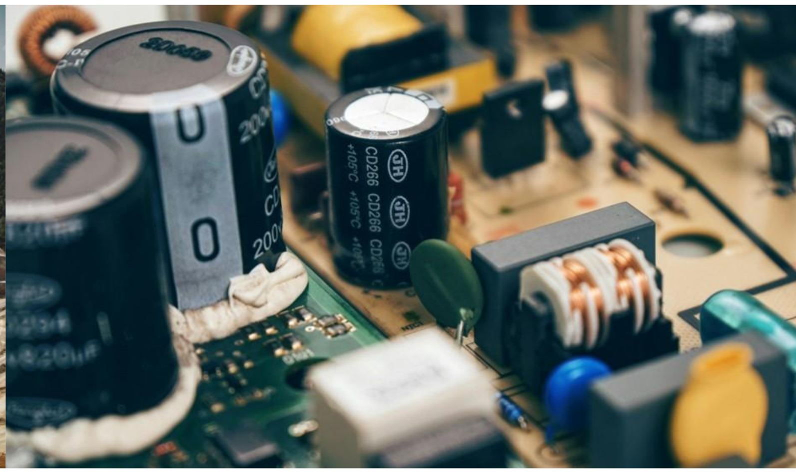

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Summary

The global energy system is transitioning to renewable energy to phase out fossil fuels and combat climate change. Large amounts of PV and wind capacity will be added and the whole transport system will change to electric vehicles to reach the global goals of becoming climate neutral. A lot of additional raw materials will be needed for all technologies relevant for these transitions. Some literature even suggests that this increased demand will lead to raw material bottlenecks in the next decades.

Power electronics is a crucial enabling technology for the transition but is often overlooked in research. While the material demand of other technologies is well examined, there are no in-depth studies regarding the material demand of power electronics. Considering the important role power electronics play in the success of the transition, this is a research gap that needs to be filled.

Therefore, this thesis was conducted to analyse the role of power electronics for the raw material demand of the energy transition. The power electronics devices necessary for energy generation technologies, energy storage and electric vehicles were considered. The innovative approach of this thesis included determining one representative device and its material demand for each technology. Based on the results of analysing six representative devices, a scenario analysis on both a global and a German level was realised. This approach determined the future material demand. While doing this, the most important technological developments in power electronics and their potential impact on material demand were identified.

This analysis shows that the material demand for power electronics for the energy transition will multiply in the coming years, regardless of which scenario is considered. It will lead to an immense demand for many different materials, especially copper, aluminium, and iron. Electric vehicles are projected to have the highest power electronics material demand among the technologies considered.

Raw material bottlenecks are not expected specifically due to power electronics for the energy transition. This is mostly because power electronics account for only a small amount of the total material demand of the energy transition. Wide bandgap semiconductors, increased voltages and more circularity through recycling and circular design are identified as the key technological developments in power electronics. This thesis quantifies the enormous potential for raw material savings these developments have.

Preface

This research was performed in the power electronics department of Fraunhofer ISE in Freiburg, Germany. I want to thank all the people working in the department for their support and the many things I learned during my time here.

Special thanks go to Henrike Köhler and Patrick Hercegfi for the very close and always supportive supervision and for ensuring that I made the best out of my time at ISE. Our weekly feedback sessions and your expertise enabled me to write a thesis about power electronics, a topic I knew nothing about a year ago. Thanks to you, a research paper based on parts of this thesis will also be published and presented at the ECCE Europe conference.

I want to thank Wolfgang Eichhammer for the valuable feedback throughout the whole process and for making sure I focused on the important parts and did not get lost while conducting my research.

My friends and family also deserve a big thanks for always supporting me in everything I do.

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Table of abbreviations

AC	Alternating current
APS	Announced pledges scenario
BESS	Battery energy storage systems
BGR	German federal institute for geosciences and natural resources
DC	Direct current
DC/DC	Direct current to direct current
EoL	End-of-Life
EV	Electric vehicle
eV	Electron Volt
GaAs	Gallium arsenide
GaN	Gallium nitride
IEA	International energy agency
IRENA	International renewable energy agency
kHz, MHz	kilohertz, Megahertz
kt, Mt	kiloton, Megaton
kV	kilovolt
LCA	Life cycle assessment
LCI	Life cycle inventory
NZE	Net zero emissions by 2050 scenario
OBC	On-board charger
PCB	Printed circuit board
PV	Photovoltaics
REMod	Renewable energy model
Si	Silicon
SiC	Silicon carbide
STEPS	Stated policies scenario
USGS	United States geological survey
WBG	Wide bandgap

1. Introduction

1.1 Problem definition

The climate crisis is worsening and the impacts are already visible worldwide with increased natural disasters, long dry and hot phases in some parts and floodings in other parts of the world (IPCC, 2023). Disasters in 2023 including floods in Zambia or storms in Mozambique and Bangladesh give some idea of the dramatic consequences of climate change (World Food Program USA, 2024). The main cause for this human-made climate change is well known: the emissions from the use of fossil fuels for energy and heat generation. Therefore, most governments have committed to phase out fossil fuels and to rely on renewable energy generation and increased energy efficiency instead. The European Union (EU) for example has set itself the ambitious goal to be climate neutral by 2050 and enshrined the target into the European Climate Law (2021). The German government is even a bit more ambitious and plans to be climate neutral by 2045 (Bundestag, 2019). Being climate neutral is only possible if the whole sectors energy generation, transport and heating for industry and buildings are running on renewable energy sources. This implies stepping up the production of many technologies affiliated with this transition, particularly a massive increase in renewable energy sources and a strong effort to reduce energy demand. Various measures are taken in order to reach the targets. These measures entail for instance zero-energy or energy-plus buildings or a change from inefficient combustion engines in cars to electric mobility. This transformation of the way energy is produced and used is commonly referred to as the energy transition.

On a worldwide level, the International Renewable Energy Agency (IRENA, 2023b) analyses that the annual deployment of roughly 1000 GW of renewable power is needed to stay close to a pathway that limits the increase of the average global temperature to 1.5 °C. In 2023, 473 GW of renewables were added globally, accounting for 86 % of new capacity compared to a 14 % share combined for fossil fuel and nuclear additions (IRENA, 2024). Broken down to a country level, in this case Germany, studies show the large added capacities needed until 2045 to reach the target of 100 % renewable energy provision. For photovoltaics (PV) alone, the predicted capacity varies between 385 and 530 GW (Prognos, Öko-Institut, & Wuppertal-Institut, 2021; Sterchele et al., 2020). In either case, there is an unprecedented growth needed in all technologies connected to the energy transition.

The expected growth, especially in renewable energy generation, also implies that the whole industry manufacturing all the necessary devices for the energy transition needs to grow at the same rate. This implies challenges for the supply chains as well as the resources and raw materials used for the energy transition technologies. To reach the German and worldwide governments targets, large quantities of raw materials are needed within short timeframes, implying that corresponding mining and production capacities have to be expanded fast.

Using less raw materials has many positive effects which are good reasons to make an effort to reduce the demand as much as possible. The first reason is the potential of bottlenecks. If less raw material is needed, the risk of running out of this material is decreasing. Besides absolute availability, also the geopolitical aspect of having to import raw materials plays a role.

Since the production of many materials is very concentrated, needing less material ensures more independence. Already, prices for raw materials are increasing and even if no bottlenecks occur, a fast-increasing demand without supply increasing at the same rate will most definitely lead to higher prices for the raw materials (IEA, 2024). So, saving material will, especially in the longer term, be necessary to control costs. Finally, the depletion of raw materials often implies ecological damage. Raw copper for example is mostly mined in the Andean mountains in Chile and Peru. These copper mines have negative impacts on nature and on local communities (Zanetta-Colombo et al., 2024). Therefore, the challenges connected to raw materials are also enshrined in the United Nations Sustainable Development Goals (SDGs). SDG 12 is aimed at a more responsible consumption and production. The first target of this goal already entails the sustainable management and efficient use of natural resources, showing the importance of this topic to global sustainable development (UN General Assembly, 2015).

Besides the social and ecological threats that the extraction of all the additional materials implies, also the feasibility of the transition as it is planned is endangered. The material bottlenecks mentioned here imply that a lower volume of materials is available than needed for a successful energy transition. Some journal articles predict such bottlenecks due to material scarcity for multiple raw materials already in the next decades (Valero, Valero, Calvo, & Ortego, 2018). The International Energy Agency (IEA) published a report in May 2024 that reached the conclusion that the supply of primary copper could be not enough for the demand already in the next few years (IEA, 2024). The global energy transition was identified as the main driver of the increasing demand. All of this shows that raw material bottlenecks are a serious risk to a successful energy transition and therefore to the international climate targets.

To tackle this problem and be aware about the situation, it is necessary to investigate individual parts of the energy system and their role in the material demand of the energy transition. One such part is power electronics. Power electronics technologies are often overlooked but are an essential component of the energy system and will play a key role in enabling a successful energy transition.

Power electronics are essentially the electronic systems used to control and convert electrical power. The basic function of power electronic devices is to adjust the voltage, current or frequency of electricity using electronic components and circuits. These systems effectively regulate the flow of electricity by rapidly activating and deactivating components. Power electronics enables the seamless transfer of energy between different types of electricity, such as direct current (DC) and alternating current (AC) (Bailey, 2020). This adaptability is essential for a wide range of applications, from harnessing solar energy for power generation to controlling the direction and speed of electric motors in vehicles and industrial machinery. Essentially, power electronics devices act as a bridge, connecting otherwise incompatible electric domains like grids, sources and loads to exchange power. The main kinds of devices are inverters which convert DC to AC, DC/DC converters that adjust DC voltage levels to higher or lower values, and rectifiers which convert AC to DC. Since most renewably produced power gets converted in some power electronics device, the efficiency of these devices is crucial. Additionally, power electronics as the connector of renewable energy generation and the grid plays a central role in the advances that accompany the rapid expansion of renewable electricity generation. They help stabilising the power grid by controlling voltage, frequency and power flows which becomes a critical challenge if many renewable power sources are connected to a grid. Power electronics is therefore crucial for keeping the energy system stable throughout and after the transition (Ratnam, Palanisamy, & Yang, 2020).

Due to the close interlinkages and the importance of power electronics for renewables, the rise of renewable energy technologies is driving a parallel surge in demand for power electronics. This also means that with every additional solar panel or wind turbine, additional power electronics devices are needed. Therefore, plans to increase renewable energy capacity always also mean increasing the use of inverters and other applications. In addition, the growth of electric vehicles (EVs) and energy storage systems further increases the need for power electronics, cementing its indispensable role in shaping the future energy system. But the rapid increase that is projected also comes with a rapid increase in material demand for power electronics.

About this particular part of the energy transition, the material demand of power electronics specifically, there is not a lot of research published. This thesis aims to fill this gap and investigates the role of power electronics for the energy transition. It does so as a part of the *Upscaling* project at the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE). The project aims to estimate the material demand and potential bottlenecks due to the German energy transition in different sectors.

1.2 Related works

The material demand and potential bottlenecks due to the energy transition are a crucial field for research since they could hinder the viability of reaching the targets climate neutrality. On a global scale, the demand for raw materials due to the energy transition is extensively researched. There is a lot of academic as well as political interest to quantify the additional material demand and how to ensure that enough supply is available. Many analyses consider the total material demand worldwide for all sectors, but a focus on the energy transition specifically is also not uncommon.

Valero et al. (2018) for example compare the global material demand until 2050 with the available resources and identify possible bottlenecks in a number of materials, including silver, cobalt, copper, gallium, indium, lithium, manganese, nickel, tin and zinc. When analysing the energy transition specifically, the material demand per GW for different technologies, together with scenarios, is often utilized to scale the demand up. Watari et al. (2019) find an increased mineral demand due to the energy transition and the switch to EVs of up to 900 % and 700 % respectively. A striking result of this paper is that the overall resource flows for electricity are still decreasing because so much coal and oil is replaced. Liang et al. (2024) use the IEA Net Zero scenario (IEA, 2021), that is also used in this work, for an estimate of the material demand of selected materials identified as critical. Like the previous papers it estimates a multiplication in demand for all the materials. Manberger and Stenqvist (2018) represent the diversity in findings regarding the risk of bottlenecks due to the energy transition. Their study found that reserves are unlikely to hinder the energy transition because through technological development and substitution the demand for some critical materials can be lowered. Schlichenmaier and Naegler (2022) estimate the global demand of 25 materials in a very ambitious energy transition scenario and conclude that current production levels of materials like nickel, lithium or cobalt are lower than the future demand for the energy transition alone. They see a risk of short-term shortages already and also in the longer term because their demand estimations exceed the identified reserves. The paper also points at a methodologically interesting subject for this work. They underline that the approach of combining energy system models and material flow analysis, as it is also done here, is not very established yet. As an example, feedbacks between the increased material demand and the extra energy demand for producing them is often not included. Some research also considers more geographically specific contexts like the German energy transition for their material demand estimations. Viebahn et al. (2015) conclude that ultimately by substituting, recycling and increased efficiency, there will be enough raw material available for the German energy transition. Some studies only focus on just one technology, for example EVs (Berr, Hischier, & Wäger, 2023) or wind turbines (Shammugam, Gervais, Schlegl, & Rathgeber, 2019). Others analyse material demand on a large scale but include detailed assessments of specific technologies or technological domains. Power electronics are not commonly included in any of these approaches.

As a rare case, Gervais et al. (2022) consider different technologies needed for a successful energy transition, also including an inverter for PV. They modelled the yearly material demand and recycling potential, but the considered inverter material demand was seen as fixed and taken from one old paper (Wild-Scholten, Alsema, Horst, Bachler, & Fthenakis, 2006). Regarding the materials, only steel, aluminium and copper were distinguished. Althaf and Babbitt (2021) focus on electronics overall, including power electronics. The main aim is more to use a wide array of factors to assess risks in material supply due to sudden disruptions. They include risks throughout the whole supply chain, but do not further focus on the raw materials while also not considering power electronics separately from other electronics.

For individual power electronics devices some papers on life cycle analysis (LCAs) exist that also entail information on the material demand of these devices. LCAs generally aim to provide a comprehensive picture of the energy and material flows throughout the whole product life to determine the emissions and other environmental and social impacts of individual products (Sonderegger et al., 2020). The LCAs of Tschümperlin et al. (2016) for an 2.5 kW inverter, Baudais et al. (2023) for an 150 kW inverter and Antoniou et al. (2021) for an EV drive inverter are examples of such papers. They can provide insights on the material demand but have a different focus than this thesis.

The raw material demand for power electronics in a scenario analysis on its own is not considered in any of the assessed studies. The literature on this field is very limited, which is why the methodology of this paper had to be adapted to the available data. Due to this scarcity of literature on the topic, this research tries to lay a basis and to provide insights for future work in this field.

1.3 Research questions

The problem definition and the assessment of the current state of the literature leads to the research questions that were answered in this work. The main research question of this thesis was:

> *What is the role of power electronics in the raw material demand of the energy transition?*

This main question was further divided into the following sub-questions that also lead the way throughout this research. First, it had to be determined which power electronics devices are relevant for the energy transition and which types and amounts of raw materials they entail.

> *a) What is the material composition of the power electronics appliances relevant for the energy transition?*

Since the energy transition is a process that goes on into the future, it was important and also very relevant to consider technological developments in power electronics and which effect they could have on the future demand for raw materials.

> *b) How do technical developments in power electronics influence the future demand for raw materials?*

To demonstrate what the material demand means in absolute terms, different scenarios that provide numbers on the added capacity of technologies like PV, wind energy or EVs were considered. These scenarios include societal and economic developments and are therefore well suited to base a future prediction of the material demand on it. First, the material demand for Germany was explored, which is an interesting example because it has quite strict climate goals that have to be achieved and the REMod model is providing very detailed data for all the relevant technologies (Brandes et al., 2021).

> *c) How much material will be needed for power electronics for the energy transition in Germany?*

Nevertheless, investigating the global demand was also crucial and therefore a similar analysis has been done for the worldwide demand, based on different scenario provided by the IEA (IEA, 2023c).

> *d) How much material will be needed globally for power electronics for the energy transition?*

Finally, by comparing the material demand determined in the previous question with the available supply for each of the identified materials, it was predicted whether enough raw material will be available at some point in the future.

> *e) Will there be raw material bottlenecks due to demand of power electronics for the energy transition in the next decades?*

1.4 Outline of the thesis

After the problem was defined, related works were presented and the research questions for the thesis were formulated in this chapter, chapter 2 will explain the way the research was conducted. To do so, the methods section first gives an overview of the workflow [2.1] and the scope of the thesis [2.2] before describing the steps performed to determine specific material demand, available supply and future developments in detail [2.3-2.6]. The results section [3] presents the findings, first covering the mass shares per technology, material demand per unit, the determined future demand, the factors for quantifying the future developments, and the analysis of potential bottlenecks. In the discussion [4] uncertainties and limitations are examined and the results from [3] are discussed in depth. Finally, the conclusion [5] summarises key findings as well as their implications and suggests pathways for future research to advance the energy transition.

2. Methods

To answer the research questions, multiple, very diverse research methods are needed. Chapter 2 guides through the working process of the thesis and examines all steps that were performed to answer the sub-questions and finally determine whether there will be bottlenecks due to the material demand of power electronics for the energy transition. The workflow and goal of this thesis changed throughout working on it. Originally, a focus solely on the question whether there will be bottlenecks was planned. In coordination with the supervisors, the focus changed to a broader question on the role of power electronics with a bigger focus on the discussion part. This way, the results of the thesis were more insightful especially regarding the effects of technological developments.

2.1. Overview of workflow

To determine the material demand for power electronics, identify potential raw material bottlenecks and define the role of power electronics regarding the energy transitions material demand, different research phases had been worked through. These phases are summarised in Figure 1, displaying the general workflow of this thesis.

1) First the scope was narrowed down to determine what is considered and what is not, specifically regarding different power electronics technologies.
2) In the second phase representative devices for different technologies were identified and their material composition was worked out in detail.
3) The third phase of the work determined the material demand of the different power electronics technologies per unit (GW or technology unit).
4) The fourth phase determined the relevant future technical developments in power electronics and their implications for the material demand.
5) In the fifth phase, databases with data for different scenarios of how the energy transition could develop were assessed.
6) The sixth phase included merging the raw material demand of the technologies with the added capacities that the scenarios predict. This way, the future raw material demand in the different scenarios was modelled.
7) In the seventh phase, the available supply for all needed materials was researched.
8) The eight phase combined demand and available supply and exposed if any bottlenecks will emerge.
9) Finally, the results were analysed, discussed and put into context in the final part of the research.

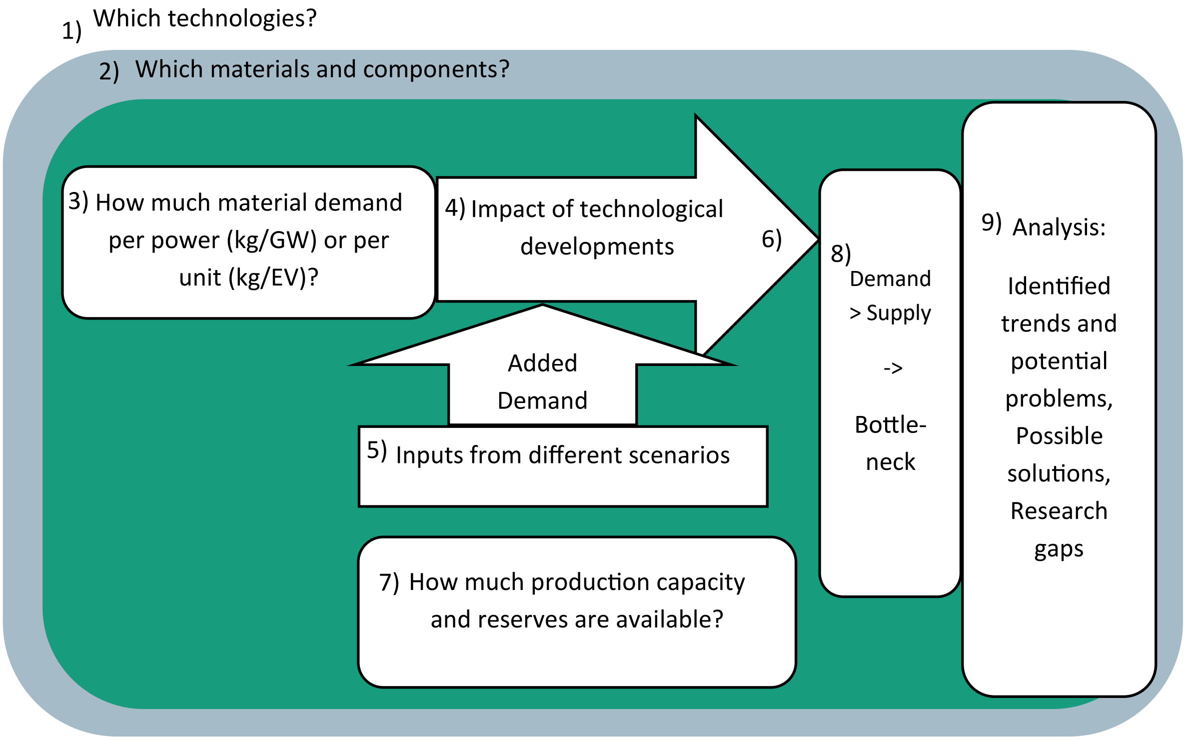

Figure 1: General workflow of the thesis

2.2 Scope

The scope of the analysis focusses on the raw materials that are available. This implies that only the first step of producing the devices is examined. The supply chain, including the processing of the materials or the manufacturing of the devices, is only considered in the discussion and assessment of the results, but not part of the calculations made here. Quantitative models and useful predictions about the future developments regarding geopolitical risks and the state of global supply chains are out of the scope of this master thesis. The EU's classification of supply risks for different materials can be helpful and will also be considered in the discussion of the results. But besides original plans to include risks within the supply chain in the calculations of this thesis, no way of doing it with reasonable effort was found.

Regarding the materials that are considered, the scope includes all materials that were identified in the analysed devices. All materials that are found are included in the results regarding the material composition and demand per GW. In the second part of the results, where potential raw material bottlenecks are determined, only metals are considered. Raw material bottlenecks are usually only occurring for metals. Plastics for example are not considered because they are made from petrochemicals, which are abundantly available since they are based on oil and natural gas. Deriving the oil and gas demand for the different plastics and comparing that with the available reserves would be out of the scope of this thesis. Additionally, the energy transition will reduce overall demand for these fuels a lot. Other chemical products including epoxy resin and silicone are also not taken into account for this latter part.

The initial geographical scope of this thesis was Germany, because the *Upscaling* project was focused on the national level. During the process of this thesis, the scope was extended to a global scope to get more insightful results.

The most important clarification of the scope is which technologies, that rely on power electronics, are considered in the analysis. Power electronics are used in a wide array of applications, from consumer electronics like chargers for laptops to larger industrial motors to automated production lines. This thesis considers the applications that are directly related to the energy transition and does not take the demand of other applications into account. But even with a focus on the energy transition not all technologies can be assessed.

This research focuses on technologies using power electronics that constitute the biggest portion of installed power capacity and are projected to experience substantial growth in in the next years. An overview of the technologies relevant for the energy transition, that rely on power electronics, is presented in Table 1.

Regarding renewable energy generation, strong growth is expected in rooftop and freestanding PV systems, as well as in wind turbine installations. Furthermore, meeting the rising demand for battery storage systems involves both mobile batteries within EVs and stationary battery systems. EVs are also key for the mobility transition because they are expected to gradually replace combustion engine cars. Only battery electric vehicles are considered when analysing EVs here, while hybrid cars are omitted because the scenarios utilized here predict very low market shares for hybrid cars in the longer term.

Certain other technologies that are relevant for the energy transition could not be included in the scope of this paper. Public transport, especially trains, rely on power electronics and will increase in number because of the modal shift away from individual mobility that is needed to save energy. But there is not a lot of data on numbers about the added demand and it is especially hard to find any data on the power electronics used in trains. Under the assumption that the demand will also not be increasing to the same extend than the energy generation technologies and EVs, it is not included in the scope. Electrolysers to produce hydrogen are anticipated to become a relevant part of the energy system in some years but are not yet very common. This also means that there is little information on the power electronics needed there which also excludes electrolysers from the scope here. Some other technologies such as heat pumps only use power electronics to a smaller extend, for example to enhance performance, and are therefore not considered.

Therefore, the main technologies considered in this work are PV, wind energy, EVs and battery energy storage systems (BESS).

Technologies	Examples of Power Electronics Devices	Relevance for Energy Transition
Solar PV Systems	Inverters, DC/DC converters	Key renewable energy sources, power electronics enable connection to grid
Wind Turbines	Rectifiers, inverters	See Solar PV Systems
Battery Energy Storage Systems	Inverters, DC/DC converters	Batteries support the transition by increasing the flexibility and reliability of the grid by reducing peak grid load
Electric vehicles	Drive or traction inverters, on-board chargers, DC/DC converters	Reducing use of fossil fuels and making transport more energy efficient
Hydrogen Systems	Rectifiers, DC/DC converters, inverters for fuel cells	Predicted to play a crucial role for energy storage and clean industry processes in the future
Public transport	Traction inverters, voltage regulators	Making transport more energy efficient

Table 1: Overview of application of power electronics for the energy transition based on Chhipa, Vyas, Kumar, & Joshi (2021) and Souza Junior & Freitas (2022)

2.3 Specific material demand for the power electronics devices

The investigation of the material composition and the material demand of power electronics appeared to be a demanding task, mostly due to the lack of data about material composition of different power electronics devices. There exists an immense research gap regarding the inventories of power electronics devices and therefore a lot of time was spent to create approximations for the different technologies. There was little literature found that would provide such an inventory for one of the relevant technologies.

LCAs published by power electronics manufacturers are one way of gathering data about the material demand. The companies publish the LCAs to determine environmental impacts of their products. These LCAs are more and more standardized with the ISO norm 14040 as the guideline (ISO, 2006). In general, an LCA is subdivided in four phases, where in the second phase an inventory of all the inputs and outputs for the product are gathered, also including the necessary raw materials. This phase is called Life Cycle Inventory (LCI) and entails the relevant data for this work focusing on raw materials. Therefore, the LCIs entailed in company's publications acted as starting points to determine power electronics material demand (Sonderegger et al., 2020).

On top of LCAs by manufacturers, the ecoinvent database (Ecoinvent Centre, 2021), also provides LCI data. The LCA modelling tool SimaPro (Pré Sustainability, 2023) was used to assess the inventory of many different products that ecoinvent entails. Similar to the manufacturer's LCA data, the LCI data in ecoinvent is intended to be used to calculate the environmental impact over the whole product life, but in this work only the data on the raw material input was considered.

Some data was also gathered from projects previously conducted at the Fraunhofer ISE. On top of this, personal communication with staff from the institute and with externals as well as in one case own measurements were used to get an appropriate picture on material demands in power electronics.

The Appendix of this thesis shows exactly which data source was used for which exact component. Not all the individual data sources are presented here to not impede the reading flow too much in the main part of the thesis. Nevertheless, all the details can be found in the Appendix to provide full transparency.

The general workflow includes the thorough analysis of one representative device from each of the mentioned sectors. Based on given component shares, the exact weight of materials in these components were derived. Different data sources were used to compile a complete raw material inventory. This workflow is visualized in Figure 2. Figure 2 also shows the difficulties due to the diverse data sources. As shown in Source 1, it was common that datasets entailed a mixture of raw materials and components. Components are defined here as parts of the technical device that are build out of different materials. As an example, if the device is a flashlight, a component could be the lightbulb, the battery, the housing or the switch. Finally, the mass shares for each material were scaled up to the GW level for the generation and storage technologies. For the EVs, the total material demand for the power electronics devices of one representative EV was determined, which can then be multiplied by the number of new cars.

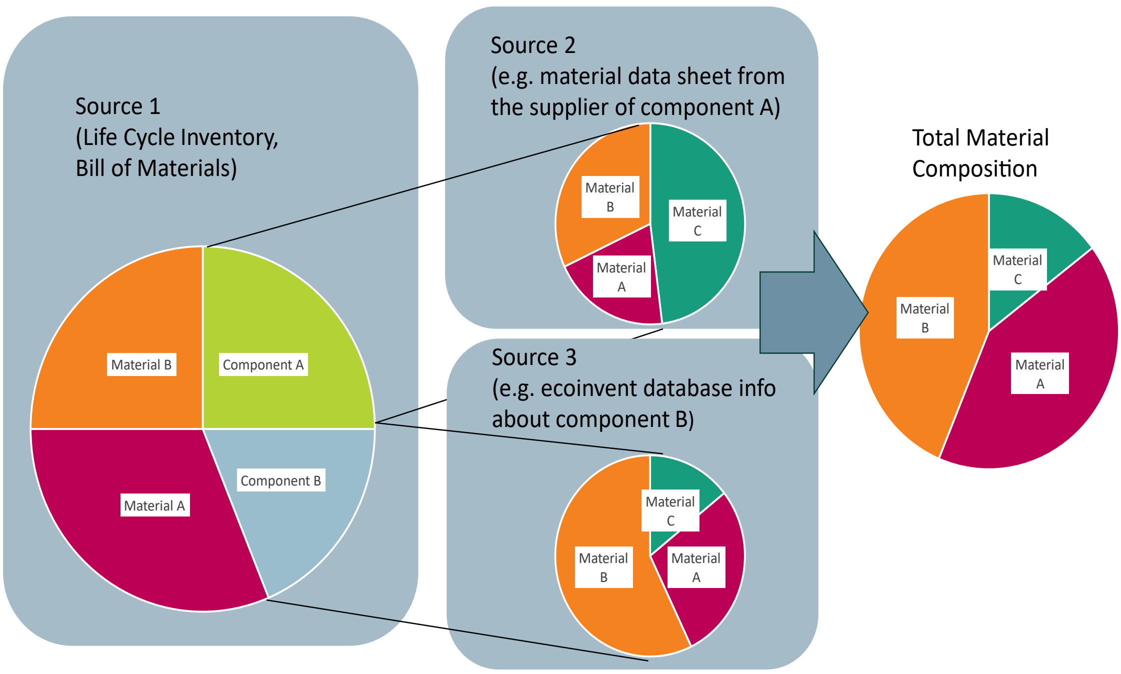

Figure 2: Workflow determining the material composition of the representative devices

Besides building the foundation for the rest of this work, the data can hopefully also help future research on raw materials for power electronics as well as LCAs regarding power electronics. The following sections explain in detail how the process of determining the material demand was approached for the different devices that were considered here.

Small PV string inverter

Small PV string inverters are used primarily to convert the DC power generated by solar panels into AC power, which is commonly used in residential electrical grids. They are mostly used in residential areas, an inverter with a 10 kW power rating, like the one researched here, would fit for around 25 to 30 average solar panels or 80 square meters of roof area (Sykes, 2023).

The materials for a string inverter with a low power rating were determined based on an exemplary inverter from Fronius International GmbH (Musil, Harringer, Hiesmayr, & Schönmayr, 2023). While other LCAs for solar inverters were also considered as a basis, this work reached a level of detail that other publications lacked. It was also a recent publication with a rather modern solar inverter, especially compared to the inverters available in ecoinvent (Ecoinvent Centre, 2021) which are based on data from a paper published in 2006 (Wild-Scholten et al., 2006).

Musil et al. (2023) performed an LCA for a 10 kW GEN24 Solar Inverter (Fronius, 2024). They point out the complexity of assessing the materials and components by underlining that this individual inverter consists of 423 components with 2547 parts (Musil et al., 2023). The first part of the paper, the LCI, which gives the weight of certain groups of components, is very interesting for this report.

Some information on the material composition was already given in their publication. For example, the weight of 28.06 kg including the packaging (with aluminium having the biggest share of 8.16 kg and technical plastics contributing 6.53 kg). One problem with analysing the components in more detail is the inconsistent labelling. In Musil et al. (2023) a component called “coils” makes up for quite some weight but is not examined further in the LCA. Since coils with ferromanganese cores are most common in this power rating class, the material data from ferromanganese core coil from a previous project at Fraunhofer ISE was used for the whole component category. Another component with a large share of the total material demand is the DC-link capacitor and Nordelöf, Alatalo, & Söderman (2018) provide data for the material composition of a DC-link capacitor.

Anders Nordelöf from Chambers University in Gothenburg, Sweden, provided access to the database underlying their papers after reaching out to him (Nordelöf, 2017). Components were broken down there into a lot of detail which was useful throughout the research and especially for the EV drive inverter. They base their scalable model of capacitors on multiple units from inverters in the power range 20 kW to 80 kW. The mass shares for the capacitor are assumed to be constant since changes in the power did not show great differences in composition. The same document also provides an example of a printed circuit board (PCB). The tool does not completely break down the data to the material level, but only to some materials and components that then had to be analysed via the ecoinvent database (Ecoinvent Centre, 2021). This is an example of the different levels that were necessary to analyse to reach a material level. Unfortunately, two of the categories chosen by Fronius (“complex components” and “simple material mix”) do not allow further research based on them, since it is unclear what is meant by it. Therefore, a small part of the materials still remains unknown in the assessment, while the vast majority of the weight could be attributed to the respective material.

Large PV string inverter

Another string inverter was considered with a higher power rating of 100 kW. This size is used on big, industrial roofs or in solar parks. The inverter that was considered was the Fronius Tauro 100 (Fronius, 2022). The approach chosen to assess the material composition was similar to the one chosen for the 10 kW inverter from the previous chapter. An LCA paper also provided a composition of some materials and components (Fronius, 2022). The inverter weighted 120 kg with all packaging material and about 100 kg without packaging. The composition of the individual components was derived from the same sources than for the one with lower power rating including Nordelöf, Infineon and ecoinvent. Therefore, the workflow here resembled the one for the smaller inverter, even though the composition data to start with was a little less detailed.

Central PV inverter

Another inverter topology, mostly for applications with higher power ratings and for large solar farms, is the central inverter. Central inverters often have a modular approach of construction, meaning that multiple inverter units are combined into one. Even though central inverters are very popular, there is a scarcity of published research about the materials used in central inverters and in contrast to the string inverters also no LCAs are available. So, the data on the material composition had to be gathered from other sources. Fraunhofer ISE previously developed a central inverter for a research project called MODUS, which follows the typical modular design of PV central inverters since two 500 MW parts are added up (Eger, Ganatra, & Häßler, 2020). The bill of materials from this project together with corresponding datasheets which include the weight of the components was used to get to the component level. The material composition for some custom parts like busbars, mounting plates and printed circuit boards (PCBs) were weighed manually. The material data of other, mostly smaller components was then derived using the ecoinvent database, material declaration sheets that are available online as well as data from Nordelöf (2017) again.

Wind converter

Wind turbines are very important for the energy transition as a main source of renewable power. Power electronics is central for wind energy since high amounts of power must be fed into the grid. Wind converter systems convert very high power, mostly several megawatts. Current state-of-the-art onshore wind turbines have an average power rating of 4.7 MW (Deutsche Windguard, 2023). In the initial research no publications were found on the material used for power electronics in wind converters and no LCAs regarding wind converters seem to be available yet. Therefore, a solution to derive the material composition had to be found.

The first approach was to upscale the available data of the central inverter from 1 MW to 4.7 MW. This approach would have generated a significant inaccuracy since wind converters and central PV inverters are constructed somewhat different. Therefore, gathering primary data was seen as the best option to get an estimation of the composition of converters for wind.

During the time this research was conducted at the Fraunhofer ISE, employees of a wind turbine manufacturing and development company were present there to test their new wind converter. They were willing to explain and share data about the components used. Component mass shares as well as the topology of a 4.8 MW low voltage wind turbine converter were provided which act as the base for the analysis, since it resembles the average onshore power quite well. The total weight of the 4.8 MW converter was 5 tons, and data on the masses of other components including the filter capacitors, inductors, DC link capacitors as well as the rectifier were supplied by the company. An exact list of the materials of the power modules utilized could be found in the material declarations which Infineon published online (Infineon, 2021b). This was very useful since many potentially interesting materials are contained in the power modules. A datasheet by manufacturer ABB for a 4 MW turbine provided data for the mass of busbars and fuses (ABB, 2018). All the components, where values for the weight specific to the wind converter were found, added up to a weight of 3.4 tons.

Further, the comparability of solar central inverters with wind converters when it comes to the topology was utilized. Since the central inverter analysed operates at a switching frequency of 4 kHz which wind converters since that is a typical frequency in wind converters. So, the components where no data was known so far were taken from the central inverter in a way that they add up to 5 tons. By doing this, the material composition of a representative wind converter was assessed as good as possible.

EV drive inverter

Power electronics play a crucial role in multiple areas of EVs, with the main devices being the drive inverter, the on-board charger (OBC), and the DC/DC converter. The latter was neglected here, as the power rating below 5 kW as well as the mass are much lower compared to OBC and drive inverter (Koroma et al., 2022).

To find a representative device in this case meant the average drive inverter and average OBC in EVs had to be determined. This is done by analysing the ten most-sold EVs in Germany of the last year and creating a weighted average of their device size (KBA, 2024).

Drive inverters in EVs convert the DC current from the battery into AC current to power the electric motor, they are therefore a crucial part of the car. Nordelöf (2017) provides an excellent LCA tool specifically designed to analyse the materials used in EV drive inverters. Access to this tool was gained as explained in the chapter on the small PV inverter. This tool includes a scalable inverter which provides the material data for the drive inverter. The only necessary input is the inverter size and voltage, and the output provides very detailed material information and only a few components were not examined in more detail. For the material composition of these missing components, material data sheets from Infineon and data from ecoinvent were used.

EV on-board charger

OBCs convert the AC currents from the charging station, and hence the grid, inside the EV into DC currents that can be stored in the battery. Kabus et al. (2020) performed an LCA for OBCs which also include an inventory of the components used in an OBC developed by Schmenger, Endres, Zeltner, & Marz (2014) in a research project. While such a modular OBC, which is also only a prototype, might not be the best representation, the details of information regarding the component share were decisive to use this OBC as a source. The paper names and links all the components used in the prototype. So, the prototype that was analysed was taken as a representative device for an OBC in this work. Based on the components provided in the paper, the materials were identified taking into account material declaration sheets as well as Nordelöf (2017) for the few components where no material data was available.

Inverter for stationary batteries

Battery energy storage systems (BESS) play an important role in the energy transition by providing flexibility that is needed due to the fluctuations of renewable sources. BESS were also identified as a technology that has to be considered to get the full picture of the material demand for power electronics. Similar to PV applications, there are two main types of BESS to consider. One type are home batteries, mostly owned by houseowners and almost always coupled with a PV system, and the other type are large-scale, industrial solar farms, often up to MW capacities. The majority of the installed battery capacities in Germany consist of the first type with around 80 % of the total capacity, while large battery systems only make up for 20% (Figgener, 2022).

Most residential solar inverters are hybrid inverters that also act as battery inverters. This is also true for the Fronius 10 kW string inverter that was analysed here (Fronius, 2024). Therefore, no need for additional power electronics parts is added by the additional battery capacity. For the further calculations it is assumed that no additional materials are needed for the small residential BESS.

Regarding the larger scale BESS, other power electronics devices are needed. The inverters needed for these BESS are similar or sometimes even identical to the ones used in big free-standing solar parks. The material composition determined for the central solar inverter are therefore used for further calculations regarding the added large-scale BESS capacities. Consequently, no individual assessment of material use in power electronics of BESS is performed but they will still be part of the modelling later on.

2.4 Scenarios

While the previous step generated data on the amounts of material used in one representative device, the next step is upscaling the material demand to a unit to be able estimate future demand. To do this, the material demand is upscaled to material use per unit. For the generation technologies the relevant unit is the material demand per GW added capacity. For EVs, the relevant unit is the material demand per car.

The other piece of information that is needed to determine potential future demand is the amount of added capacity of the examined technologies.

The energy system model REMod, developed by Fraunhofer ISE (Brandes et al., 2021) models the current and future German energy system and develops cost-effective paths to reach the target of climate neutrality in 2045. The model provides data for different scenarios showing yearly added capacities of PV, wind, battery storage, EVs and more. The scenarios entail varying levels of acceptance for the energy transition within the German society, which results in diverse rates of diffusion of the different technologies. The *Upscaling* project is closely connected to the REMod model because the original aim of the project was to gather data on potential material bottlenecks that could then also be included in the model.

The scenarios entail a *Reference Scenario* that explores the cost-optimal transformation of the energy system without assuming significant societal acceptance for change or altered consumption behaviour. It does include significant expansion of photovoltaic and wind energy, an exit from coal as planned and an increase in electricity imports. Secondly a *Status Quo Scenario*, which assumes a limited public willingness to adopt new technologies, resulting in a delay in the adoption of new technologies. A *Resistance Scenario* envisages lower expansion of large infrastructure projects due to complex approval processes and local resistance, while a *Sufficiency Scenario* examines the impact of behavioural changes leading to a significant reduction in energy demand. This scenario anticipates a 45% reduction in electricity demand for lighting, cooling, information technology, and mechanical energy, along with efficiency improvements in transportation and building heating (Brandes et al., 2021). All of these scenarios will be modelled to show different paths regarding the future material use for power electronics.

The total demand for material goes further than just the added capacities in the future. Power electronics devices that were already build and sold have to be replaced at some point. Consequently, data on the historical added capacities is needed as well. The data for Germany regarding the generation technologies wind energy and PV as well as batteries was taken from the federal network agency (Bundesnetzagentur, 2024). The stock of EVs in Germany was found in data from Impey (2024). Additionally, it has to be known when the old devices have to be replaced and how much of the materials can actually be recovered and used again. Where this data was taken from and how it was used to integrate recycling into the modelling is explained in more detail in the chapter on recycling as an important development in power electronics (3.3).

The REMod model divides added PV capacity into rooftop and freestanding PV. The aim here was to represent these differences and take into account the different sizes of inverters used in both categories. Therefore, the material demand per GW of rooftop PV was evenly divided between the representative 10 kW and 100 kW inverters material demand without transformers. For freestanding PV, the 100 kW string inverter and the 500 kW central inverters were used while also adding the transformers that would be needed for both.

On the global level, the International Energy Agency (IEA) also publishes scenarios about the future of the global energy system and provides a database with a large amount of data (IEA, 2023c). The scenarios include the *Stated Policies Scenario (STEPS),* which takes into account the policies regarding climate and energy that are in place or planned right now, and the *Announced Pledges Scenario (APS)* modelling a potential future where all countries fulfill the emission reductions they pledged in the Paris Agreement. The *Net Zero in 2050* Scenario (NZE) models how the target of global climate neutrality in 2050 could be reached (IEA, 2021). But the data basis of the IEA scenarios is less consistent compared to the REMod ones for the use case of this thesis. The necessary data is divided in three different datasets that have different layouts and are not easy compatible. One dataset (IEA, 2023c) provides cumulative power ratings for the different technologies PV, wind and battery storage in 5-year intervals until 2050. Another dataset (IEA, 2023b) provides predictions on the annual sales and stock for EVs globally, but only until 2035. As a useful tool for comparisons the IEA also reports on the demand for different critical materials (IEA, 2024). While the reports named here visualise the data quite well, the raw data for each of these reports was downloaded from the IEA data explorer website (IEA, 2023a).

The different datasets with their different layouts had to be combined to create a complete and comprehensive dataset to work with. The generation capacities are given in 5-year intervals and only provide the cumulative GWs for PV, wind energy and battery storage at that time (IEA, 2023c). Predictions on the future stock of EVs were unfortunately only available until 2035 (IEA, 2023b). For the STEPS and APS scenarios a prediction by Wood Mackenzie (2021) was taken into account which claims that realistically in 2050, 700 million EVs are used globally. The report on the NZE scenario clearly claims that it would be necessary to replace all almost 2 billion passenger vehicles globally by 2050 to reach the net zero target (IEA, 2021). The data also does not entail a separation into rooftop and freestanding PV as REMod does. To still use the different material demands that were calculated for the different categories, data on the global division of rooftop and freestanding PV from SolarPower Europe (2023) was consulted. This data showed that the modelled distribution is almost 50 % for both right now but will change towards freestanding with 57 % share long-term which is used in the global scenario analysis.

While the modelling extends to 2050, 2035 will also be selcted as the year of comparison for some results. Until 2035, there is still more coherent data from both sources and the IEA report on the global demand for some critical materials (IEA, 2024) provides data for comparison until then.

Similar to the German case, historical data needed to be gathered on the global level. IRENA (2023a) publishes data on the GWs of PV and wind energy in use globally as well as the stock of EVs from 2000 on. This data was used in the global analysis.

2.5 Supply

The counterpart to the demand is the supply, so the next step was to research what supply of a certain material is available. The main source for data on the supply for different materials is the United States Geological Survey (USGS, 2024) which provides data on the global production and reserves for all metals considered here. The data are also broken down to the countries the reserves are found in, and the production takes place. Additionally, there are comments and informational texts on the uses of the materials and ways to substitute them. The publications are also always kept up to date with monthly updates on each material. Therefore, the USGS commodity information (USGS, 2024) provides a solid database for the global supply.

Breaking this further down is a sophisticated task. The initial approach in this thesis was to determine how much of the global production is available for Germany to make it comparable to the REMod scenario data. To do this, there are two main strategies, which are both based on the budget approach of allocating resources, which is mostly prominent in climate justice debates (WBGU, 2009). One approach, the equity approach, would assign 1.00 % to Germany because that is the share of the total population. The economic power approach would assign significantly more, since it is granting the share of the global gross domestic product (GDP) of Germany which is around 4.00 % (World Bank, 2024). Both approaches seem very arbitrary, so none of them are used in the calculations. The German Federal Institute for Geosciences and Natural Resources (BGR) publishes a report on the state of resources in Germany that entails data on some of the materials considered here (BGR, 2023). The annual demand and the production in Germany for different materials across all sectors can be derived from this report. But such an approach would conceal the fact that a lot of power electronics devices and especially their pre-products are imported to Germany.

Therefore, these possible approaches still seemed quite approximative and are not necessarily reflecting the real situation. Other master theses written in the Upscaling project could also not offer solutions to these problems. Consequently, it was decided to not take one of this numbers as the basis for modelling and just show the demand trend based on the different scenarios taken from REMod. Still, the numbers were useful to visualize the order of magnitude of material demand determined in this work.

It would have also been necessary to break down the total supply to the supply that is available for power electronics. The approach was based on the share of the global GDP the power electronics industry has. The assumption behind this approach is that all sectors have the exact same material demand per part of GDP they are adding which is far from realistic. Taking into account data from YOLE intelligence (YOLE, 2023) and the World Bank (World Bank, 2024), this calculates to a really low number. If only that share of the total supply would be available for power electronics, the amount would be very small. Applying this approach would imply serious material shortages already in 2024 due to power electronics which is not the case.

At this point the original plan of determining bottlenecks for Germany specifically was changed because none of the approaches presented here was convincing enough to base credible results on it. The analysis for bottlenecks was only be performed on a global level. The data sources and approaches presented here are only used where they can show interesting trends or findings as a comparison. Other publications like the one from the IEA (2024) are already comparing total demand, including all sectors, also non-energy, and the supply and are identifying bottlenecks. So, the approach is to put the demand for power electronics into perspective and compare the orders of magnitude regarding the influence of power electronics on raw material bottlenecks.

Other than that, the results of this chapter will also include qualitative findings that are related to the problem of material scarcity, which were found while doing the research.

2.6 Future developments in power electronics

A very important part of this work was to identify what impacts the main developments in power electronics will have on the material demand. First, the relevant developments that will be considered had to be chosen and afterwards the effect of these developments had to be estimated. For the decision on which development to consider, the main criteria were that they have a clear effect on material demand and that the widespread diffusion of these developments is likely. The decisions which ones to consider were based on an overall impression from literature and on input from experts working at Fraunhofer ISE.

3. Results

3.1 Specific material composition per technology

In the first part of the research the material shares of the different technologies were examined in the way that was described in chapter [2.3].

String inverter 10 kW

The outcome of the analysis, the material share of the 10 kW string inverter, is displayed in Figure 3. The biggest shares of the total weight are taken up by aluminium and plastics for the housing and the heatsink, while some iron and copper for the coils also play a significant role. Some percentage points also are allocated to other, less common materials like nickel, manganese, or zinc. While the manganese and zinc come from steel alloys used in the coils, other materials such as silver and glass fibre are part of the PCB. Also interesting is silicon used as a semiconducting material here, which only makes up for a very small percentage of the total weight. Nevertheless, the material features of silicon are having a crucial impact on the inverter. The total weight of this specific inverter is around 25 kg, so for one individual inverter the weight of most materials is in the gram size range.

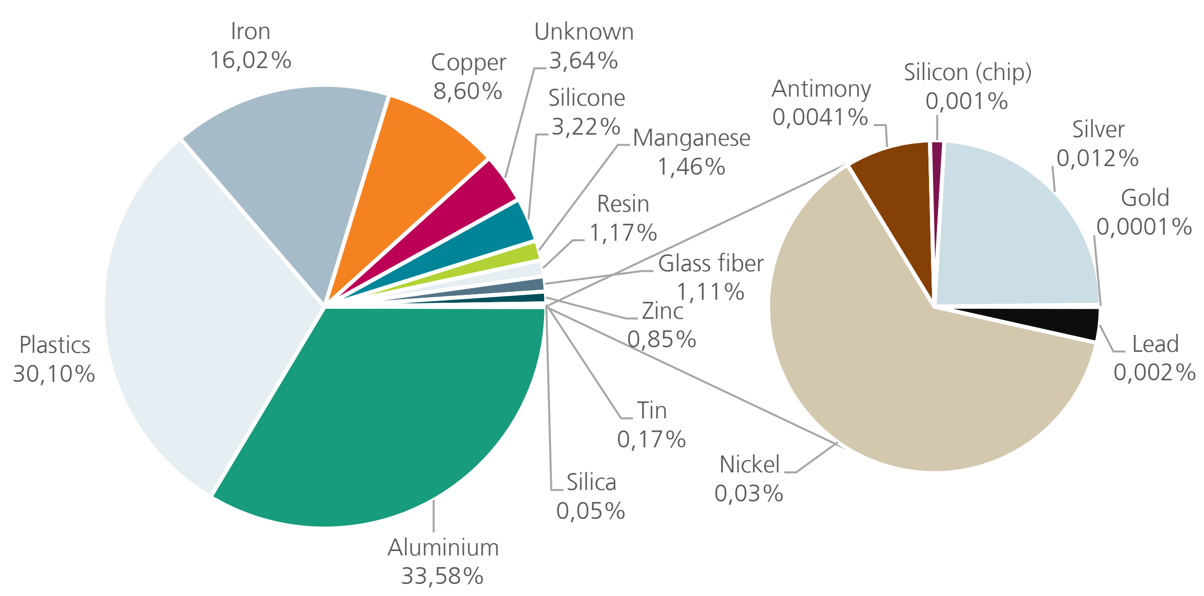

Figure 3: Material composition of a representative 10 kW PV string inverter (25.6 kg)

Shortly before the end of working on this thesis, an LCA on a small PV inverter entailing a very detailed LCI breaking down the whole device to a raw material level was published by EPD Italy (EPD Italy, 2024). While it was not used to influence the results of this work, it is a nice source of data for a comparison. The analysis of the material composition of this 6 kW inverter shows that the aluminium part is way higher than in the inverter that was analysed here before with 50.28 %. Iron is almost not used in the inverter with only 2.06 %, which is a difference to the big part it played here in the cores of the coils of the 10 kW inverter. Plastics and copper with 20.01 % and 6.42 % respectively are in the same order of magnitude for both devices.

String inverter 100 kW

The 100 kW string inverter weighs around 100 kg without the packaging for shipping it. This already shows that linear upscaling does not work, because ten times more power only compiles to four times more material demand in this case. Figure 4 displays the material composition for the 100 kW inverter. Besides the high contributions of aluminium in both string inverters, the analysis also demonstrates the variety of other materials used in different parts of the inverter. For example, manganese is used as part of ferrites, that are typically used in higher frequency chokes, or antimony and silicon located in the power module. While the smaller material shares are pretty similar, since the same component material data were used for the analysis, a significantly larger share of aluminium and copper is visible.

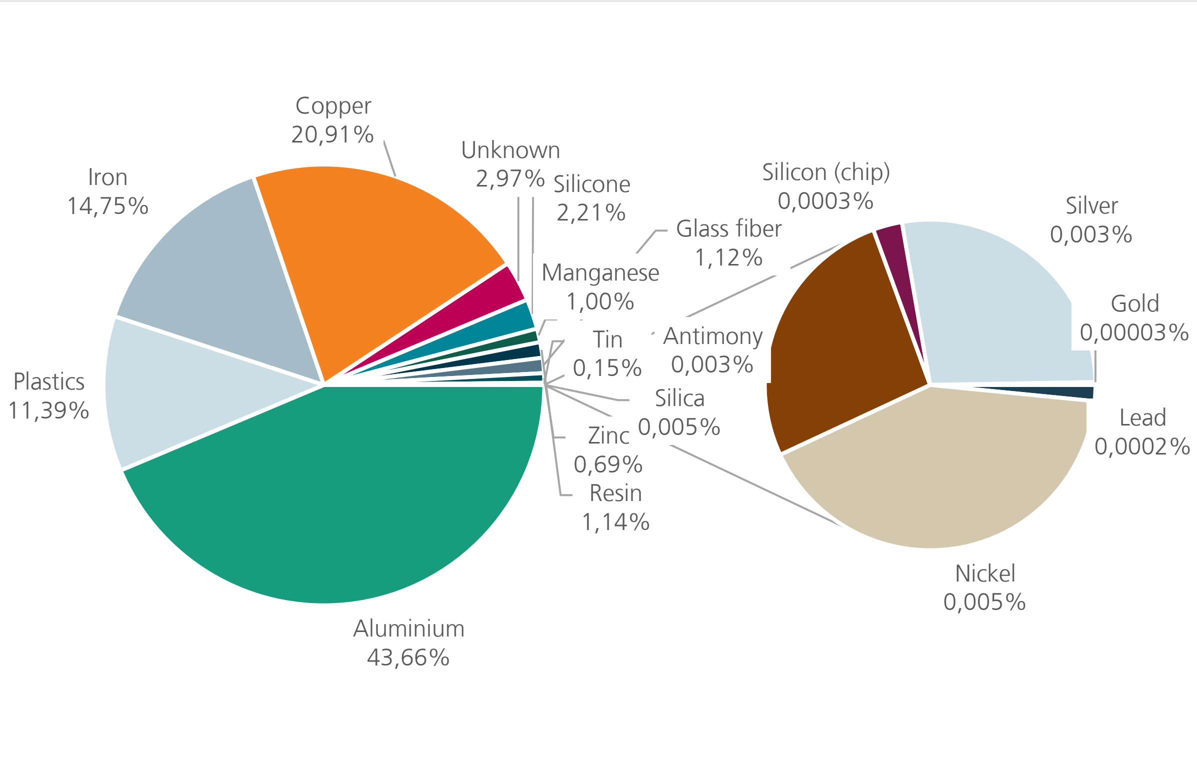

Figure 4: Material composition of a representative 100 kW PV string inverter (101 kg)

PV central inverter

The 500 kW central inverter chosen here weighs around 400 kg and has a steel housing. Compared to other central inverters of similar capacity, it is quite lightweight due to its status as a research project. Nonetheless, given the strong endeavours by industry to reduce material, it is expected that similar weights will soon become the technological standard. The heaviest parts of the inverter are the steel housing and the chokes, which consist mainly of iron and copper. This results in the substantial share of these materials, as depicted in Figure 4, and also explains the completely different composition compared to both string inverters. It is important that steel for housing is in this work modelled as iron if no more details about the steel properties are known.

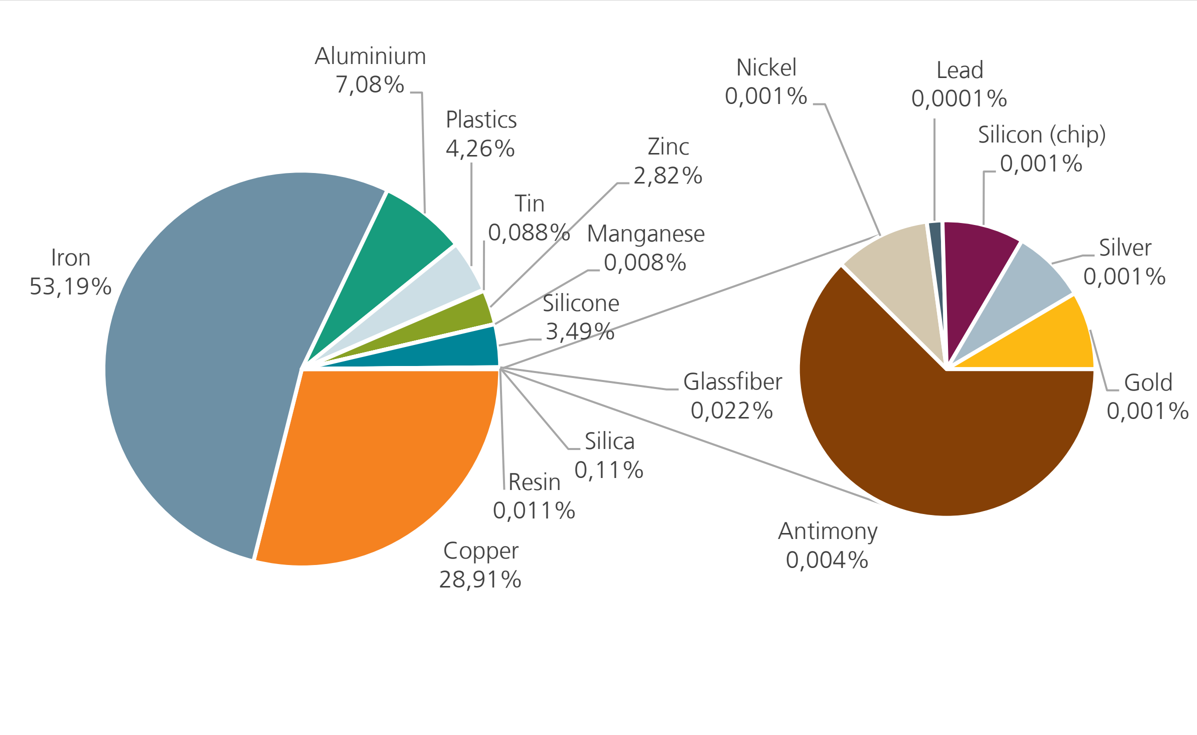

Figure 5: Material composition of a representative 500 kW PV central inverter (390 kg)

Wind converter

The exemplary 4.8 MW wind converter weighs 5 tons, and the material composition closely resembles the central PV inverter. In both cases the largest share is iron and copper for housing and coils. Overall, the large wind converter has a lot of components that mostly contain the most prevalent materials, shares of other materials like zinc make up a smaller part here. The material demand for power module and small electronics components, where the materials with small shares such as silicon or antimony are used, does not increase proportional to the power rating of the devices. Therefore, higher power ratings lead to lower share of these materials in the materials.

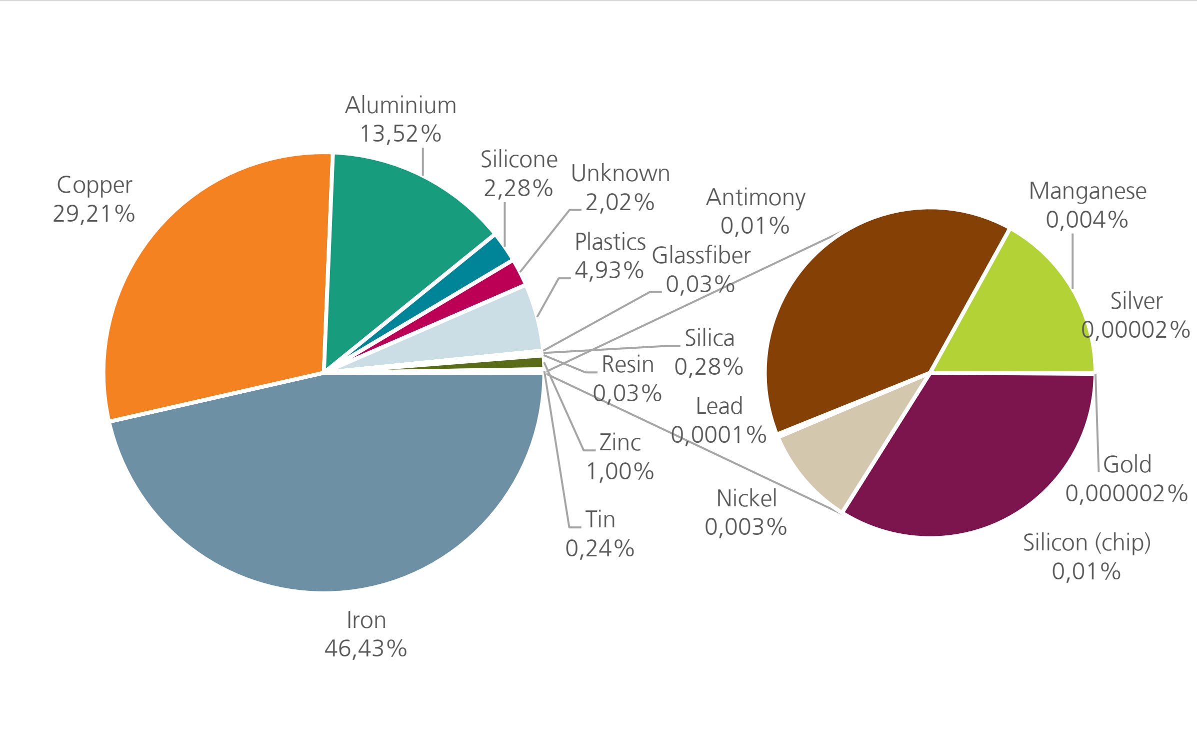

Figure 6: Material composition of a representative 4.8 MW wind converter (5000 kg)

EV drive inverter

To model a representative EV, an average driver inverter size had to be found. Taking the weighted average of the ten most sold EVs in Germany in 2023 according to the German Federal Motor Transport Authority gave 185 kW as a weighted average drive inverter size (KBA, 2024). This number appears to be quite high but reflects the ongoing trend of larger cars being sold in the EV market with a Tesla Model Y being the by far most sold EV in Germany in 2023 (KBA, 2024).

Entering the power of 185 kW and a standard voltage of 400 V into the tool developed by Nordelöf (2017) gave the mass contribution that can be seen in Figure 7. The inverter is relatively lightweight for its power rating, weighing about 16 kg. This is partly due to the absence of filter components on the AC side of the inverter which are not necessary in an EV. It can further be seen that the predominant housing material, aluminium, has a significant impact on the overall weight. It is worth noting that, compared to the small string inverter, there is a relatively large percentage of copper, mainly due to the much larger relative weight of the power module.

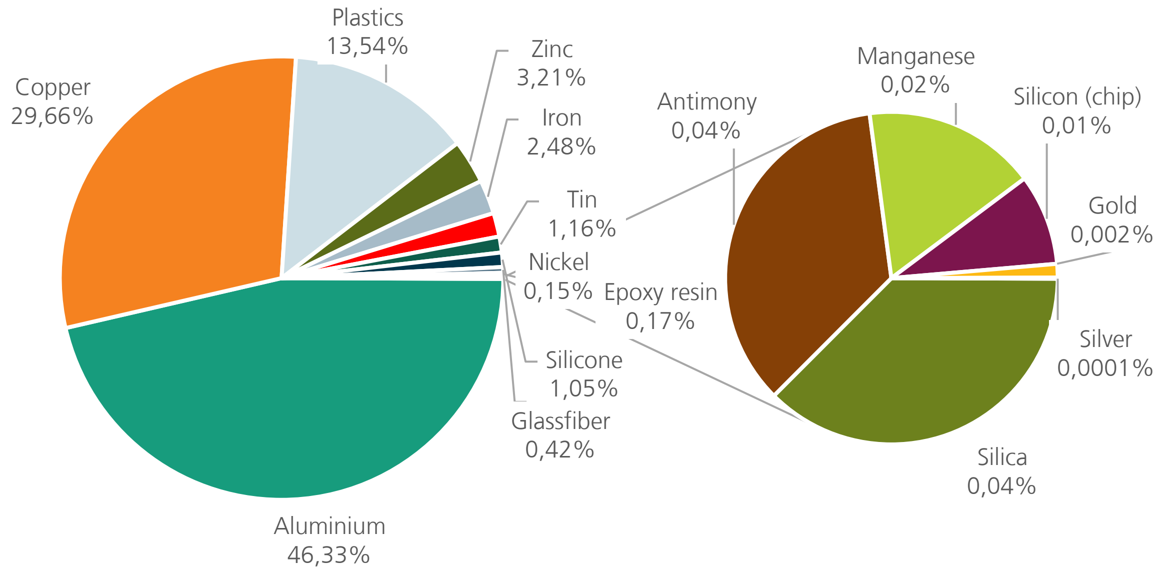

Figure 7: Material composition of a representative 185 kW EV drive inverter (16.8 kg)

EV on-board charger

The representative OBC that was analysed has a power rating of 11 kW which is the state of the art. The modular design of the device modelled by Kabus et al (2020) might be one of the reasons for the quite high mass of this device compared to other OBCs. The material composition of the OBC is presented in Figure 8. The three largest material shares are iron, aluminium and copper, which can all be allocated to the housing, which is made out of aluminium, and the coils, which make up for the biggest part of the weight. Since the OBC in an electric vehicle works at high frequencies, the choke cores are most likely made from ferrites including iron, zinc and manganese. Since the coils have such a large share of the mass, the prevalence of these materials is also comparatively high.

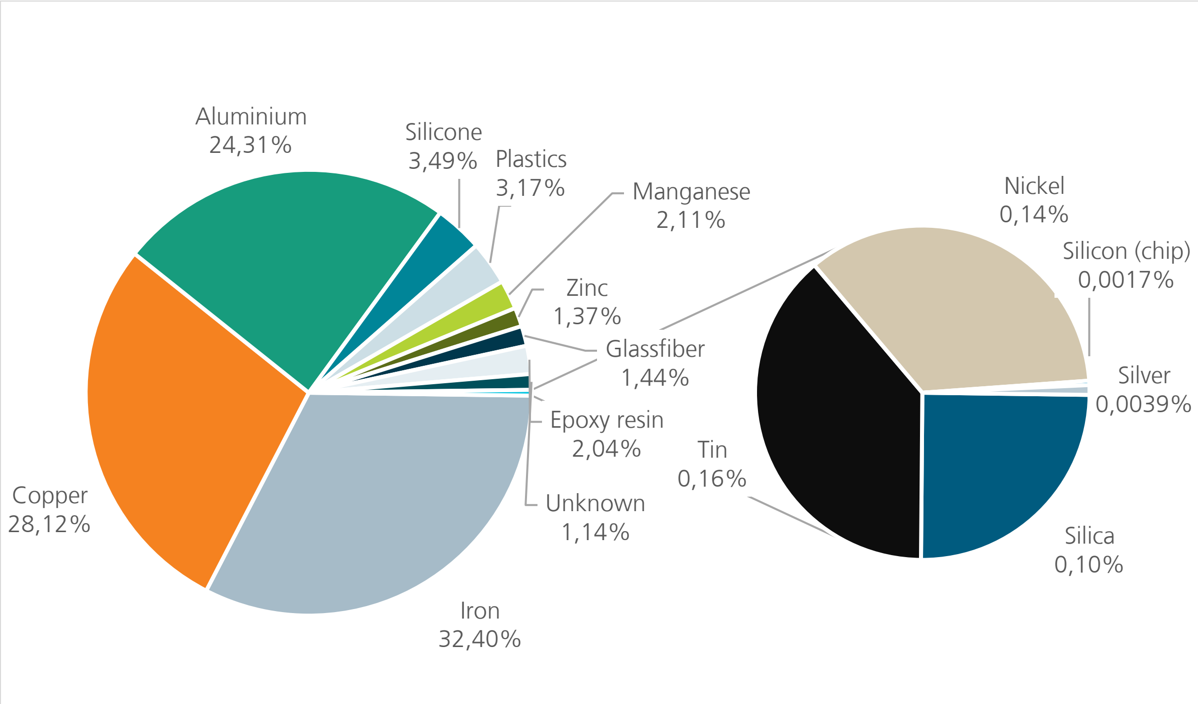

Figure 8: Material composition of a representative 11 kW on-board charger (12kg)

Comparison

Figure 9 gives an overview of this chapter and enables a direct comparison between different technologies. The general material share clearly changes with a higher power rating of the device. The aluminium housing of the string inverters and the EV drive inverter leads to large aluminium shares. The devices with higher power ratings, namely central inverters and wind converters, have steel housing and therefore iron makes up for a huge amount of the materials used. Since coils are the most copper-dense parts, the devices where coils make up for significant amounts of the weight, more copper is used. Light housing and lightweight design are not so crucial with increasing power rating and the share of the power module is not increasing proportionally. These are the reasons why the big parts and therefore more prevalent materials are playing a larger role with higher power ratings, while the materials with lower overall mass shares, such as antimony or zinc only make up for a small percentage. Overall, a kind of similar structure can be seen with big differences when it comes to individual material comparisons.

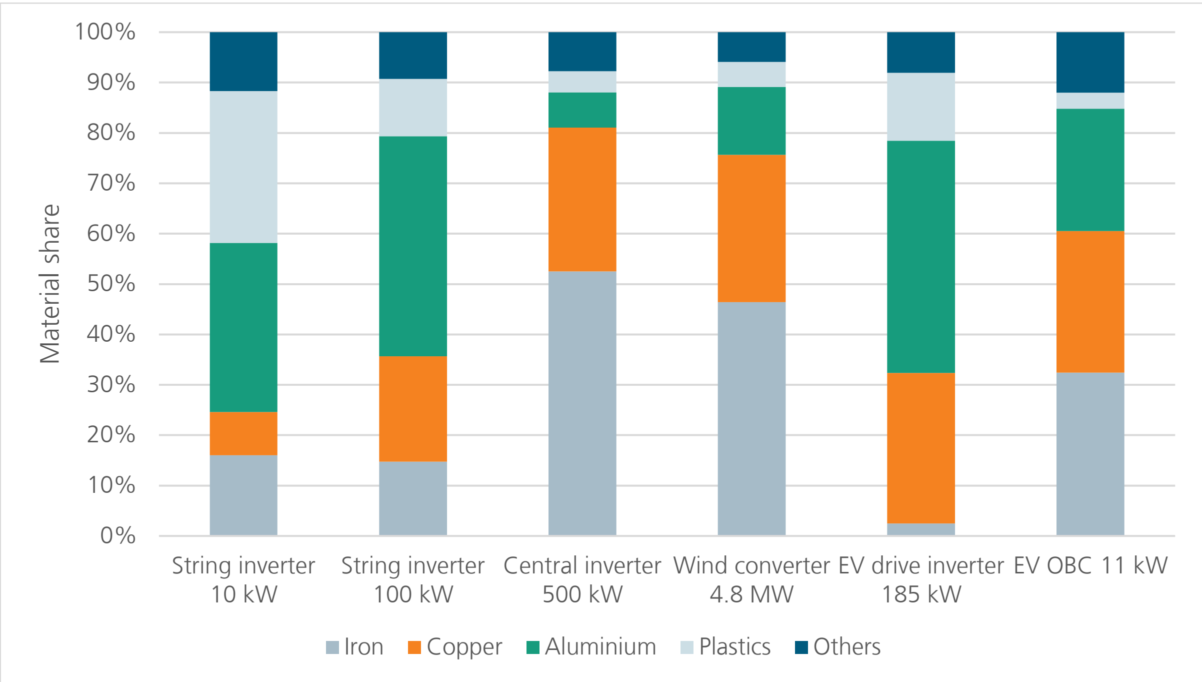

Figure 9: Material share comparison of the representative devices

3.2 Specific material demand per unit

Upscaling the material demand for the technologies to the tons per GW level enables comparisons on an absolute level. Figure 10 shows the two PV string inverters, the central inverters as well as the wind converter mass in comparison. The devices inside the EV are not included since an upscaling to one GW does not makes sense in the case of EV because the motor power rating cannot be compared to the power rating of generation technologies.

So far, only the material shares for the inverters themselves were considered. For the case the 100 kW and the central inverters as well as wind converters feed into the high voltage grid, another power electronics part is missing, the transformer. The electricity produced in smaller string inverters of rooftops is mostly directly consumed and therefore, no transformer is needed for them. For the transformer weight, also a representative device was chosen that only contains iron, copper and aluminium (ABB, 2018). Figure 10 shows very clearly how important the transformer is when it comes to the overall material demand. Without adding the transformer, the devices with higher power ratings perform better regarding material use, but the transformer changes this picture, because the transformers use even more material than the converters themselves.

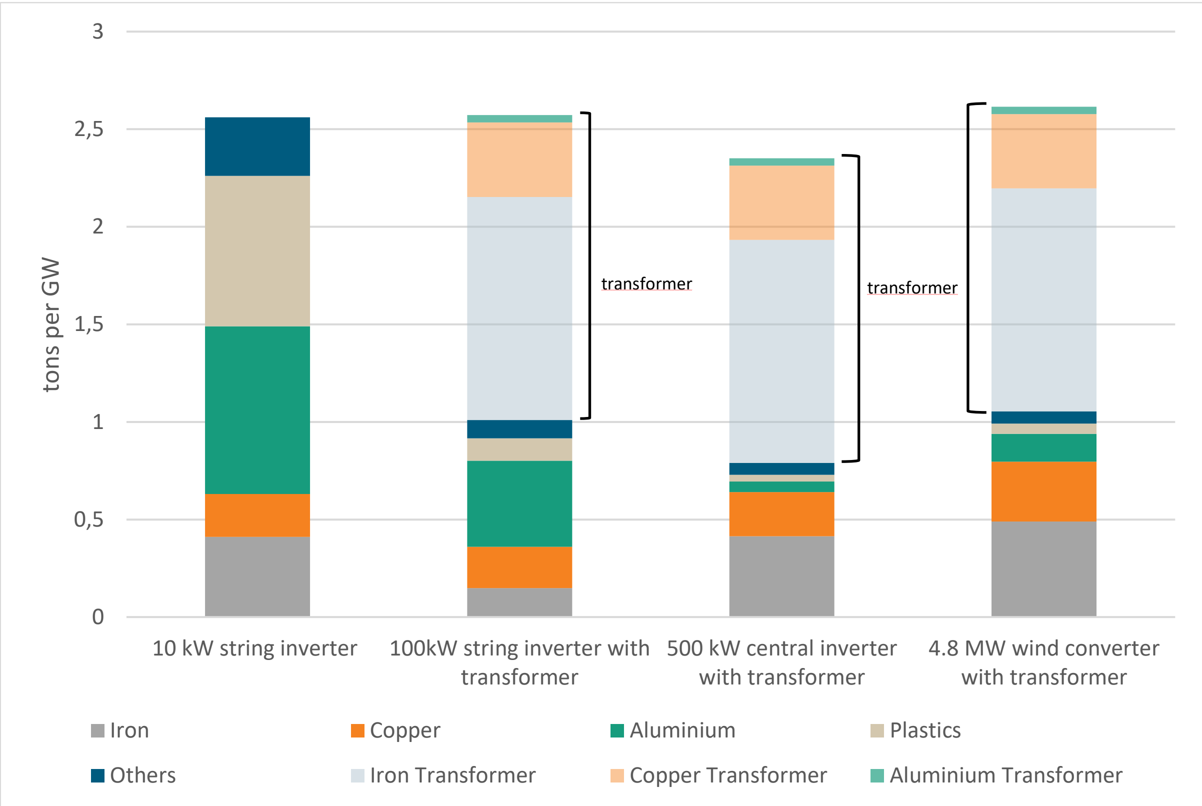

Figure 10: Material demand in tons per GW

3.3 Future developments in power electronics

The most relevant trends in power electronics that are foreseeable right now are the use of new semiconducting materials, switching from Silicon (Si) to Silicon Carbide (SiC) and especially to Gallium Nitride (GaN) semiconductors. These new materials enable higher switching frequencies which have positive effects on the efficiency of power electronics. Another development that will be affecting the material demand is the trend towards using higher voltages. Finally, increased focus on recycling due to multiple reasons is also a development which is taken into account. While there are other developments in the industry that might have effects on the material demand of power electronics, these three seem to be the most relevant ones. Table 2 gives an overview of the trends and their general effects that will be explained further in the next chapters.

Development	Impact on material demand	Affected parts/materials	Time horizon	Barriers/ Challenges
Higher frequency (GaN and SiC semiconductors)	Lower material demand in passive components	Passive components, cooling	First commercial solutions now, larger market shares starting in the 2030s	Cost of GaN devices, slow market adjustment and availability of gallium
Increasing voltages	Lower material demand in passive materials and cables	Passive components, cables inside and outside the inverters	Prototype already available, so also gaining market shares in the 2030s	Mostly legal obstacles regarding safety and technical challenges for insulation
Circularity	Lower overall raw material demand	Potentially all parts	At the end of the life of the devices (approx. 15 years)	Dependent on overall recycling rates and infrastructure development

Table 2: Overview of future developments in power electronics and their effects on material demand

Wide-Bandgap Materials

The selection of semiconductor materials is crucial for all kinds of electronics because their ability to manage electrical conductivity is essential for the functioning of electronic devices. Currently, silicon (Si) is the most widely used material in semiconductors. However, as technology evolves, the importance of materials with wider bandgaps, such as silicon carbide (SiC) and gallium nitride (GaN), is growing with bandgaps of 3.26 and 3.7 eV. Silicon in comparison only has an 1.1 eV bandgap (Wilhelm, Wienhausen, Hensel, Kranzer, & Burger, 2014).

These wide-bandgap materials have significant advantages compared to silicon. SiC and to an even larger extend GaN are capable of operating at higher efficiencies and are more thermally stable. This enables their much higher power efficiency. Also, GaN and SiC have lower switching losses, which is a critical factor in reducing energy losses during the conversion. The lower switching losses enable devices to operate at higher switching frequencies which enables them to manage more power. Since GaN semiconductors with their even wider bandgap can be more efficient and have higher frequencies than SiC devices, only GaN will be looked at here in more detail.

The most interesting feature that this implies for this work is its effect on the size and weight of the passive components like capacitors, inductors and transformers in power electronic devices (Wilhelm et al., 2014).

In general, a higher switching frequency through GaN devices leads to a lower material demand because of the direct inverse relationship between the switching frequency and the inductance of the passive components. An example for such a passive element is an inductor that stores energy in a magnetic field made of a core and copper wires wrapped around them. Since less energy must be stored because of higher switching frequencies, the core and the wires, which are mostly made of copper, iron and alloys such as manganese or nickel, can be significantly smaller. The direct inverse relationship implies that doubling the frequency would halve the inductance, which determines the material demand. If a silicon semiconductor with a frequency and 150 kHz and a GaN semiconductor with 1 MHz are considered, it becomes clear that the theoretical order of magnitude could be a material reduction of about five to ten times in the parts of the devices that are affected. Besides the previously mentioned passive parts, this also includes the material needed for cooling which makes up for a significant amount of material. The housing, as the heaviest part for most devices is only affected indirectly. If the parts inside are getting smaller this also requires a smaller housing around it. Therefore, the material for housing, mostly aluminium for the smaller devices, can be reduced indirectly. While in theory there is a huge potential for material savings with GaN semiconductors, the actual material demand is determined by design choices based on trade-offs that have to be made. For example, every topology must balance efficiency and power density, while cost always plays an important role in the decision-making process as well. Regardless of the decisions on topology, using GaN will definitely lead to a way lower material demand compared to silicon (Vauche, Guillemaud, Lopes Barbosa, & Di Cioccio, 2024).

Using gallium as a material does not only have an effect on the amount of other materials that are needed, but it also has to be produced itself. Gallium as a material is affected by multiple developments or problems regarding the criticality of materials. The EU labels gallium as a strategic material, meaning it is critical and economically important. The supply risk score of gallium in the latest EU report is the fourth highest of all considered materials (European Commission, 2023b). This rating is reached because of the immense geographical concentration with China supplying 94 % (European Commission, 2023b), Gao et al. (2024) even identify a 97 % concentration. China imposed restrictions so that export licenses are now needed to import gallium products in August 2023 (Reuters, 2023). Because of this, the problem of gallium dependency became known to a broader audience especially since it also caused a big price increase. A typical strategy to avoid such dependencies is to rely on recycling. But regarding gallium, the End-of-Life Recycling Input Rate is 0 %, meaning no gallium recycling infrastructure exists so far at all (European Commission, 2023b).

Glaser et al. (2023) conducted interviews with experts from academia and industry to get rough numbers of realistic material savings in different parts of the devices. Table 3 divides the potential into changes in size of different function blocks. Since the scenario where these numbers are used is seen as an ambitious scenario, the upper percentages expressed as potential are used to model the reduction in material demand. According to YOLE (2023) GaN will be used in EVs and PV inverters with lower power ratings. Therefore, the effect is only modelled for the EV driver inverter, OBC and 10 kW inverter.

Function block	Components	Potential change in size
Input filter	Coils	-50%
Power processing unit	Power module	Core: -20%
Energy buffer	Capacitor	No impact
Cooling system	Heat sink	-50%
Output filter	Coil	-50%
Remainder	PCBs	No impact

Table 3: Changes in size GaN compared to Si power electronics devices, taken from Glaser et al. (2023)

The demand for Gallium itself should also be assessed, but determining how much gallium would be needed in a representative GaN device is sophisticated. Unlike for silicon power modules, there are no publicly available material content data sheets for GaN devices. Since it is a new technology, the manufacturers do not want to provide too much information. The gallium only replaces a small amount of the silicon, but the chip as a whole also gets way smaller. Schiro (2023) even claims that less than 1 % of the silicon would be replaced.

Chen et al. (2017) gave the range of three to five times less material demand for the chip and Dalla Vecchia et al. (2019) who compared similar GaN and Si chips, showed that the GaN ones were around threefold smaller. Therefore, the estimation for the material demand that was decided on is 33% of the amount of silicon used in the representative device. Overall, silicon is reduced here while only a small fraction of gallium is needed for the GaN chips. Schiro (2023) even predicts that through more efficient manufacturing for GaN in contrast to Si, the resource use for the chip can be reduced by more than 50% overall by switching to GaN.

Figure 11 to Figure 13 show the effect of the changes in size on the three different devices. Substantial amounts of material, especially copper and iron can be saved here.

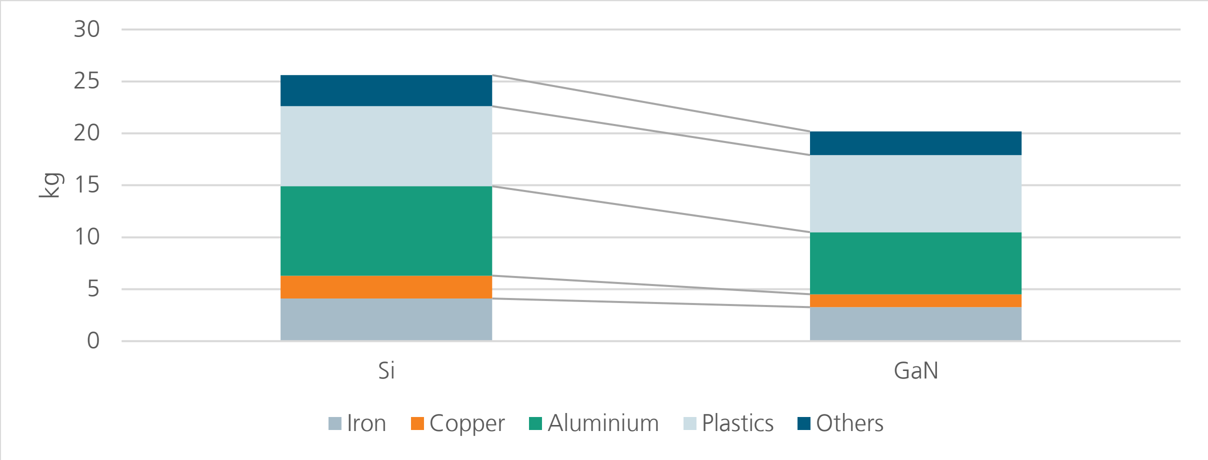

Figure 11: Weight comparison 10 kW inverter Si and GaN in kg

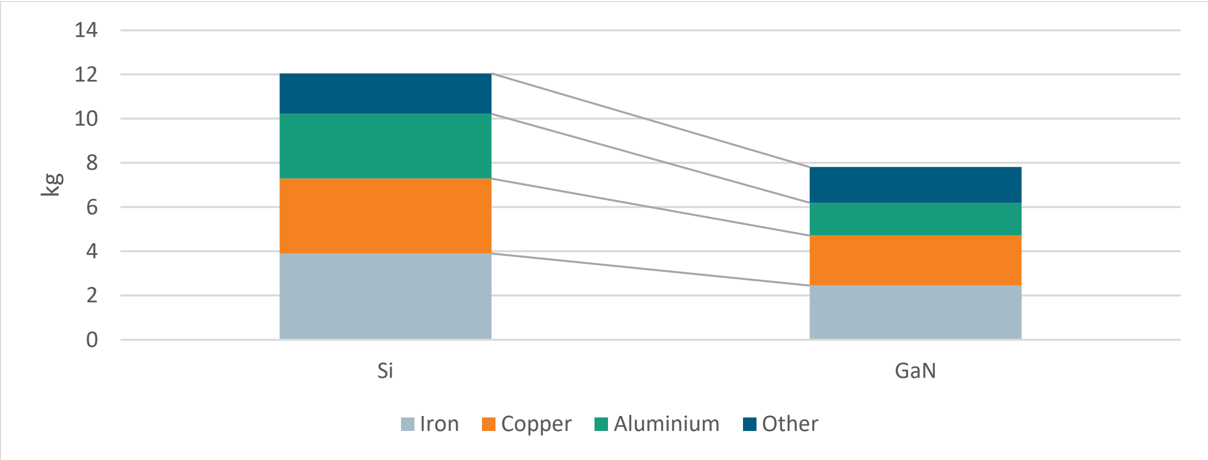

Figure 12: Weight comparison OBC with Si and GaN in kg

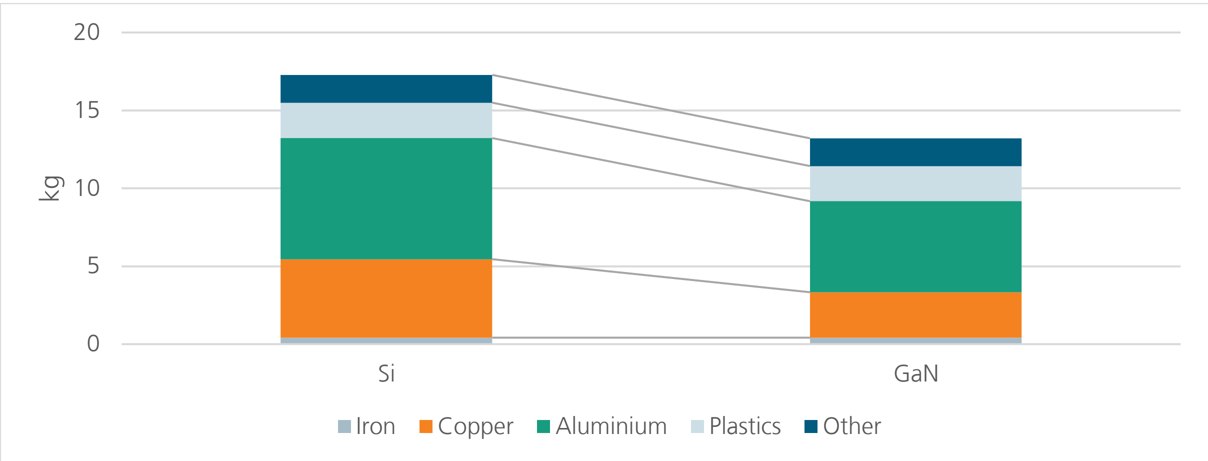

Figure 13: Weight comparison EV drive inverter with Si and GaN in kg

Medium Voltage

Since power electronics is about controlling the different parameters of electricity, there is a lot of development in this area. Besides using wider bandgaps another approach to reduce material demand is increasing voltages. This is especially interesting for bigger installations like solar parks that feed into the grid. Normally the electricity within the power plant is transported with low voltages and then converted to higher voltages for the grid by the transformer. The key categories referred to here are lower voltage which internationally includes all voltages below 1 kV, medium voltage up to 35 kV and high voltage everything above that (Iberdrola, 2024). Nowadays, within PV plants or BESS parks, the voltage is limited to lower voltage and the critical development would be to shift to medium voltage here to save material in cables and transformers (Geiss, Hensel, Derix, Thoma, & Kranzer, 2023). As shown earlier, the transformers are responsible for a remarkable amount of the materials needed. Needing less transformers would therefore have tremendously positive effects on the material demand.

By increasing the system voltage, currents can be reduced at the same power, which is beneficial for the material demand in different parts of the power electronics devices and in the systems surrounding them. The most important effect of an increase in voltage is that the cross-sections of the cables can be significantly reduced for the same power, leading to substantial savings in the cable material, which is mostly copper. The cross-sections shrink quadratically with the current running through the cables. Doubling the voltage leads to half the current which results in a material saving of about 75 %. This decrease is even higher because the cables are normally laid in bundles. Due to the heat dissipation, more power is lost if bigger bundles of cables are used. Since the smaller cables lead to smaller bundles, this further accelerates the material savings. While copper in vast amounts can be saved by this, it must be taken into account that higher voltages mean that more isolation material is needed (Geiss et al., 2023). The new wide bandgap semiconductors play a role as well, because the higher switching frequencies and thermal resistance of SiC compared to Si enable power electronics for such high voltages in the first place.

Besides the material savings in cables, the transformers, which are responsible for a large amount of the power electronics material demand of PV power plants, wind farms and battery farms, are also affected. Currently transformers are limited to a certain power rating because at some point the windings around the core in the coil reach their limit and switching the higher currents is not possible anymore. So, by increasing the voltage and therefore decreasing the current, the same power plant would use way less transformers are needed (Geiss et al., 2023).

The potential effects of implementing medium voltage will be included in this model in a similar way to the effects of GaN on the devices with lower power ratings. A lot of savings, especially in copper is expected due to the reasons explained in this chapter. Switching to higher voltages also implies using SiC semiconductors, this might also have effects on material demand similar to switching to GaN, but those are not investigated more closely here. The devices where the effects are taken into account are the 100 kW solar inverter and the central solar inverter with 500 kW, because they are used in large freestanding PV parks where this technology is aimed at.

The exact same mechanisms also apply to large BESS, so similar savings in the power electronics materials for the stationary batteries are assumed. In wind energy, there also is less potential to reduce demand in inverters, because of the differences in layout of a wind farm compared to a solar farm. Onshore wind farms are already mostly connected by a medium voltage network. Therefore, wind turbines are not affected by the developments identified here so far. But with the same principle, offshore wind farms sometimes already save a lot of copper since they operate at high voltage levels of 66 kV (Siemens Energy, 2020).

Other ideas of increasing efficiency on a system level through power electronics innovations are also being explored. An example of a development that is already seen in practice is the concept of DC-industries. Companies, especially ones which also produce parts of their own power via PV, save themselves the conversion from AC current to DC current and build a power system within the factory completely running on DC (DC-Industrie, 2021).

Figure 14 and Figure 15 show the amounts of material used with a doubling of the operating voltage. Only effects that are clearly calculable are taken into account. Therefore, the differences only lie in the reduced copper within the inverters due to the reduced cable size. As pointed out here, the overall need for transformers decreases by two thirds which makes up a bigger reduction than pictured here.

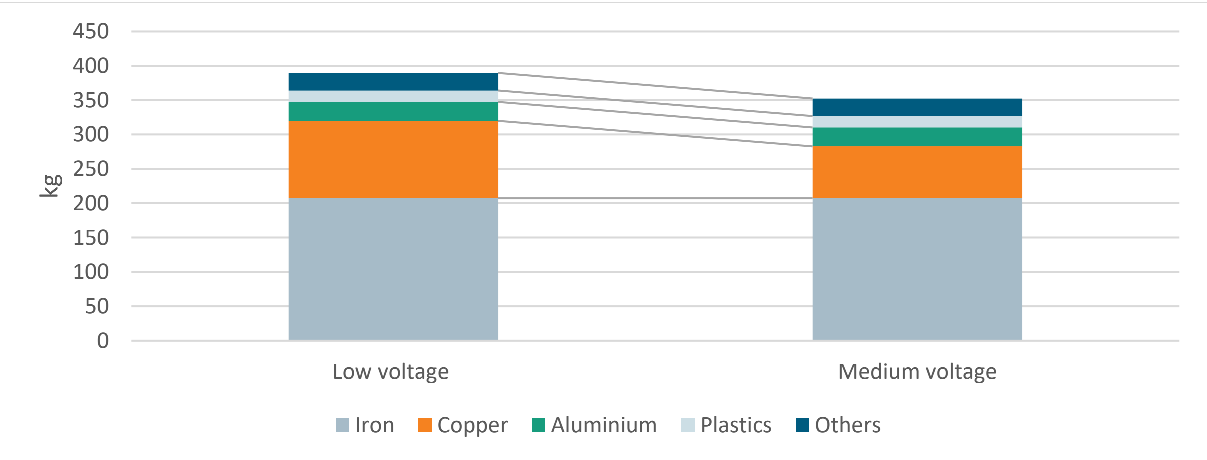

Figure 14: Weight comparison of a representative 500 kW central inverter with doubled voltage from low to medium voltage in kg

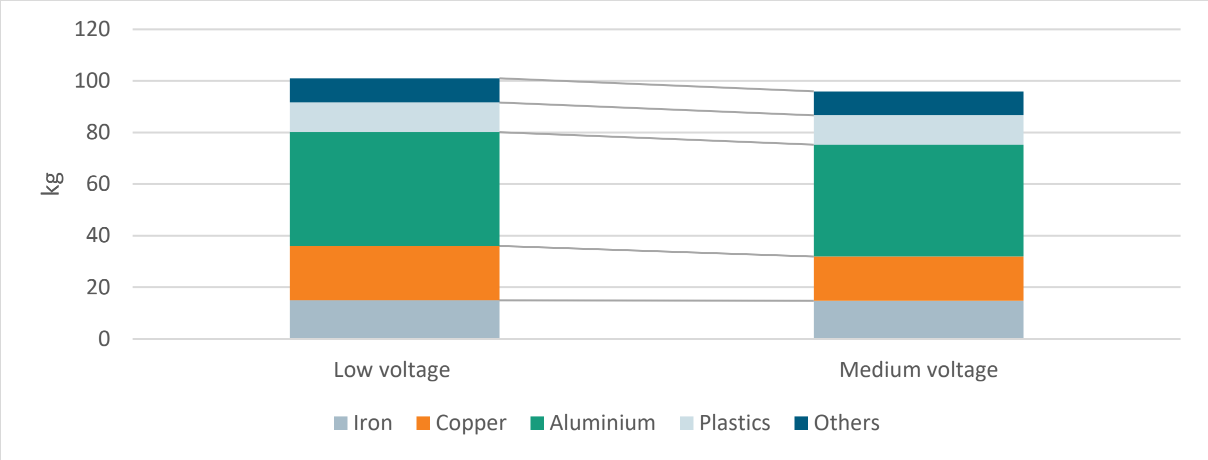

Figure 15: Weight comparison of a representative 100 kW string inverter with doubled voltage from low to medium voltage in kg

The potential copper savings when considering the whole PV system including module, inverter, transformer and cables is schematically shown in Figure 16. Gervais et al. (2022) provide data on the material demand of the module and the cabling, the data for transformer and inverter are taken from the results in this work. The bar labelled as future clearly indicates how big the savings could potentially be when doubling the voltage.

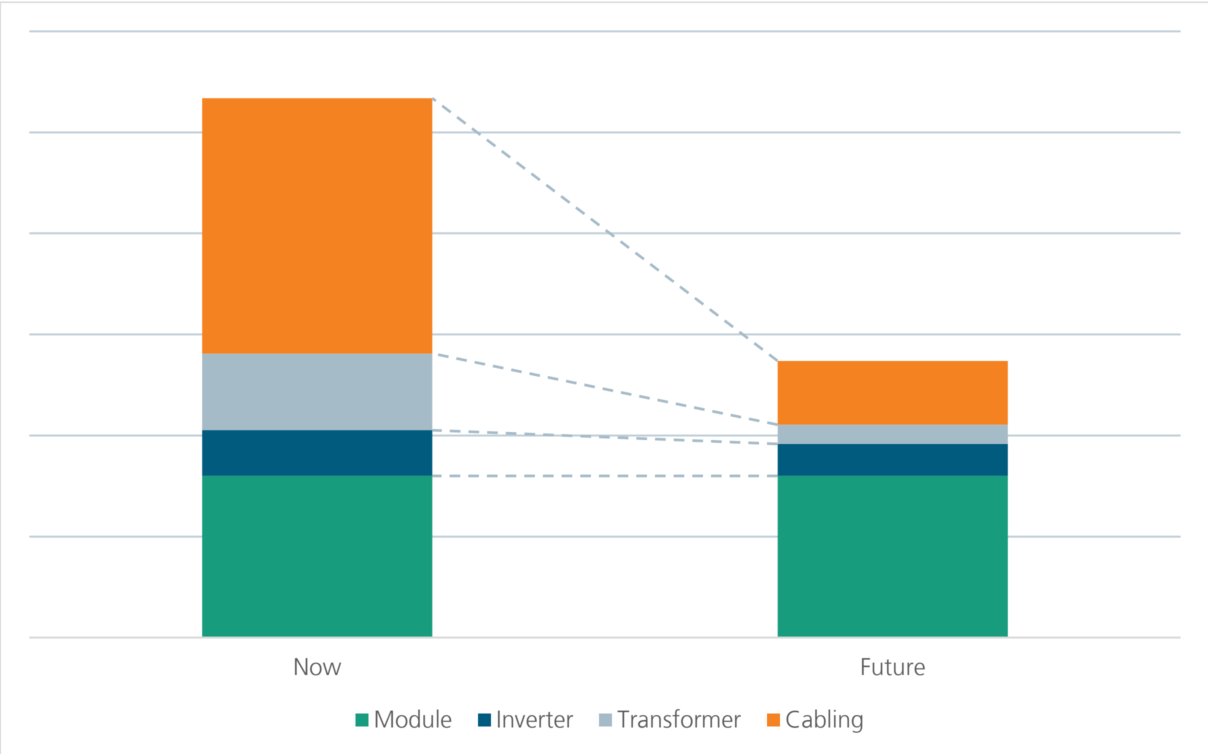

Figure 16: Outline of potential copper savings in the whole freestanding PV system if the voltage is doubled based on data from Gervais et al. (2022)

Circularity

The most straightforward way to save raw materials is to reuse or recycle the material that are already used. There is an increasing trend towards using less raw materials and more secondary materials. The development is described with the umbrella term circular economy, which is not clearly defined, but often entails the just named concepts of reducing material demand, reusing devices and recycling materials (Kirchherr, Reike, & Hekkert, 2017).

Adapting circular practices is facing many challenges, for power electronics specifically, the biggest one is most likely the high complexity. As Huber et al. (2024) point out, power electronics are very complex devices with a lot of small parts that are not easy to separate. Recycling of power electronics devices is also very complex matter because many different materials are concentrated and highly integrated into the components. Most conventional recycling strategies are not aimed at recycling small amounts of different materials (Andersson, Ljunggren Söderman, & Sandén, 2017). Li et al. (2022) present very informative graphs on the life cycle of some materials including gallium from mine to the end of life. It can be seen that the vast amount of gallium is labelled currently unrecyclable which refers to the possibility to recycle it under current technical conditions. This shows that the technical expertise here needs to be developed first.

On the other hand, the materials used in the power electronics devices are very valuable since some of them are rather scarce and also valuable in monetary terms. Bulach et al. (2018) evaluated the potential of increasing the recycling rates of power electronics within EVs. On the one hand they found that adding a stage to the recycling process would theoretically enable collecting up to 98 % of the considered metals. The current way of recycling EVs via shredders only collects up to 25 % of these metals from the PCB. On the other hand, they also found that this additional step makes the recycling way less financially attractive while most importantly, no recycling plant entailing extra steps to also cover metals from power electronics was operating in 2018. For EVs, the most relevant future development therefore appears to be to change the recycling process towards a larger focus on electronics components.

For PV inverters, the challenges already start with collection. PV cells are not recycled on industrial dimensions at all by now, while PV inverters can at least be disposed in the normal electronic waste (Ngagoum Ndalloka, Vijayakumar Nair, Alpert, & Schmid, 2024). But the problem of insufficient recycling methods for some materials is applicable for the electronics waste in general. Besides this, the trend towards decentralized renewable energy, especially residential PV also leads to more decentralization of the devices. It seems likely that this will also imply lower collection rates since each household would have to take care of it individually. This is a big problem if for example off-grid PV is employed in rural areas where no collection infrastructure exists. New collection methods are critical to combat this.

Larger devices were identified to have a high share of different types of steel. In this work, the steel shares were broken down into the individual raw materials wherever data on this was available, for example into iron, manganese and zinc for a specific type of steel. If this data was not available, the whole steel was accounted for as iron. While the collection rate of steel is quite high, breaking the different types up into raw materials is extremely complicated which leads to loss of quality of the recycled steel, commonly referred to as downcycling (Harvey, 2020). Savings here could be achieved by improving the recycling methods for steel.

This identified status quo shows that there is huge potential regarding circularity that is not utilised at all. Literature points to a very effective way to increase circularity via new approaches to designing power electronics devices. Huber et al. (2024) argue that up to 80 % of the environmental impact is already determined while designing. Eco-design for power electronics is a proactive approach to reduce the environmental impact which is so far mostly focused on the positive effects of increasing energy efficiency (Fang, Lefranc, & Rio, 2023). Including circularity into eco-design thinking is seen as the next step. This would include taking the environmental impact of the devices into the metrics of factors to optimize through design. In contrast to conventional LCAs which determine the environmental footprint of existing products, a priori LCAs already conduct such an analysis in the design process to see in which way the impact could be minimised.

Many approaches for design strategies to increase the circularity exist that try to intervene on different stages of the products life. Riesener et al. (2023) give an overview of the existing design approaches. On a material level, design with recycled materials, design with waste and design with only one material are proposed. To increase circularity on a component level, design for remanufacturing, for repairability and for reuse are presented. The final stage, the product level, includes design for upgradability, for refurbishment and finally for circular business models, which is more focused on ensuring profitability. Abuzied et al. (2020) add design for disassembly to this list of different approaches that can be taken and have the potential to reduce the material demand significantly.

The potential of circular practices implemented in power electronics technologies cannot be assessed in its whole depth in this work, but an estimation on the potential plays a role for the modelling. The focus hereby lies on recycled materials. Power electronics are seen as one independent system here. Therefore, no recycled material from other sectors can be used since it is assumed, that it will already be consumed in these sectors. This makes it easier to focus on the added raw material demand for power electronics. Only the existing stock from devices build before will be taken into account for recycling. So, the effect of recycling is only considered regarding devices that have to be replaced. To find out when the material stock that is used in active inverters is available for recycling, an average life expectancy for power electronics devices is assumed and the historic data about the capacity that was build up earlier is determined.

The life expectancy of solar inverters is normally assumed to be around 15 years, which is significantly lower than the expectancy for PV cells, implying that the inverter must be exchanged throughout the life of a PV system. New research find evidence that the inverters might last longer than 15 years (Bucher et al, 2022), but as a conservative approach the 15 years can still be used as an approximation. It is also used for the power electronics devices within the EVs, in contrast to the PV systems, it is more likely that the power electronics devices outlast the batteries.

The other necessary part is to determine how much of the materials will be available again to consider the recycling rates for the materials. (Minke, Mallwitz, Burfeind, & Hu, 2023) did a case study on the circular economy potential of an OBC that also includes data on the End-of-Life (EoL) Recycling Rate for the different materials they found in the analysed OBC. The EoL Recycling Rate shows the percentage of material that is recycled when the OBC reaches its EoL. It has to be differentiated from many different recycling indicators like the Recycling Input Rate which measures the percentage of the production that is done with recycled materials. In this case, Minke et al. (2023) get their data on the recycling rates from the UN Environment Program (Graedel et al., 2011) and two other more recent publications (Graedel, Reck, & Miatto, 2022) & (Sverdrup, Ragnarsdottir, & Koca, 2017). Since it is data specifically about a power electronics device, this will be considered for the modelling.

For most materials a range of rates was provided by Minke et al. (2023). Since the recycling rates will also be used for modelling in the future and it is likely that there will be improvements in recycling, the upper value will be taken into account for this thesis. This also seems more realistic since the rates are partly based on data from 2011. Antimony was the only material that appears in the material compositions presented here but not in the paper, so data from Van Brink et al. (2022) was used to determine the rate. According to Minke et al. (2023) the EoL recycling rate of aluminium is only 42 % even though Graedel et al. (2011) give a range of up to 70 % in the publication the table is based on. The 70 %, which seem more in line with other literature, is used here. For the scenario analysis, the share that is not recycled will be multiplied with the demand for devices that have to be replaced. This way the new raw material is needed, and it can be calculated how much can be taken from the old device.

Material	EoL Recyling Rate (%)
Iron	52-90
Aluminium	42-70
Copper	43-60
Zinc	20
Manganese	45
Tin	20-75
Nickel	57-68
Silicon	0
Antimony	25
Silicon for chips	0
Silver	19-55
Gold	20-24
Lead	75-80
Gallium	0

Table 4: End of Life recycling rates of materials analysed here, taken from Minke et al. (2023) and van Brink et al. (2022)

3.4 Supply

The USGS provides and very frequently updates data on the global production and reserves for all materials that are considered in this work (USGS, 2024). They provide data on the annual production of the material, for certain raw materials divided into mine and refinery production, the available reserves and the resources worldwide. In short, the difference between reserves and resources is that while resources refer to the total quantity of the material in the earth's crust, reserves only include the part of the resources that is economically feasible to mine (USGS, 2024).

Besides the availability of the raw materials, which are the focus here as explained in chapter [2.2], a crucial constraint to the availability of materials is the supply chain. Metals are extracted from the earth's crust in the extraction phase, but until it is used in for example a PV inverter, many steps need to be taken. All these stages include the risk of delaying or completely slowing down the availability of materials. This can include unexpected events like the obstruction of the Suez Canal in 2021, unsafe transport routes like in the Gulf of Aden in Yemen in 2024. It can also include geopolitical reasons like Chinas gallium export blockade, or the US import tariffs on steel or EVs or simply decisions by economic actors.

The EU publishes a supply risk score as one part of their attempt to measure the criticality of raw materials for the EU. The supply risk score starts at 0 and everything over 1 is considered critical with 4.8 being the highest number in the report (European Commission, 2023b). The calculation is mostly based on the concentration of the supply with a Herfindahl-Hirschman Index for country concentration, weighted by the World Governance Index, which calculates the governance and reliability for all countries in the world. The other factors that are included in the EU's calculation are the import reliance regarding the material, the EoL recycling input rate, and an index to indicate the potential to substitute the material (European Commission et al., 2017).

Table 5 shows the supply risk scores of the materials found in this thesis and mentioned in the EU's report. It further entails where these materials are used in the devices analysed here. By far the highest supply risk is identified for gallium, while copper and nickel in the European context do not have high supply risks, mostly because of the geologically rather diversified supply.

Material	Supply Risk	Use in power electronics
Gallium	4.8	Semiconductors
Antimony	1.8	Solder
Silicon	1.4	Semiconductors
Manganese	1.2	Ferrites in choke cores
Aluminium	1.2	Mostly housing and heatsink
Nickel	0.5	Steel alloys and contacts
Copper	0.1	Cables, chokes and most other components

Table 5: Materials analysed in this thesis, their supply risk according to the EU and their use in the power electronics devices analysed

3.5 Future demand

This chapter entails the results of the modelling part and shows the future material demand. On the German and the global level, different graphs will visualise the main results. Regarding materials, for most visualisations copper will be used as the material for which the demand is modelled. This makes the different graphs and scenarios more comparable. Furthermore, copper is interesting since it was identified by the IEA to be potentially scarce in the next years (IEA, 2024) and is used in many different parts of the devices analysed here. It is also the material with the most savings potential by adopting the technological developments that were identified in chapter [3.3].

Germany until 2045

Figure 17 shows the copper demand according to the four different scenarios in REMod (Brandes et al., 2021). It does not show a difference between the scenario where people act more sustainably conscious and use less energy (sufficiency) compared to the ones where the people oppose any big changes of their lifestyle (status quo). The explanation for this unexpected observation is that the scenarios such as the resistance scenario bridge the gap between the energy demand and supply by immense electricity imports through energy carriers like hydrogen, which are not pictured here. Since there is also no useful data on the needed extra capacity outside of Germany, a meaningful scenario comparison within Germany appears very complicated. The reference scenario will therefore be taken as the main source of data to determine the future demand and comparisons between the scenarios will not be in the focus of the analysis of the future material demand in Germany.

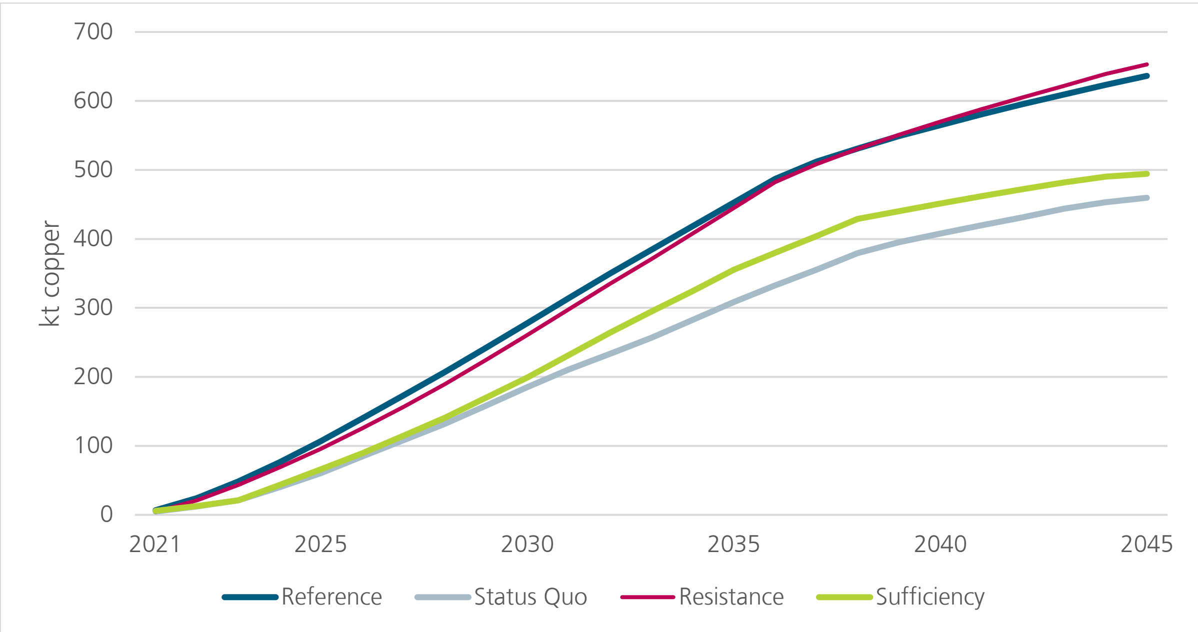

Figure 17: Cumulative demand for copper in different REMod scenarios in kt

The accumulated metal demand for the energy transition in Germany according to the REMod Reference scenario, without taking into account the demand for replacing devices, and only considering the metals identified in the analysis, is displayed in Figure 18. The dominance of the three main metals can be seen, with all other metals only making up for 3 % of the total material demand. The biggest share of most materials flows to the EVs, which only use slightly less than all the other sectors combined in this scenario. Overall, the analysis showed that 2149 kt would be needed overall for power electronics needed for the German energy transition.

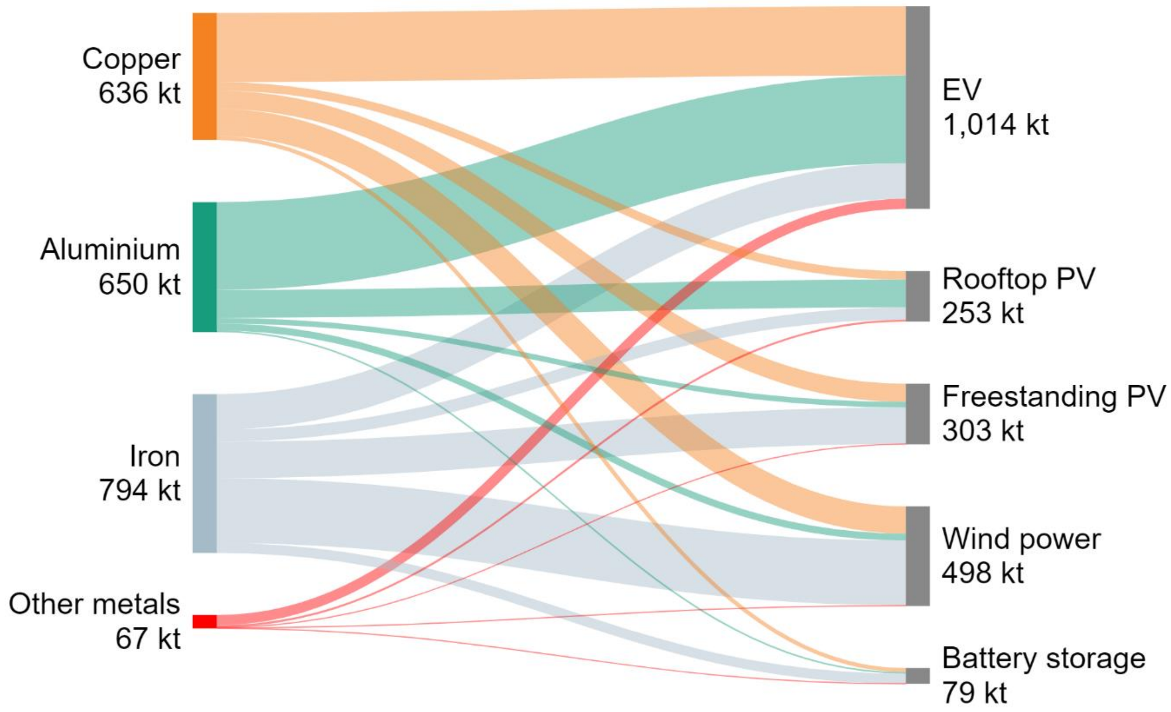

Figure 18: Sankey diagram of the cumulative demand for metals for the German energy transition according to the Reference scenario in kt

The importance of replacing devices for the findings are shown in Figure 19. According to the Reference scenario the annual copper demand already peaks in 2035 and way less is needed until 2045. This is mostly because the number of car sales decreases since it is assumed that the biggest share of combustion engine cars is replaced by EVs by then already. When it is considered that all devices, also the power electronics within the EVs, have to be replaced after 15 years, this picture completely changes. From around 2038 on, the majority of copper is needed for replacing old devices and in 2045 only a small amount of material is needed for newly added capacity. Then, it is mostly about the replacement of the EVs already. The REMod data predict way more EVs in 2024 than the historic data in 2023 showed. This explains the peak in 2039, 15 years after the change. The main takeaway here is that the limited lifetime of the devices implies that there will be a constant material demand if no measures are taken against it.

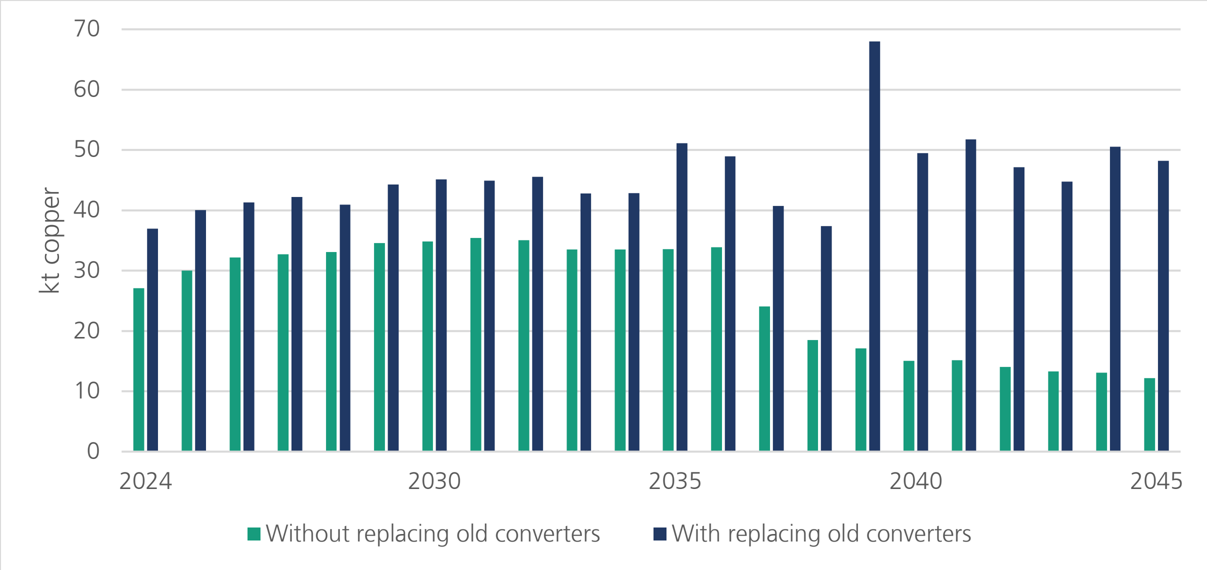

Figure 19: Annual copper demand in Germany with and without considering devices must be replaced after 15 years in kt

Global until 2050

For the global demand modelling, the IEA provides the scenario STEPS, which models a business-as-usual development. The APS scenario takes into account the pledges towards climate protection countries made. The NZE scenario shows the way that would be necessary to reach climate neutrality in 2050 (IEA, 2023c).

First, the importance of including historical data and devices that have to be replaced is pointed out again in Figure 20. The figure shows the cumulative copper demand of power electronics until 2050 in the STEPS scenario. The blue bar shows the effect of the devices that need to be replaced with an assumed lifetime of 15 years. The energy transition, especially regarding the expansion of EVs and PV, started in the early 2000s and accelerated in the 2010s. Therefore, the impact of old devices that have to be replaced is only visible from 2035 on, when larger amounts of devices break down.

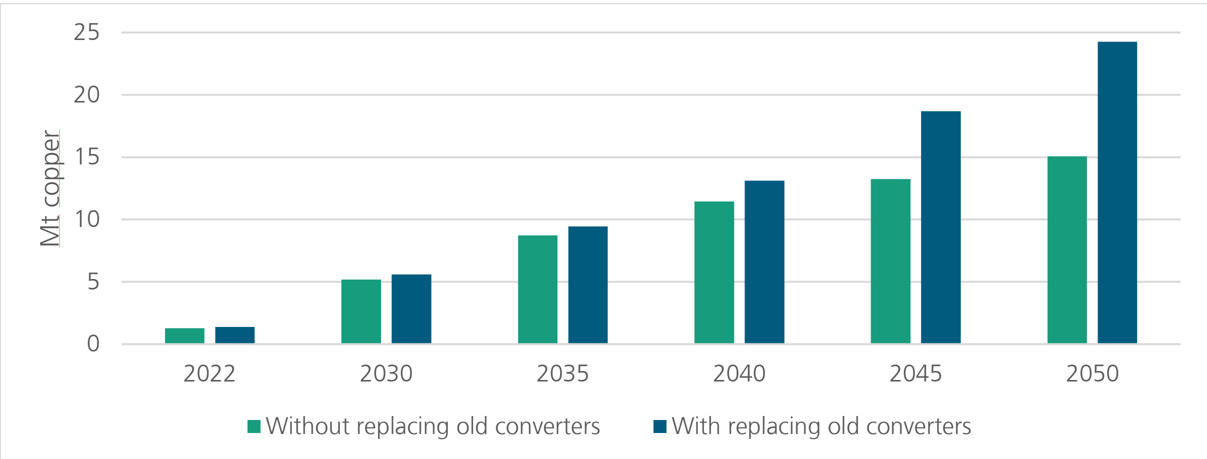

Figure 20: Cumulative copper demand in the STEPS scenario with and without replacing devices after 15 years in Mt

While still only considering the STEPS scenario, the impact of the developments described in chapter [3.3] can also be shown regarding the demand for copper. The new developments identified within this thesis, namely switching to wide-bandgap materials and increasing the voltages within large renewable energy applications are not going to be adopted immediately. They are predicted to diffuse into the market more and more but according to literature rather slowly. The YOLE reports (YOLE, 2023), an in-depth market analysis and forecasting report on the power semiconductor market, estimates GaN to start taking off more from 2028, so for the year 2030 a 5 % share of the stock seems realistic. The next steps are 10 % in 2035, 30 % in 2040, 50 % in 2045 and finally 60 % of the stock of devices in 2050. The same rate of market diffusion is also assumed for increasing the voltages to medium voltages and all the effects on material demand coming with implementing it. The different material demands for the different devices can be seen in more detail in Figure 11 to 15 in chapter [3.3]. Recycling copper was also taken into account, but only regarding the replaced devices. An 60 % EoL recycling rate of copper, as shown in the last chapter, implies that 60 % of the copper from the old devices, that must be replaced, can be used for the new one. Only 40 % of its copper demand must be replaced with new raw material. So, only 40 % of the inverters demand build 15 years before is added. These assumptions are also summed up in Table 6.

	2022	2030	2035	2040	2045	2050
Part of the stock using GaN and medium voltage (Recycling rates are assumed constant, e.g. 60 % of replaced copper demand)	0 %	5 %	10 %	30 %	50 %	60 %

Table 6: Assumed diffusion of the future developments into the overall stock of considered technologies

In 2050, a very clear effect can be seen even though only 60 % of the devices use the lower material demand solutions. The analysis shows that the three future developments would lead to remarkable copper savings in the range of 8 Mt, which can be achieved until 2050 just for power electronics in the STEPS scenario. 3 Mt of the saved material can be assigned to the WBG and medium voltage, while 5 Mt are due to the recycling. Overall, this means that 33 % less copper is needed.

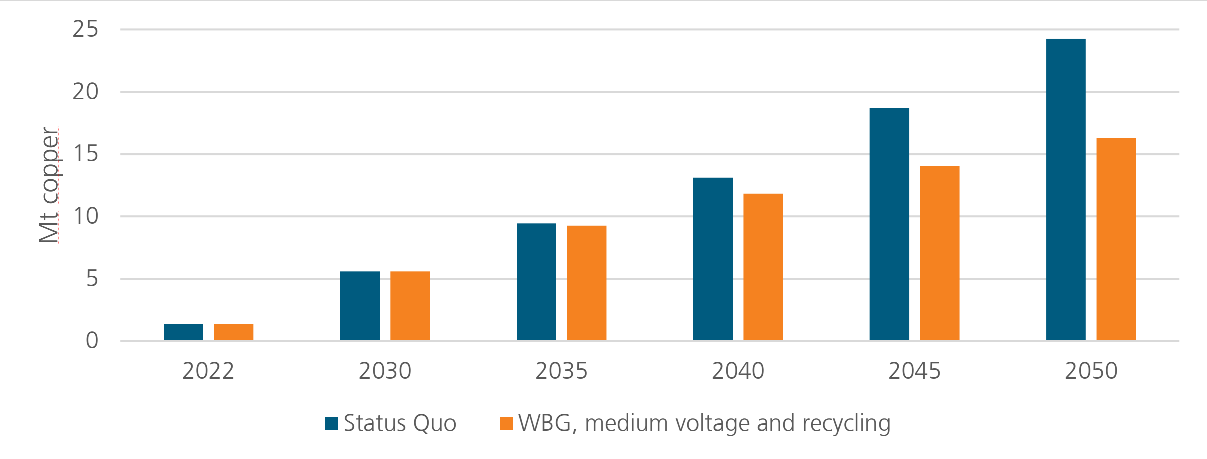

Figure 21: Cumulative copper demand in the STEPS scenario with and without future developments in power electronics in Mt

The next step is to compare the different IEA scenarios. To not be too focused on copper, even though it is the key material that can be saved, the demand for tin in the different scenarios is shown here for representation. After this figure, the focus will lay on copper again. The scenarios STEPS and APS, which reflect the policies in place at the moment and the announced climate protection pledges of individual countries, look pretty much similar when it comes to the material demand as visible in Figure 22. Consequently, only the STEPS and not the APS scenario will be presented in the following graphs.

The NZE scenario shows a way higher demand, which is mostly because the scenario entails that almost 2 billion internal combustion engine cars are all going to be exchanged with EVs.

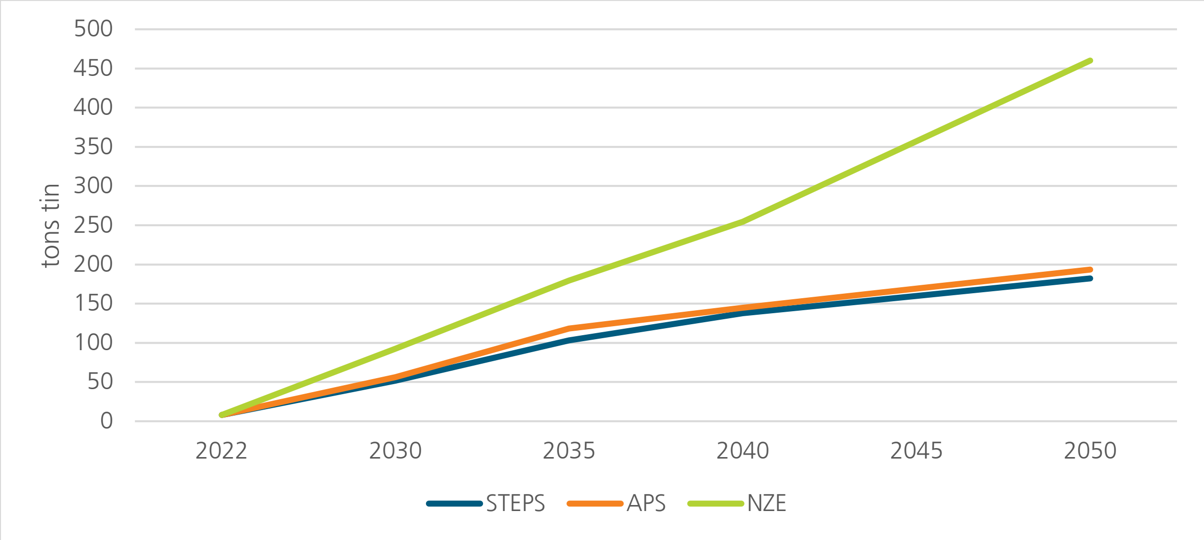

Figure 22 Scenario comparison of IEA global scenarios with tin demand in tons

The NZE scenario assumes 1.9 billion cars and for the STEPS scenario only 700 million EVs are assumed in 2050. Accordingly, Figure 23 shows the immense difference in copper demand between the two scenarios if replacement is considered but none of the future developments.

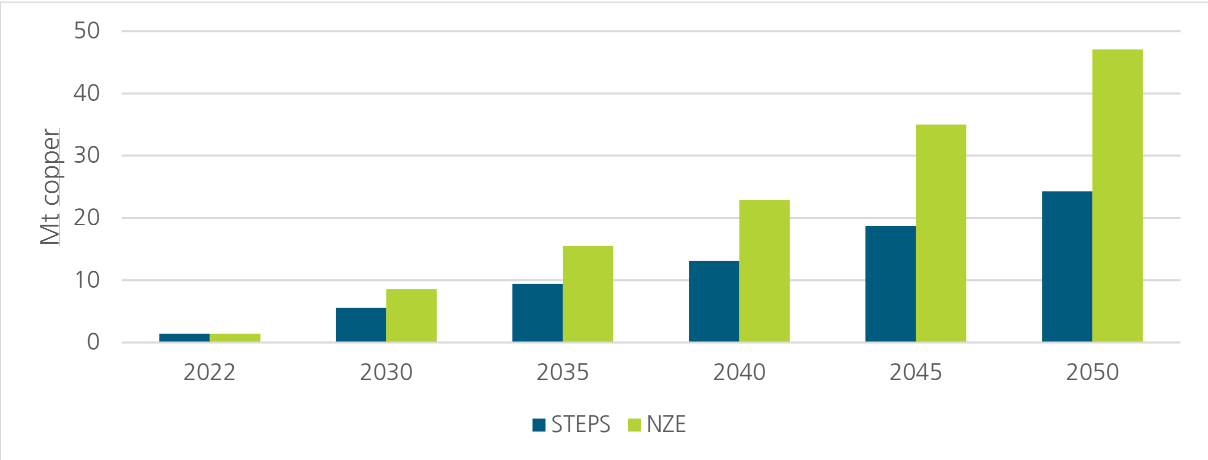

Figure 23: Cumulative copper demand in the STEPS and NZE scenario with replacing devices after 15 years but without future developments in Mt

To exclude the immense impact of the different EV roadmaps, Figure 24 shows the demand according to both scenarios for just the added PV, wind energy and battery capacity. It can still be seen that this way still 66 % more raw copper would be needed to get on track for net zero emissions in 2050.

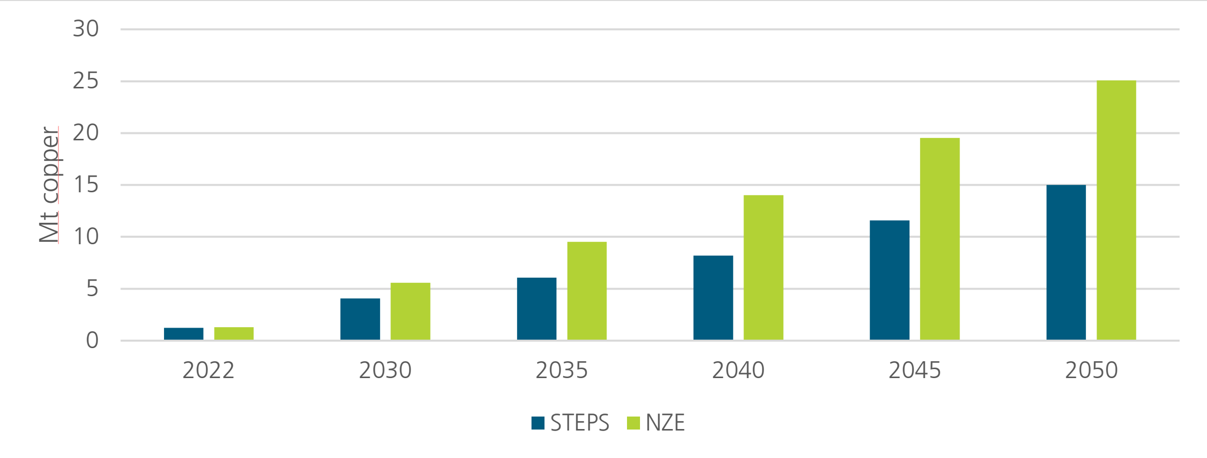

Figure 24: Cumulative copper demand in the STEPS and NZE scenario without EVs including replacing devices after 15 years but without future developments in Mt

The difference in total demand already indicates the importance of EVs for these scenarios. The impact of the number of cars and the material demand coming with it can also be seen in Figure 25 which further divides the use of copper for the different technologies. The quite low copper demand of rooftop PV as well as the huge demand for wind, mostly due to the ambitious targets regarding wind power expansion is also visible here.

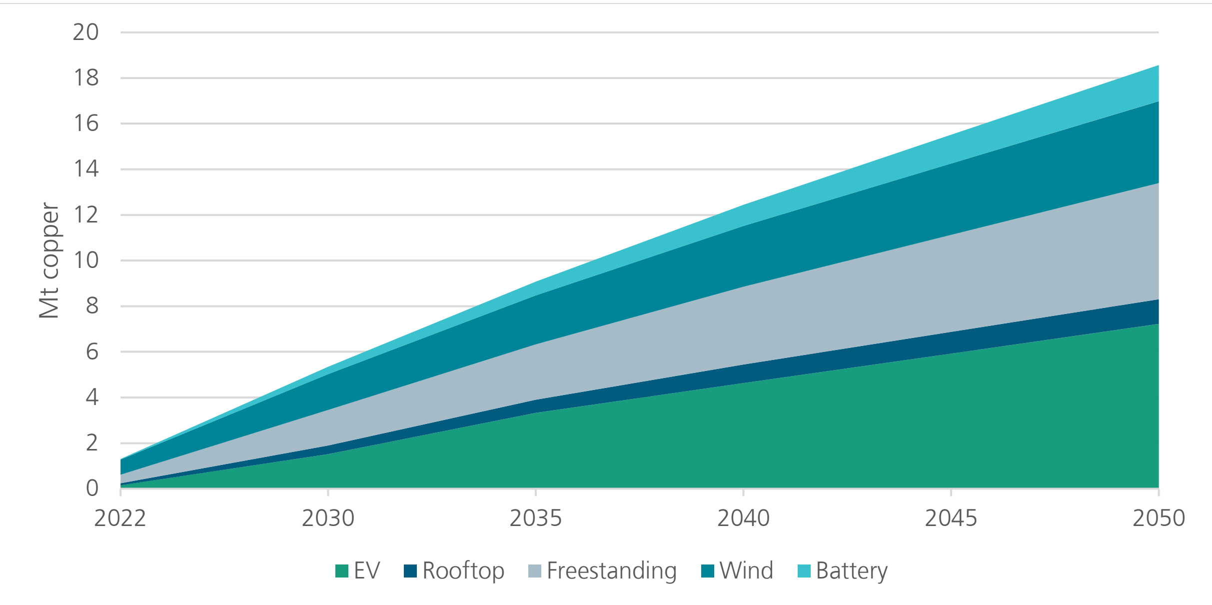

Figure 25: Cumulative copper demand in the STEPS scenario divided in sectors including replacing devices after 15 years but without future developments in Mt

Figure 26 shows how the immense need for copper in the NZE scenario could be decreased if the developments described here would be implemented. It therefore shows the same as Figure 20 but for this way more ambitious scenario. The potential savings here are immense 15 Mt for copper alone.

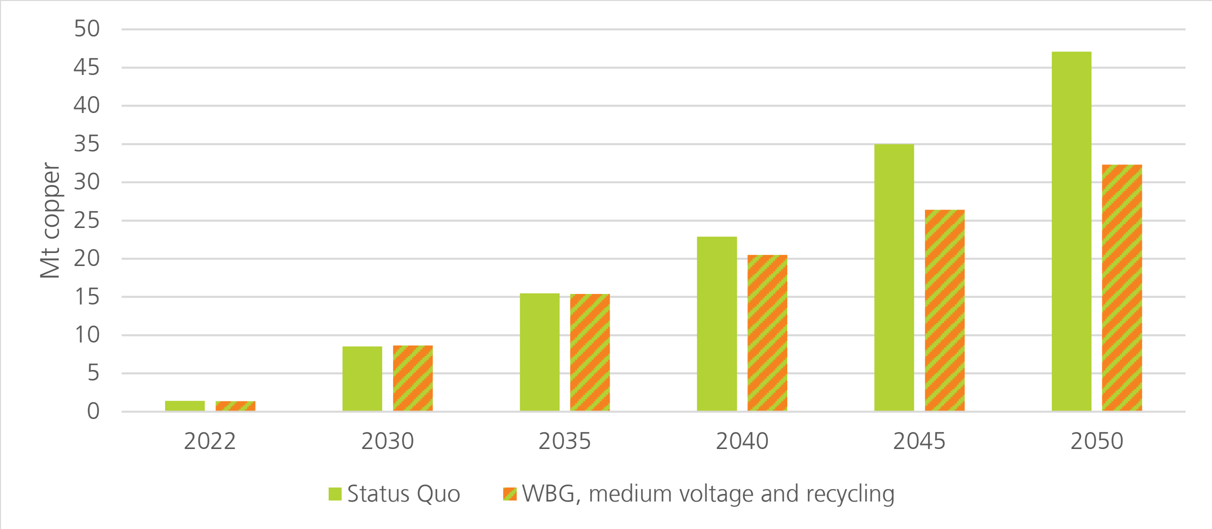

Figure 26: Cumulative copper demand in the NZE scenario without and without including the future developments in Mt

Besides results on individual material perspective, a number for overall raw metal demand for perspective is also interesting. The whole cumulative demand for NZE scenario including the future developments is shown in Figure 27. In these flows, again, only metals are included due to the reasons explained in [2.2]. Compromitted into one number, if none of the developments shown in this work are applied, in the NZE scenario 180 Mt of metals would be required. With WBG materials, medium voltage, and recycling of some of the replaced devices in the NZE scenario, this demand goes down to 80 Mt. More than half of the raw metals could therefore be saved if all the developments are applied.

The Sankey diagram of the cumulative amount of all metals until 2050 for the NZE scenario in Figure 27 clearly shows the importance of the three most prominent metals copper, iron, and aluminium. The total demand for copper is around 32.3 Mt, 15.1 Mt of aluminium are needed, and 30.7 Mt of iron would be built into power electronics devices. All other metals only make up for less than 2 Mt.

Regarding the use of the metals, the flows seem to be way more balanced if compared to the flows in German case shown in Figure 18. The impact of GaN on the demand of the EV devices is rather high, while the wind converter was not considered to be impacted by the technological developments. This might be an explanation for the rather balanced material use of the different technologies.

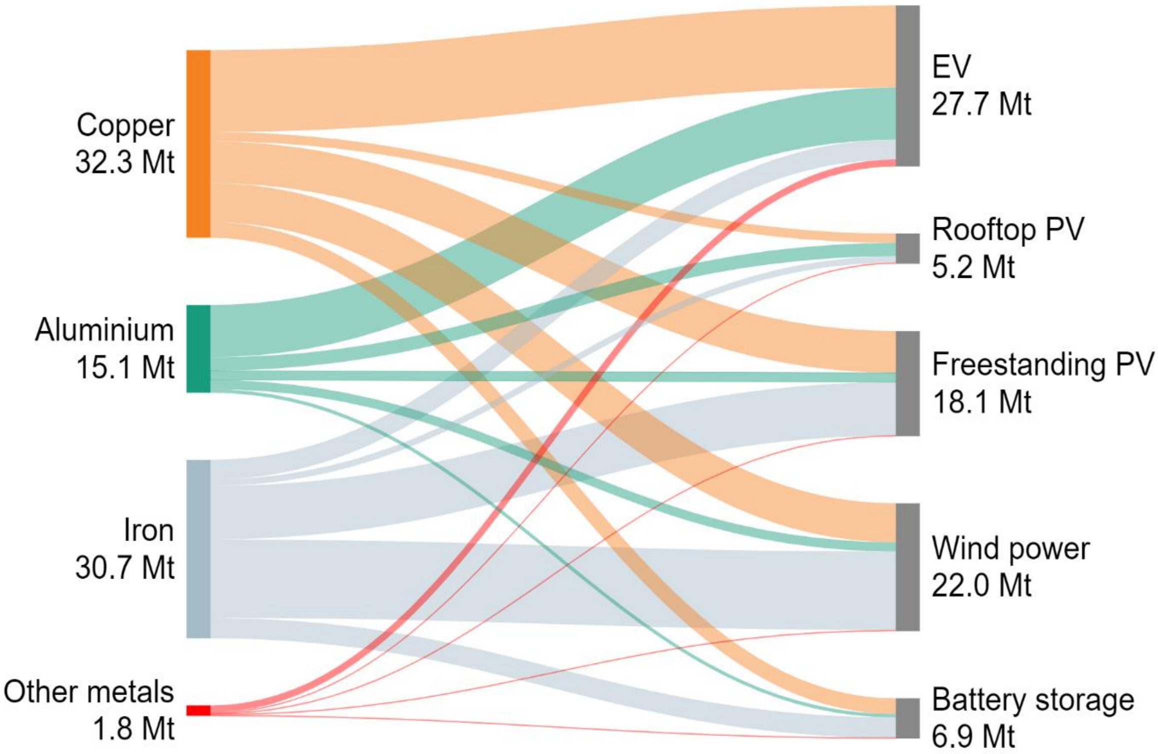

Figure 27: Sankey diagram metal demand until 2050 in the NZE scenario taking into account the future developments in Mt

Comparison with other sectors

In this subchapter the total material demand of power electronics is set into perspective by comparing it with the information on demand of other sectors. It mostly shows how small the material demand of power electronics specifically is in comparison to other sectors. Figure 28 compares the annual demand for copper that this work identified for the year 2035 with the demand of copper in other sectors like electricity networks in the STEPS scenario (IEA, 2024). The copper is mostly used outside of the energy transition. Of the sectors regarding the energy transition, electricity networks make up for the largest share of necessary copper. This is most likely due to the rapid expansion of electricity networks that is necessary to facilitate the energy transition. From the methodology of the critical material assessment by the IEA it was not evident where and if the power electronics demand is included in the data, but this would not change the overall impression (IEA, 2024).

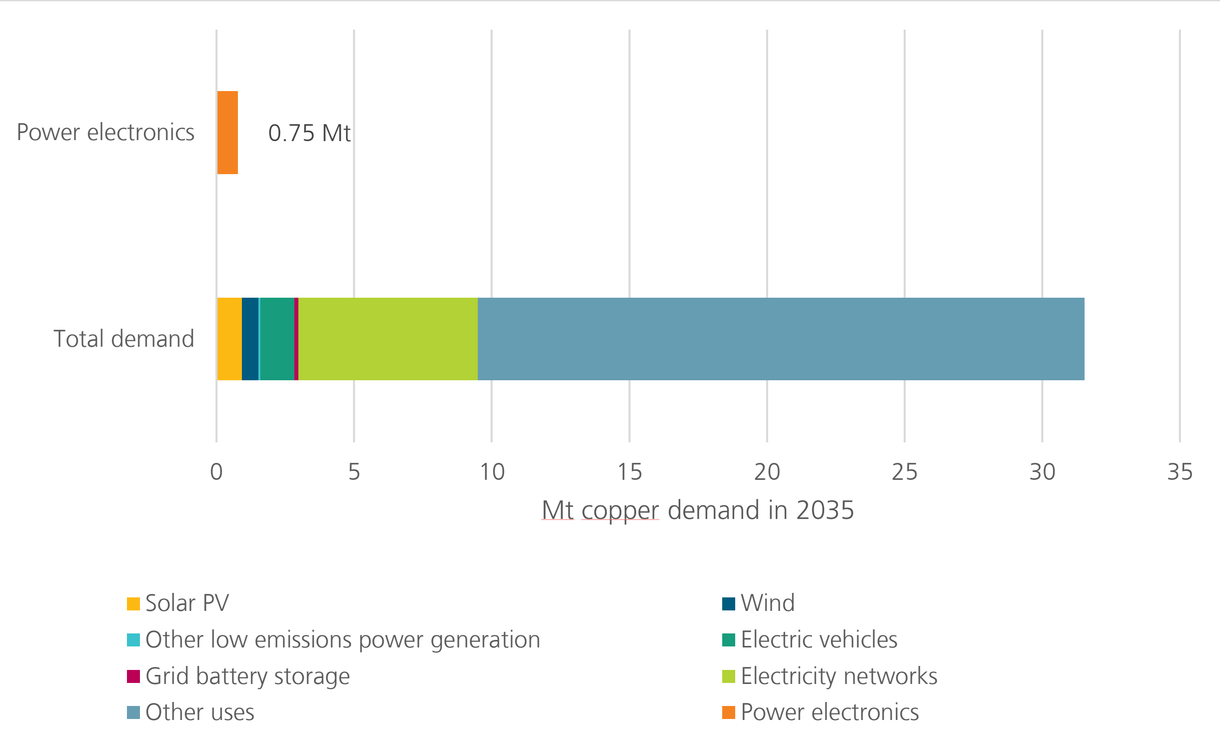

Figure 28: Demand for copper across different sectors in the year 2035 according to the STEPS scenario in Mt

The demand for power electronics compared to the overall demand increases from 2.4 % to 3.4 % when the NZE scenario is considered. The share of materials needed for the energy transition is also higher in the NZE scenario which projects around double the amount of copper for that while assuming less necessary copper for other uses. Figure 29 also shows that in the NZE scenario besides the demand for networks, EVs and solar PV play a significant role regarding material demand.

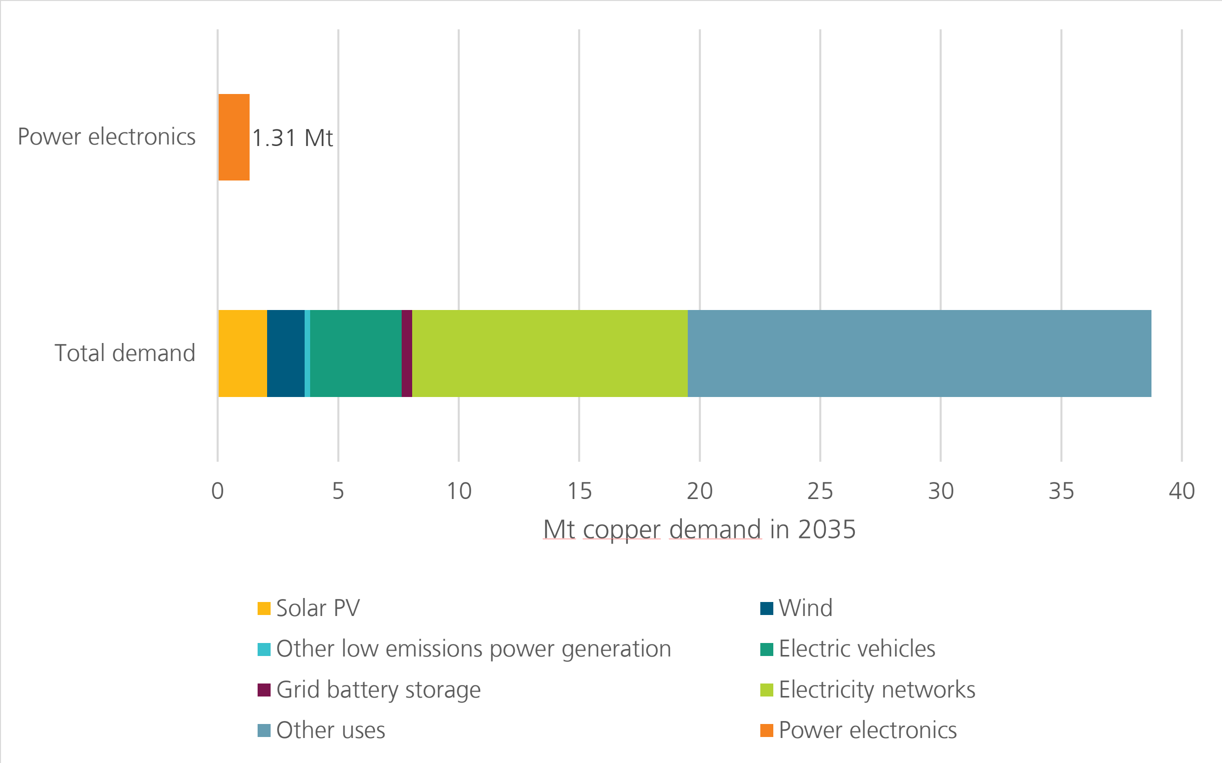

Figure 29: Demand for copper across different sectors in the year 2035 according to the NZE scenario in Mt

Figure 30 shows the same overall impression when considering the demand for nickel in the STEPS scenario. Only 2 kt are needed for power electronics compared to 4164 kt overall demand. Uses not affiliated with the energy transition make up for the vast amount of nickel demand. Sectors like electricity networks and solar PV which made up some copper demand need almost no nickel. The biggest part regarding the energy transition sectors is needed in the EVs, where nickel plays a crucial role in the batteries.

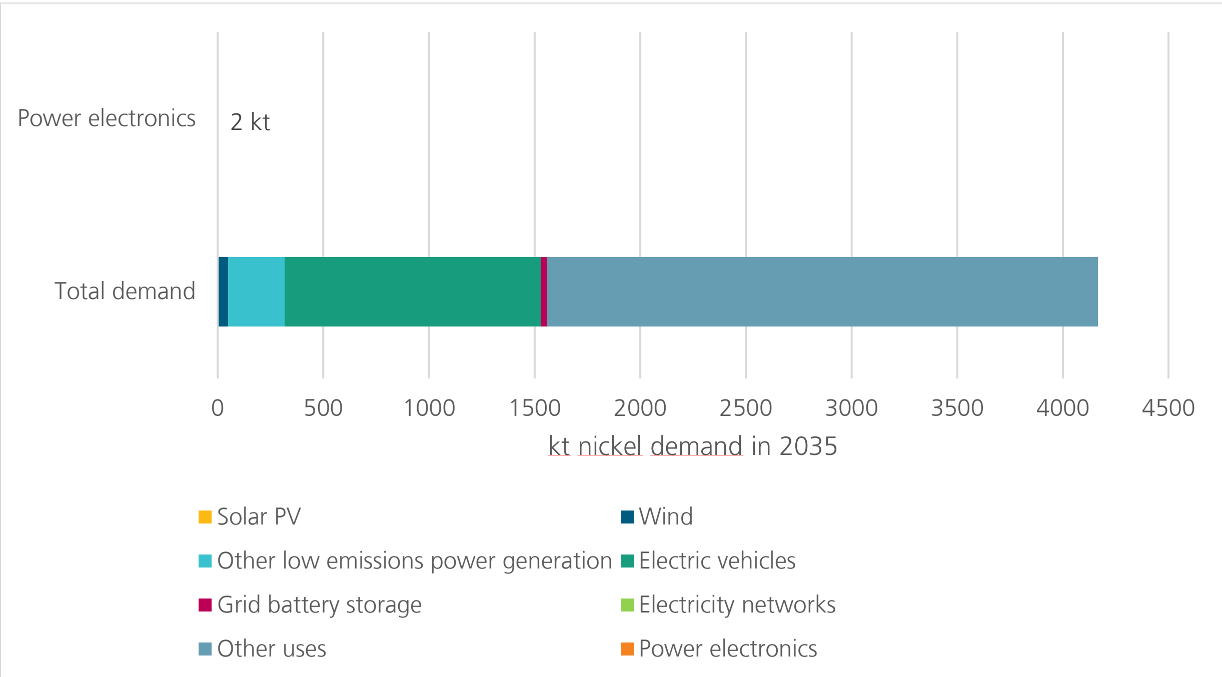

Figure 30: Demand for nickel across different sectors in the year 2035 according to the STEPS scenario in kt

Figure 31 shows the demand for nickel in the NZE scenario and while still only around 0.05 % of the total demand is used for power electronics, the overall demand composition completely changed. The energy transition demand now makes up 65 % of the total demand, mostly for EVs and their batteries that are assumed to increase rapidly as explained here before.

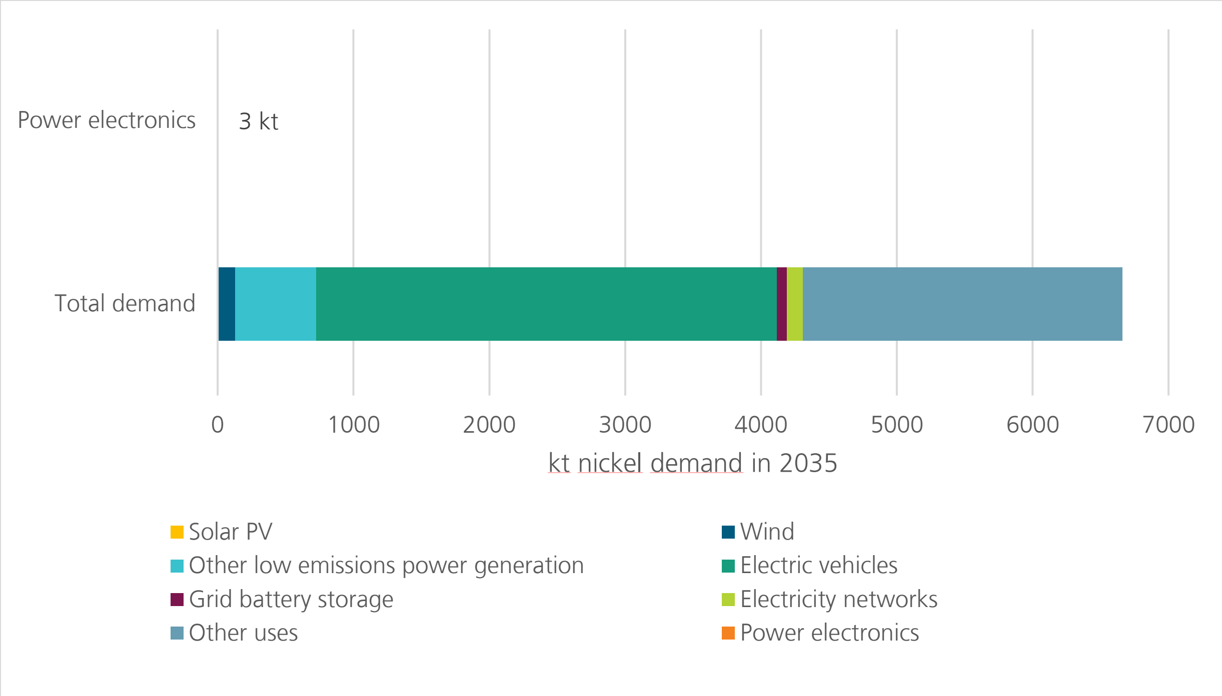

Figure 31: Demand for nickel across different sectors in the year 2035 according to the NZE scenario in kt

3.6 Bottlenecks

Finally, the identified demand is compared to the supply part in this chapter. The results of the global material demand for power electronics for the energy transition show that there is no risk of bottlenecks because of power electronics alone.

Table 7 shows a comparison of the available reserves that the USGS determined (USGS, 2024) with the material demand including all technological developments identified here. Almost all materials would not even need 1 % of those to satisfy the cumulative demand until 2050. Materials like antimony and gold are in the range of 0.5 % which is rather high comparatively. This is especially interesting because both are mostly used in completely other fields. Gold is mostly used in jewellery and as an investment while antimony is mostly used in flame retardants (USGS, 2024). Tin, which is used for soldering in the devices, shows the highest percentage of the materials assessed here with more than 5 % of the identified reserves. The material is not in the focus of many criticality analyses but necessary for many electronics appliances. Therefore, this is a noteworthy result.

	NZE demand until 2050 (Mt)	USGS Reserves (Mt)	Share of reserves needed for power electronics
Copper	32.304	1000	3.23 %
Aluminium	15.109	30000 [1]	0.05 %
Iron	30.693	87000	0.04 %
Manganese	0.366	1900	0.02 %
Zinc	0.977	220	0.44 %
Nickel	0.039	130	0.03 %
Tin	0.219	4.3	5.10 %
Silica	0.063	Almost unlimited raw material reserves	
Antimony	0.008	2	0.41 %
Silicon (Chip)	0.003	Almost unlimited raw material reserves	
Silver	0.001	0.61	0.13 %
Gold	0.0003	0.059	0.47 %
Gallium	0.00002	1 [2]	0,002 %

Table 7: Raw material demand for power electronics for the global energy transition based on NZE scenario compared to global reserves taken from USGS (2024)

[1] Bauxite reserves, the ore aluminium is refined from.

[2] The USGS has not yet published reserves data on gallium, but estimates resources of at least 1 Mt.

4. Discussion

4.1 Discussion of research questions

The results of this thesis will be discussed in depth by answering the research questions formulated in 1.3 one by one.

> *a) What is the material composition of the power electronics appliances relevant for the energy transition?*

Determining the material composition of six significantly different power electronics devices was a main focus and also the biggest added scientific value of this thesis. Since there was scarce literature and very limited data as a basis, the approach chosen was to create representative devices for each relevant technology. The results of this step, having reliable in-depth raw material compositions of six different devices can be utilised as a foundation for future work regarding the material demand of power electronics. It could be seen that these devices are extremely complex. An inverter could contain more than 400 components and more than 2500 individual parts according to Musil et al. (2023). This shows a wide variety of materials and many manufacturing steps are needed to produce power electronics devices. Comparisons of the devices underlined the differences in composition within the field of power electronics, implying that different sizes and types of inverters have completely different proportions as can be seen in Figure 9. The differences in the results were quite evident but have to be taken with caution because of the approach chosen to analyse one representative device for each technology.

To create representative devices for an EV, the average EV being sold right now in Germany was determined. The result showed that the trend towards bigger cars is also applicable to EVs since a weighted average power of 185 kW for the 10 most sold cars was found. This is equivalent to 250 horsepower, which is typical for very large SUVs. The Volvo XC40 would fit into the average motor size identified here for reference (Zajicek, 2024). Even though the conversion from kW to horsepower has flaws, it still shows the trend which is also pointed out as a key problem by other papers (Bulach et al., 2018). The demand for EVs is way more influenced by individual preferences and decisions which makes it slightly different from the other considered technologies that are rather power generation or storage technologies. For those technologies, the size of the systems and the converters is determined by the overall power demand and less by individual decisions.

Regarding stationary batteries, it was considered that the converters needed for PV and batteries are similar, so no specific battery inverter was analysed. Literature showed that 80 % of the battery capacity is found in residential systems which can be taken care of by hybrid inverters such as the one analysed here. This shows the importance of residential solutions to enable the energy transitions since a lot of battery capacity will be needed to stabilize the grid and using EV batteries can only be part of the solution.

The demand per GW capacity of different power converters was compared afterwards. Based on the material demand for the individual devices the material demand per GW capacity was inducted. This made the demand more comparable and showed multiple results. Generally, a higher power rating leads to a lower material demand per GW. Less material would be needed to convert one GW of solar power when ten 100 kW inverters are employed compared to when one hundred 10 kW ones are used. This is again only based on the representative devices developed in this work, but such a scale effect of decreasing material demand with increased power rating seems plausible.

Since the ambition of this thesis is to include the whole power electronics for the energy transition, transformers are also taken into account. It was identified that transformers have a larger material demand than the actual converter in the cases analysed here. Consequently, a lot of material demand is added per GW for all the technologies that are connected to the grid. While wind energy always feeds into the grid, different PV applications must be considered individually. The REMod-model used in this master thesis for scenario analysis, differentiates between rooftop PV and freestanding PV which was taken over for this work. In rooftop PV systems, the power is usually used immediately, so no transformer is needed. On a per GW comparison level, the freestanding PV technologies and the wind power technologies that need transformers to feed into the grid have a similar material demand compared a small rooftop inverter. If no transformers are considered, the material demand per GW of the devices with a higher power rating is significantly lower than the demand of small rooftop inverters.

The two considered devices that are used within the EV, the EV drive inverter and OBC, have different functionalities compared to the power converters and therefore also differ greatly in the material composition. Comparisons to the other devices were therefore not made in this thesis.

The material compositions identified indicate that there is potential to provide the same performance with less material. This potential should be used since there are many reasons why minimising the demand for raw materials is worth pursuing.

b) How do technical developments in power electronics influence the future demand for raw materials?

The three main identified technological developments in power electronics are predicted to be the emergence of wide bandgap semiconductors, operation under increased voltage and increased recycling. They all decrease the material demand of power electronics overall but have different ways of how this is happening. While these were the developments to be identified as the main ones in terms of impact on material demand, other developments might also become important in the time horizon of this work.

Wide bandgap materials

The main intention of technological process generally, and also in this case, is to increase the efficiency of the process. For power electronics, this means minimising the power losses in the power conversion process. The emergence of wide bandgap semiconductors in power electronics is aiming for this by operating at higher switching frequencies, which is a way to increase material efficiency. Switching from Si to GaN or SiC saves a lot of material within the device itself, because less material in passive components is needed. But additionally, and maybe even more importantly, this enables a higher efficiency of the power conversion which saves material in the whole system.

There exist some uncertainties and technical application problems regarding the widespread adoption of GaN. But as the example of the other WBG material SiC shows, the widespread adoption of such improvements will happen eventually if there is a research focus on it. Cost is so far an obstacle for a more widespread use of GaN as well. But it is highly likely that this will be overcome as well since the prices will most likely decrease with increasing quantity of GaN products.

Availability of GaN semiconductors remains as a main barrier. The results showed that the total demand might not be high in absolute terms, but the example of gallium shows the problems of bottlenecks on different places along the supply chain very well. As discussed in [3.4], gallium is mined all over the world as a byproduct of bauxite which is the ore aluminium is produced. From a German perspective, the final step, producing the GaN wafers, is also not critical because the biggest purchaser of gallium for GaN and Gallium arsenide (GaAs) wafers is the German company Freiberger Compound Materials (2024). But the step in between, refining primary gallium from bauxite, is concentrated almost 100 % in China. Because the refining process requires a lot of energy, the last German factory stopped producing raw gallium in 2016 due to economic reasons (BGR, 2023). The availability of the raw material is explicitly not the problem here. New studies show that the waste of old aluminium factories in eastern Germany entail 2500 tons of gallium that could be refined which is more than twice the global annual production in 2023 (Geißler, 2024).

Plans to revive the German gallium production were already communicated in 2021, but since then nothing happened (Holderness, Velazquez, Carroll, & Cook, 2023). As explained in detail in this work, gallium-based devices will become more and more relevant and have a very positive effect on the material demand of power electronics. Therefore, investing in building a solid, resilient supply chain within Germany would be very advisable and rather easy to implement.

Medium voltage

Besides a higher energy efficiency, there are also other ways to reduce the material demand in other parts of the system. An initiative mostly driven by Fraunhofer ISE is developing inverters suitable for medium voltage (Fraunhofer ISE, 2024; Geiss et al., 2023). With increasing voltage, the cross section of cables needed to transport the same power gets remarkably lower. This principle can be applied to solar farms as well as battery farms and hybrid solutions. Increasing the voltage within the system could save a lot of copper which is expensive and might become scarce in the next years as the IEA predicts (IEA, 2024). The main material saving of this development would be outside of the power electronics device itself, where it could have a huge impact.

There are still some technological challenges especially around the capability of semiconducting materials and insulation. If very high voltages are transported through cables, they have to be well isolated which brings some common insulation materials to their limits. Other than that, the development is very recent and not used in practice yet while there are regulations regarding higher voltages which prohibit such solutions so far. Strict regulations, specifically regarding safety, are an obstacle for innovations in power electronics. If regulations are adjusted and these voltage levels are becoming the new standard, megatons of copper could be saved globally.

Circularity

The third identified trend is a more conscious way of using raw materials. Using less raw materials and focusing on repairing devices and reusing or recycling materials is on the agenda of governments. Examples are the German plan for a transition towards a circular economy or the EU's right to repair and sustainable product design (BMUV, 2023; European Commission, 2023a, 2023c). The conducted research on potential bottlenecks also unanimously points out the importance of circularity to avoid bottlenecks (Althaf & Babbitt, 2021; Månberger & Stenqvist, 2018; Schlichenmaier & Naegler, 2022). Nevertheless, the literature research on these practices regarding power electronics showed that they are not well developed so far. While for the more common materials like aluminium, copper, and iron the recycling rates are quite high and a lot can be recovered, the electronics parts with many different materials have very low recycling rates. For silicon or gallium, the recycling rates are below 1 % since the recycling is such a complex matter and make up so little of the total material that it is often not considered worthy to focus on recovering it (Fröhlich, Lorenz, Martin, Brett, & Bertau, 2017) (Gao et al., 2024) (European Commission, 2023a).

The problem does not only lie in the recycling but also in collecting the devices in the first place. As the literature on collection of electronic waste (e-waste), which power electronics is a part of, suggests, only 22 % of the global e-waste is properly collected and recycled (Baldé et al., 2024). For the devices presented here, no one fits all solution to this could be found because the problems and possible solutions regarding collection and recycling differ.

Since the trends show that the demand for electronics will increase while no significant trend towards enhancing collection and recycling is visible on a global scale, the rate of proper collection and recycling will decrease in the foreseeable future. Kolar et al. (2023) predict 120 Mt of e-waste per year in 2050 which is more than double the current amount while the combined collection and recycling rate stays very low. This implies such an immense waste and lost amount of raw material that Kolar et al. (2023) make the claim that "*Net-Zero-CO2 by 2050 is NOT Enough*".

A possible solution that is brought forward in this context is design for circularity. Enabling circularity already starts at the design phase of the products, Kolar et al. (2023) make the claim that 80 % of the environmental impact is already decided in the phase of design. There are multiple design concepts that enable this, which are applicable for power electronics design as well (Huber et al., 2024). A-priori LCAs can be a way to already consider the whole life cycle in the design phase and design the product accordingly. Another concept amongst others that can be very helpful in this context is design for disassembly, which entails actively designing products so that they can be easily deconstructed (Abuzied et al., 2020).

The potential to improve the design, the collection and recycling rate as well as the recycling process and therefore use less raw material is immense. Power electronics can take a leading role here since they are rather large electronics devices compared to for example mobile phones or chargers and therefore entails a comparably high mass of individual materials per device (Fang et al., 2023).

Applied to every material and all electronics devices the wasted potential is enormous. But the necessary infrastructure is not in place yet, which is partly because even though increased circularity is promoted as a key ambition, other factors are prioritised in practice. Since most decisions are towards the cheapest option, especially in a very cost sensitive market like PV, a lot of potential for recycling gets lost. Besides making it economically attractive to recycle and also reuse more devices and materials, also research on circularity in power electronics is missing.

It should not be forgotten that waste is a problem beyond loosing raw materials, it is also a threat to nature and people if it is not properly collected. Therefore Kolar et al.'s (2023) drastic wording seems very appropriate for the situation regarding circularity in power electronics. Improving the circularity of electronic parts should be the focus of any policy trying to reduce the material demand. To help the recyclability it is of utmost importance to already have that in mind from the design phase of power electronics devices. So far, the key criteria have been the cost, power density and energy efficiency. But to effectively decrease the material demand, recyclability as well as durability of the devices also must be considered from the design phase onwards to fulfil the raw material saving potential of these practices.

c) How much material will be needed for power electronics for the energy transition in Germany?

To enable the energy transition in Germany, a significant amount of power electronics devices is needed. And therefore, raw materials in an order of magnitude of multiple kilotons are needed to produce these devices every year. The scenario analysis shows that the demand will increase year for year in the next decades. This is especially happening because most devices have to be replaced at some point during the time period considered in the scenario analysis. Power electronics devices have an estimated lifespan of 15 years which implies that an inverter produced in 2024 must be replaced in 2039. This emphasizes that the material demand is not reaching a peak around 2045 when the needed capacity is added and all cars in Germany are predicted to be electric. Figure 19 shows that there will be a constant demand for materials because technical devices break down. In line with the previous chapter, this shows that design that is focused on prolonging the lifetime is important to decrease the raw material demand.

The material flows based on the REMod scenario analysis show that the biggest contributors to the material demand are the power electronics needed for EVs. The copper demand for EVs in Germany is projected to be higher than the demand for all generation technologies and batteries together in some years. In a scenario which models net zero emissions in 2045 every car in stock by then has to be powered without fossil fuels. The EV drive inverter and OBC used in EVs are designed to be relatively light, but the amount of sold EVs in all scenarios still leads to this huge demand for power electronics for EVs.

EVs can play an important role for the energy transition since their batteries will be used as storage capacity for the grid. The concept behind this is bidirectional charging of EV batteries (Adegbohun, Jouanne, Agamloh, & Yokochi, 2024). In this case the battery can feed the power that is stored within it back to either the home or the grid. This is seen as a solution to stabilize the grid because the EVs will draw power if too much renewable power is available. They can also feed power back into the grid or the home when not enough renewable generation is available. The technological feasibility of the concept is given at this point, while through innovations in power electronics, the efficiency of such bidirectional charging processes is also increasing (Eckardt et al., 2018). This solution has its appeal, but many questions are still open. First of all, the question is how much the potential would actually be exploited since it would require the cars to be connected to chargers for long times and at the right times. Also, the possibility that the car might be not completely charged at times when users want to drive the EV is a serious concern. Bidirectional charging will also lead to more charging cycles, which might affect the lifetime of the battery negatively (Dubarry, Devie, & McKenzie, 2017).

Multiple uses are always good for material efficiency, as it is the case for hybrid inverters that can have a battery and a PV system attached to them, so for the sold EVs bidirectional charging should be implemented. Nevertheless, it is questionable how much positive impact on the grid stability they will have. Stationary batteries for example require the same materials but are also guaranteed to actually fulfil this function. The potential positive effects of EVs on the grid stability and the absolute necessity to not have combustion engine cars, which emit greenhouse gases, anymore, must be acknowledged. Nevertheless, simply replacing all non-EVs with EVs implies an immense additional material demand and has to be assessed critically. Especially if the trend goes on further towards an ongoing increase in size of cars of all sorts, the solution to decrease the material demand must be to simply have less cars overall.

During the process of this thesis the difficulties of determining raw material bottlenecks for individual countries became apparent. Arbitrary approaches of how to break down the global available reserves or production would be necessary to determine how much raw material is available for Germany. Within a globalized world where the production steps from raw material to installed device are performed in many different countries, an analysis on a country level is very difficult and needs many assumptions and simplifications.

REMod provides four different scenarios that differ greatly in terms of the power consumption. Comparing these scenarios showed that this is not reflected in the added renewable capacities within Germany. The additional power demand is predicted to be met by imports of different forms like hydrogen from far away or directly as power through cables. This once again underlines the interconnectedness of the energy transition. It would have been more informative to model the necessary added renewable capacity for the German energy transition outside of Germany, but no data on this was available which is also due to the many uncertainties this would face. A comparison between PV power potentially imported to Germany from Austria and Saudi Arabia shows these uncertainties. In countries with higher solar radiation like Saudi Arabia, less capacity needs to be added to generate the same power. On the other hand, the transport of this power over longer distances, for example by converting it to hydrogen and then transporting it by boat, is way less efficient because more conversion steps have to be done. Therefore, the provided data on the necessary power that is imported is not enough to conclude the capacity that needs to be added to deliver this.

All these concerns regarding breaking down a complex global matter to one country finally led to a focus on modelling the global demand and analysing trends on a global scale in more detail.

d) How much material will be needed globally for power electronics for the energy transition?

Analysis of IEA scenarios showed that an immense demand of materials will be needed for power electronics to make the global energy transition happen. The net zero emissions in 2050 scenario (NZE) especially points to the very huge challenge that reaching this goal will be and also underlines that the world is not on track of reaching it. The NZE scenario assumptions already are quite remarkable regarding the order of magnitude, showing that the transition will be an even bigger challenge on the global scale compared to the German case. If every car using fossil fuels needs to be replaced in the world, this would mean 1.9 billion EVs would have to be built until 2050. The global capacity of solar PV would have to be increase 16-fold and wind energy capacity would have to increase 8-fold. Considering these numbers, it is quite straightforward that the need for material for all technologies connected to the transition will be immense.

Similar to what was discussed in the German case, the impact of the devices that have to be replaced was also seen on the global level. To model how much new raw material is needed, recycling rates were assumed as displayed in Table 4. The assumption of applying them is that all inverters are collected, which is not necessarily given, especially on the global level as pointed out by the E-Waste monitor (Baldé et al., 2024). Figure 21 shows the difference recycling is making and its more likely than not that this number cannot even be reached implying that even more raw materials is needed than identified here.

The Sankey diagrams Figure 27 and Figure 18 are showing where the different materials are used. It can be seen that EVs are responsible for a larger share of the materials in Germany compared to the global case. While the 1.9 billion EVs having to be replace globally seem extremely high it is still significantly less cars per capita than for the German case.

The trends of WBG materials and medium voltage have the potential to save 6.7 Mt of copper inside the power electronics considered here until 2050 even with only 60 % of the whole market having adopted the technologies by then. With this amount of raw copper, the overall copper demand of the EU and UK could be satisfied for more than two years (International Copper Institute, 2023).

If recycling is also considered, the potential is 15 Mt of copper. This would be 60 % of the current yearly worldwide demand. As pointed out here before, even bigger effects will appear outside of the devices themselves, indicating the immense saving potential there.

e) Will there be raw material bottlenecks due to demand of power electronics for the energy transition in the next decades?

It can be concluded that there will be no material bottlenecks because of the material demand of the power electronics technologies for the energy transition within the scope of this thesis. If the required demand is compared to the existing global reserves of the materials, it shows that less than one percent of most reserves would be needed. This can be seen in more detail in Table 7 which takes into account the most ambitious IEA scenario (NZE).

However, power electronics are only one small part of the energy transition and are not the key driver of the demand for most of the materials that were analysed here. It is crucial to note that this analysis was only focused on the material demand of power electronics for EVs, PV, wind energy and battery energy storage systems. Therefore, if all power electronics devices, especially the ones in consumer electronics would be considered, the demand would be way higher. How the selection of the technologies influenced the results regarding demand will also be discussed further in the chapter below.

When the whole material demand for the energy transition is added up, the risk of bottlenecks especially regarding copper, rare earth metals and lithium becomes very real. Publications like the new critical material report by the IEA (2024) or Valero et al. (2018) point out potential bottlenecks already in the coming years.

The reports and papers mentioned, similar to this work, are still only considering the raw materials. These are only the first stage of the supply chain. Factors like production shortages or geopolitical tensions are not even included in the scope of those publications. If a complete picture is considered, including supply risks as they are assessed in the Europeans Commissions critical material risk report (2022), the risk of shortages regarding certain materials is very prominent.

These bottlenecks are not unavoidable, even if the scenarios are accurate. As for example Manberger and Stenqvist (2018) point out, technological developments can help to save raw materials and avoid those. Some examples of how to do this for the case for power electronics were given here.

4.3 Uncertainties and limitations

The results of this thesis face some limitations and uncertainties. They are mostly rooted in the fact that multiple different kinds of data had to be aggregated and a new methodology was created to answer the research questions and provide an added scientific value.

Methodological limitations

The first part of the research was the material demand of different power electronics devices. The lack of data and literature was the reason to choose the methodology of analysing one representative device for each technology within the scope. This required a multitude of assumptions which introduces a significant degree of uncertainty already at this point. Decisions were made to use the material data of components that are representing the device as precisely as possible but ultimately there are hundreds of different products for each of this technology. Breaking it down to just one representative device therefore is a limitation.

As mentioned in [2.2], due to data and time limitations, not all power electronics technologies that are relevant for the energy transition were included into the scope of the thesis. Electrolysers and public transport are increasing sectors which also need power electronics. There are reasons for focusing on the ones considered here which are set out in chapter [2.2] including data availability, fitting into the methodology used here and importance for the energy transition. But this scope limits the conclusions that can be made here to only the technologies within the scope and not power electronics for the energy transition as a whole.

The second part of this research, the projections towards the future are naturally facing uncertainties, because not all developments in the next 25 years can be foreseen. Using multiple scenarios, as done here, helps to get more realistic results. Still, the findings are also contingent on scenarios that may themselves be inaccurate, which is also compounding to the uncertainty of the conclusions.

Nevertheless, the decision was made not to include a sensitivity analysis or a certain corridor where the material demand lies within, because there was not enough data available for this. Every relevant data that was found was used to create devices as representative as possible. Adding a confidence interval would have not been possible, because no additional data, to validate the results with, were available. A confidence interval would also pretend a certainty regarding the representative device that would not be appropriate in this case. A scenario analysis as performed here always implies that just one potential case is represented. These scenarios are modelling a certain behaviour or the necessary steps towards a certain goal and not necessarily the real future developments.

In cases where a range of data was found, best or worst case was assumed, considering which seemed more realistic for the case where it was applied. For recycling rates for example, the currently best case was used since future developments would hopefully go towards an increased recycling rate. For the average EV in contrast, the representative device was based on the most sold EVs in Germany which is most likely still bigger than the average car worldwide. But since the trend of ever-increasing car sizes is seen globally, this worst-case assumption seemed to be appropriate.

Data limitations

In both parts, data from different sources were used which significantly complicates comparisons due to the inconsistencies in definitions and methods of collecting the data. Trying to build a consistent database out of data about components from different sources once again added uncertainties to the presented results.

Similarly, the scenario data was not complete which required additional assumptions and data from other sources. As discussed here in more detail before assumptions that influence the results on a global level greatly had to be made regarding the IEA scenarios. Where this was done it was made explicit in the work. While a lot of effort was put into finding as up to date data as possible, some inconsistencies were already visible. The REMod scenarios are published in 2021 but are already off by more than half regarding the stock of EVs in Germany compared to real data. While this data seems very far off, it has to be taken into account that REMod is modelling a scenario to reach climate neutrality. Instead of concluding that the data is predicting false values this rather implies that Germany is already far off its path towards climate neutrality.

Besides the methodological and data limitations explained here, still valid conclusion about general trends and material compositions can be made. The used methodology made the most out of the very limited data availability and can be used as a starting point for future works on the topic.

5. Conclusion

5.1 Summary

The objective of this thesis was to analyse the role of power electronics for the raw material demand of the energy transition. The approach chosen to do so was to determine one representative device and its material demand for each technology within the scope. The material demand per GW added capacity was then derived to make it more comparable and to simplify its use in the second part of the thesis, the scenario analysis. Using the data of added capacities globally and on a national level in Germany enables to make predictions about the future demand for materials in power electronics. Besides comparisons of different scenarios, the possible impact of selected technological trends in power electronics was determined. Therefore, this thesis provides the first comprehensive analysis specifically of the material demand for power electronics for the energy transition.

The scenario analysis showed that the demand for power electronics for the energy transition will multiply in the coming years regardless of which scenario is considered. In the case of Germany as well as on a global level, this also leads to a large decrease in the demand for materials such as copper, aluminium or iron. Besides these three, which make up for the majority of the required supply of materials, other materials such as tin, gold or silver are going to be needed in vast amounts in the next decades.

Comparing the identified demand to other sectors it became apparent that power electronics only makes up for a small part of the overall material demand. Other sectors need significantly more raw materials. Examples are the generation technologies themselves including the wind turbines or the solar panels, the cables to distribute the power or the batteries in the EVs.

Power electronics play a central role in an energy system relying on renewables. The results regarding technological advances show how this position enables them to increase material efficiency and decrease material demand of the power system as a whole. Wide bandgap semiconductors help reduce losses, which increases the material efficiency of the entire system. Increasing the voltage can reduce the copper demand for cables within solar farms to only a fraction of the status quo. The analysis also points out how the adoption of these technologies significantly decreases the material demand for power electronics devices. Circular practices, including recycling, are identified as the probably most important trend in power electronics because wherever materials are saved or reused, less amount of raw material must be mined.

5.2 Outlook

The first part of this work, to the best of the authors' knowledge, is the first time that detailed material compositions of different power electronics devices are estimated.[3] Since this work is the first to address the raw material demand of power electronics for the energy transition in this grade of detail, there is no recent literature to entirely compare and validate the results with. But even with the number of assumptions that had to be made and the uncertainties predictions of the future always entail, the results presented here are a solid basis and estimation that maybe future research can build upon.

As underlined before, this analysis only considers the raw materials. More research on the supply chains of the raw materials as well as the devices themselves is needed to get a comprehensive picture of the state of material supply for power electronics. Such an effort to model out the complete state of the supply chain of power electronics for the energy transition would need considerably more resources, access to data and time than this thesis could provide. The mentioned challenges that were presented here, mostly in regard to gallium can provide some hints and insights that might also be useful for such a large-scale project.

The results should provide a good starting point for other works on material demand for power electronics devices and for LCAs by providing detailed material compositions for different power electronics devices. Those can be used as the LCIs used to perform LCAs. If researchers want to analyse the environmental footprint of a residential PV system as a whole, the material composition of a 10 kW solar inverter gives an approximation of the materials needed for the inverter part. Based on this, the environmental footprint of this inverter could be evaluated. This would be an advantage to the status quo where inverters are excluded from the scope due to lack of detailed data on the materials.

Research like this work regarding power electronics for the technologies not included in the scope could also be very insightful. Electrolysers and public transport are important fields that rely on power electronics so an in-depth analysis on the potential material demand would be interesting as well.

This thesis can still only be a first step, way more research is needed in this field. A proper database for the material composition is needed to make it easier to retrace material use. There is public discussion on more transparency regarding the resources used in products and the European parliament recently agreed upon new, more strict eco-design regulations (Canas, 2024; European Commission, 2022). The plans also include a digital product passport that contains detailed information about the products. When trying to put this into practice for power electronics, it is very hard to find the necessary data for such an assessment. While expensive databases that are specialized on LCAs use almost twenty-year-old data for their inverters, only a few manufacturers publish data regarding the material composition of their

[3] The results on material demand which are presented in chapters 3.1 and 3.2 as well as some parts that are mentioned in the discussion, will also be published in a conference paper for the ECCE Europe in Darmstadt, Germany happening in September that was written by the author of this thesis, Henrike Köhler and other colleagues at Fraunhofer ISE (ECCE (2024).

products. This makes detailed analysis very complicated, since only a few components, which might not have the right specifications, are available on a detailed level (Huber et al., 2024). More transparency here would be crucial to perform more analyses similar to this one. Companies could certainly also benefit from this on their way to create more sustainable products.

More research analysing the status quo, like performing LCAs to find out about the environmental footprint and resource use of the products, is very important. But it also needs intensified research on sustainable design of power electronics devices. Considering recyclability and environmental impact in the design phase already has a huge potential but is not very common at the moment. A focus on this specific field would be extremely beneficial and has the potential for a lot of positive environmental impact.

The technological developments mentioned here, with their positive effects on the material use of the energy transition, will not automatically gain larger market shares but need support. Especially in regulatory and financial considerations of which innovations to support and which standards to set, the raw materials aspect should have priority because of the great potential presented here.

Finally, investments and frontrunners regarding circular infrastructure are necessary. There is a lot of potential for research and technical developments regarding circular practices. It should be an absolute priority to support new ways of reusing the precious raw materials that were already mined.

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Appendix

Devices and sources of component composition	Components	Sources
10 kW inverter (Musil et al., 2023)		
	Transistor	(Infineon, 2022b)
	DC-Link capacitor	(Nordelöf, 2017)[4]
	Resistor	(Bourns, 2016)
	Relays	(ABB, 2022)
	Coils	ISE internal data[5]
	IGBT module	(Musil et al., 2023)
	Inductor	(Ecoinvent Centre, 2021)
	PCB without parts	(Nordelöf, 2017)
	Diode	(Infineon, 2022a)
	Integrated circuit (IC)	(Infineon, 2021a)
100 kW inverter (Fronius, 2022)		
	Transistor	(Infineon, 2022b)
	Dc-Link capacitor	(Nordelöf, 2017)
	Resistor	(Bourns, 2016)
	Relay	(ABB, 2022)
	Coils	ISE internal data[6]
	IGBT module	(Musil et al., 2023)
	Inductor	(Ecoinvent Centre, 2021)
	PCBs	(Nordelöf, 2017)
	Diode	(Infineon, 2022a)
	IC	(Infineon, 2021a)
500 kW inverter (Eger et al., 2020)		
	IGBT module	(Infineon, 2012)
	AC capacitor	(Nordelöf, 2017)
	Relay	(ABB, 2018)
	DC capacitor	(Nordelöf, 2017)
	Coils	ISE internal data[7]
	AC contactor	(Siemens, 2024a)
	Fuse switch disconnector	(Siemens, 2024b)

[4] The online link to the database appears not to be working. Anders Nordelöf from Chambers university provided access after contacting him via email. So, for more information, requesting access from him seems to be the best option.
[5] The identified shares are 33% iron, 33% copper, 3 % zinc, 8 % manganese, 7 % aluminium and 16 % silicone
[6] Same composition than 5
[7] Same composition than 5

	AC condensator	(Electronicon, 2024)
	Mounting plates, bus bars, sleeves, driver PCB with transformer	Weighed
	HL modules	(Vincotech, 2019)
	Current transducer	(LEM, 2018)
	Semiconductor fuse	(Cooper Bussmann, n.d.)
	PCBs	(Nordelöf, 2017)
	Cables	(TKD-Kabel, 2001)
Wind converter (personal communication)		
	IGBT module	(Infineon, 2021b)
	Busbars and fuses	(ABB, 2018)
	Rest was scaled up from 500 kW PV central inverter	
EV drive inverter (Nordelöf, 2017)		
	Most materials and components	(Nordelöf, 2017)
	Transistor	(Infineon, 2022b)
	Small transformer	(Ecoinvent Centre, 2021)
	Electric connector	(Ecoinvent Centre, 2021)
	IC	(Infineon, 2021a)
	Resistor	(Bourns, 2016)
OBC (Kabus et al., 2020)		
	MOSFET AC/DC	(Infineon, 2022c)
	MOSFET DC/DC	(Infineon, 2022d)
	Coils	ISE internal data[8]
	PCB	(Nordelöf, 2017)
	Heat sink and housing	(Nordelöf, 2017)
	Small transformer	(Ecoinvent Centre, 2021)
	Diode	(Infineon, 2022a)
Transformer (Siemens, 2021)		

[8] Same composition than 5