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Even before you discharge: environmental assessment of vehicle-to-grid

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Abstract

This thesis addresses two rarely seldom considered aspects of vehicle-to-grid (V2G) using life cycle assessment (LCA) – the EV charging equipment and the impact that the EVs have on the low voltage distribution grid. The thesis presents three papers and original work, aiming to answer four research questions on the environmental burden of the charging equipment and the power electronic transistors used, as well as the environmental impact of reinforcing the Swedish low voltage distribution grid.

The environmental burden of the charging equipment is calculated by carrying out an LCA of four different EV charging equipment options. Two such options represent the state-of-the-art bidirectional and today's typical unidirectional designs, both modeled after existing designs. Between these designs there is a gap in power rating, directionality and transistor technology. Two additional equipment options are theoretically constructed to cover this gap and allow understanding of the impact of each change. The results show the state-of-the-art design has a lower climate change impact and material resource use than today's current design. This is driven by production-related impacts of the charging equipment.

The production of power electronic transistors is assessed by first comparing two alternative production routes for silicon carbide (SiC) wafers. These wafers are used in the production of the transistors used by the state-of-the-art onboard charger. The production routes are: Acheson process, followed by physical vapor transport (PVT), or high temperature vapor deposition (HTCVD). It was found that the climate change impact of an SiC wafer can vary by a factor of 70, depending on energy supply mix and production route. Then, in an assessment at a packaged transistor level, the thesis shows that the climate change impact of an SiC transistor produced with the HTCVD route can be lower than that of an equivalent silicon transistor. Coupled with an improved performance and indirect benefits linked to SiC, using SiC MOSFETs instead of silicon IGBTs leads to lower impacts in an onboard charger.

The thesis assesses the impact of reinforcing the low-voltage distribution grid to allow home charging of a fleet composed of 100% EVs. Three charging strategies are assessed: charging directly when arriving home, charging optimized to follow the spot price, and a mixed strategy, where the EV fleet is split 70/30 between direct and optimized charging. Depending on the charging strategy followed, reinforcing the low-voltage distribution grid in Sweden requires the installation of between 3900 and 5700 MVA additional transformer capacity. The reinforcements needed by the low voltage distribution grid can have an impact of over 150 thousand tons of CO_2-equivalents if a direct charging strategy is followed. In the mixed strategy, 30% of the fleet performing spot-price optimized charging reduces this impact by 50 thousand tons.

Overall, the thesis presents environmental impacts that can be expected in any V2G implementation. In doing this, it sets an environmental performance floor for V2G: the impacts of burden from the charging equipment and the necessary grid reinforcement. State-of-the-art charging equipment can reduce the environmental burden of the production and improve the efficiency during its use-phase. The role of the charging strategy followed by the EV fleet can set the V2G performance floor higher, as direct charging can significantly increase the impact of the reinforcement of the low-voltage grid.

Keywords:

Life cycle assessment, LCA, vehicle to grid, V2G, Electric vehicle, Charging, Silicon Carbide, SiC, low voltage grid, distribution grid

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Cambia el sol en su carrera
Cuando la noche subsiste
Cambia la planta y se viste
De verde en la primavera
Cambia el pelaje la fiera
Cambia el cabello el anciano
Y así como todo cambia
Que yo cambie no es extraño

Pero no cambia mi amor
Por más lejos que me encuentre
Ni el recuerdo ni el dolor
De mi pueblo y de mi gente
Y lo que cambió ayer
Tendrá que cambiar mañana
Así como cambio yo
En estas tierras lejanas
…

“Todo cambia”

Julio Numhauser

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List of Included Papers

Paper 1

Anchustegui, P., Nordelöf, A., Bernander, M., Fotouhi, A., 2026. The burden of electric vehicle bidirectionality: Environmental impact of Vehicle-to-Grid capability.

Status: Manuscript submitted for publication in Environmental Science and Technology

Paper 2

Anchustegui, P., Nordelöf, A., 2026. Life cycle assessment of two alternative production routes for silicon carbide wafers.

Status: Manuscript ready for submission

Paper 3

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Status: Peer-reviewed conference article, published in proceedings

Table of Contents

1 Introduction 1

1.1 Background 1

1.2 Aim and research questions 2

1.3 Scope and limitations 3

2 Technical scope: V2G and charging 5

3 Methods 7

3.1 LCA framework 7

3.2 Methodological choices of paper 1 9

3.3 Methodological choices of paper 2 10

3.4 Methodological choices of paper 3 11

3.5 Methodological choices of the thesis work 12

4 Results 15

4.1 EV charging equipment: impacts of power rating, bidirectionality and transistor technology 15

4.2 Impact potential of SiC production routes 18

4.3 HTCVD-route SiC MOSFETs: how do they compare? 20

4.4 Environmental impact of low voltage grid reinforcements 22

5 Discussions 25

5.1 Answering research questions 25

5.2 Future research 28

6 Conclusions 29

7 References 30

1 Introduction

1.1 Background

Efforts to reduce greenhouse gas emissions are ongoing in all sectors of society to mitigate the global threat of anthropogenic climate change. Two such sectors are the transportation and the electricity production sectors. Energy systems are shifting away from fossil fuels by increasing the share of intermittent renewable energy, such as solar and wind power. The transportation sector is experiencing rapid growth in electric vehicles (EVs) for passenger transport, both with hybrid and fully electric drivetrains with battery energy storage. These transitions also entwine the two systems together, presenting new opportunities and problems. Charging of EVs becomes additional demand for the electricity system. This demand will require additional energy and may increase congestion problems with electricity transmission. Since home is the main place for charging (Babrowski et al., 2014), it may also affect the distribution grid. On the other hand, EVs can be used not only as loads, but also as energy storage for the electricity system, in what is commonly referred to as vehicle to grid (V2G).

There are many potential implementations for V2G (Noel et al., 2019; Sovacool et al., 2020): as individual actors or aggregated as a coordinated fleet; in ancillary electricity markets or performing energy arbitrage. The EV can interact directly with the grid or act behind the household meter. These implementations all have different requirements and needs from different actors in society, as well as different potential benefits (Sovacool et al., 2020). Common to all, however, is the need for the charging equipment allowing for a bidirectional flow of energy.

Charging an EV, regardless of where and how it is done, employs AC/DC and DC/DC converters to deliver power to the charging systems (Sithara S. G. Acharige et al., 2023). Home charging is done with AC power, requiring both an onboard charger (OBC) and electric vehicle supply equipment (EVSE). Both converters are housed in the OBC. The EVSE consists of the charging cable, the wallbox, and additional devices to measure, protect and control the operation. Power electronics, used as switches, allow for high efficiency conversion (Batarseh and Harb, 2018). These are commonly made of silicon (Si), but newer technologies like silicon carbide (SiC) can have higher operating efficiencies due to them having lower resistance and allowing for faster switching (Ozpineci and Tolbert, 2011). SiC semiconductors also have a higher energy demand during their manufacturing (Díaz Triana et al., 2021; Musil et al., 2023). Conversion losses are more relevant for V2G operation, since losses take place both when charging and discharging. Therefore, any V2G implementation is tied to the performance of the different converters and the power electronics that compose them.

For any widespread use of V2G, the impact that a fleet of charging EVs has on the distribution grid is another topic to consider. EVs may increase local electricity demand and, in doing so, put additional stress on the distribution grid (Kumar et al., 2023). The grid's infrastructure may need to be reinforced with additional equipment to accommodate the increased load and maintain the grid's functioning adequately. Different EV charging strategies could mitigate or exacerbate the reinforcement need (Veldman and Verzijlbergh, 2015). This reinforcement carries an economic and environmental burden that should be considered when assessing V2G operation of aggregated EV fleets.

Assessing the environmental performance of V2G is made difficult by the many possible use cases and implementations. Existing assessments largely focus on large-scale aspects, such as shifting the demand load of the electricity system or V2G allowing for a higher penetration of renewables in the energy system (Babrowski et al., 2014; Chen et al., 2025; Fernandes et al., 2012; Wang et al., 2022; Xu et al., 2020). Some studies have also considered the role of battery and the potential impacts that V2G can have on its state of health (Xu et al., 2020; Zhao and Baker, 2022), but uncertainties about these impacts remain. However, charging equipment and distribution grid reinforcement impacts remain overlooked.

1.2 Aim and research questions

This thesis aims at quantifying the potential environmental burdens that V2G-capable chargers may have, as well as the environmental impacts of the reinforcing the low voltage distribution grid to accommodate for a 100% EV fleet. The potential impact of different supply pathways for the power electronics in the charging equipment is also assessed. Four research questions are formulated.

The first research question addresses the charging equipment– both inside and outside the vehicle – as this is a necessary local aspect of V2G. The environmental burden of V2G-capable charging equipment is highly relevant and should be mitigated by any implementation of V2G, as it is a necessary impact for V2G performance.

RQ1. What are the environmental burdens of the EV charging equipment needed for performing V2G, and how do they compare to the burdens of current equipment?

This question is addressed in Paper 1, via a comparison between a state-of-the-art bidirectional EV charger and today´s typical unidirectional charger. The comparison is made in terms of power rating, energy directionality and transistor technology. Climate change impact and resource scarcity potential of four charging equipment options are assessed, from cradle to grave. This allows thorough understanding of the environmental burden that the updates in devices, topologies and operation add to the charging equipment.

Power electronic transistor production, for both Si and SiC devices, was modeled in detail in Paper 1. The wafer production stage was found to drive the lion's share of impacts for the SiC devices. This led to the next research question, looking into the environmental impacts of different SiC wafer production routes.

RQ2. How does the environmental impact of SiC wafers vary depending on the production route used?

This second research question is investigated in Paper 2. Two current production routes for SiC wafers for are assessed. The results revealed a wide range of impacts for the production of SiC polished wafers. Since wafer production is the first stage of transistor production, the next research question investigates the environmental impacts of both production routes at a packaged transistor level and in an onboard charger (OBC). Si devices are also included as a reference.

RQ3. What is the environmental impact of SiC transistors when accounting for different production routes, how do they compare to Si transistors, and what is their impact in the OBC of EVs?

RQ3 is investigated through work presented in this thesis. Using the transistor production model from Paper 1, an SiC transistor for each wafer production route is modeled. These are compared to an equivalent Si device. Finally, these three transistors are placed into both the state-of-the-art bidirectional OBC and today's current OBC from Paper 1. The impacts of these combinations are assessed in terms of climate change and resource scarcity impacts.

Beyond the charging equipment, RQ4 addresses the potential impact of reinforcing the low-voltage distribution grid due to EVs. Widespread V2G necessitates a large EV fleet constantly interacting with the low-voltage distribution grid. This interaction may require the low voltage grid to be reinforced to ensure it can continue its operation as intended. Similar to the burden of the charging equipment, the environmental impacts caused by these reinforcements represent an unavoidable burden that any environmentally feasible V2G implementation should mitigate.

RQ4. What are the environmental impacts of reinforcing the low-voltage distribution grid to support charging of an EV fleet and how do different charging strategies affect this?

This question is assessed in Paper 3 by applying a combination of energy systems modeling and LCA of the reinforcement equipment. The consequences that different EV charging strategies have on the reinforcement needs for the low-voltage grid are estimated. The climate change impact of these is then quantified.

1.3 Scope and limitations

The work on charging equipment presented here is based on existing designs and components. However, there is a large variety of converter designs, both for the AC/DC and DC/DC converters. A large array of different electronic components exists as well. Production processes and compositions can differ drastically between them. Making a thorough assessment of all possible combinations of circuit topologies and used components is not within the scope of this work. Regarding the transistors used in this work, they are all assumed to be discrete devices. Module components are integrated systems that include multiple components in a single system. This type of component is also outside the scope of this work.

The equipment from the low voltage distribution grid is limited to aluminium-wound transformers. Reinforcement of other equipment, such as distribution cables, can also be needed as a result of operational exceedances.

Other aspects relevant to V2G, such as impacts on the battery or methodological questions regarding allocation and multifunctionality remain unexplored in this work. The second part of the project aims to address them. Even so, this work can serve as a steppingstone for addressing these and other aspects of V2G and make comparisons to other energy storage technologies.

2 Technical scope: V2G and charging

This section details the objects of study of this thesis. It is not a thorough review of the topics. Rather, it provides background information, ensuring the reader has a “good enough” understanding of the topics discussed in the rest of the text. The topics covered are the following: EV charging, energy converters, power electronics, the electrical distribution grid.

V2G, also referred to as bidirectional charging, refers to an EV charger that allows energy to flow both to and from the EV. The energy stored in the EV battery can be then discharged, either to the power grid, the house, or any other load. The concept of an EV discharging back to the electricity grid was first introduced by Kempton and Letendre (1997). An appealing aspect of V2G is that the investment cost is covered by individuals who buy an EV as a means of transportation. The EV owners profit from the energy provided back to the grid and the grid gains access to a large, if decentralized, storage system. This storage provides flexibility to the grid and allows for the potential replacement of fossil fuels with renewable energy (Noel et al., 2019; Noori, 2015).

Electrical energy is needed for charging the battery of an EV. This electricity needs to be provided as direct current (DC) at the specific voltage of the battery. Most electricity systems currently transmit and distribute electrical energy in alternate current (AC) form. An EV charger needs to transform the incoming AC electrical energy into DC and adjust the power and voltage incoming to match that of the battery (Safayatullah et al., 2022). The first conversion stage, AC to DC, is done in an AC/DC converter; the adjustment is done in a second conversion stage, in a DC/DC converter. The form taken by interconnected components in a circuit is referred to as the circuit topology. A variety of circuit topologies can be used when designing an AC/DC or DC/DC converter (Safayatullah et al., 2022; Sithara S. G. Acharige et al., 2023). These topologies determine, among other performance characteristics, if a converter is unidirectional or bidirectional. If both AC/DC and DC/DC converters are in the OBC of the EV, the setup is commonly referred to as AC charging, since AC electrical energy is supplied by the EVSE to the inlet plug of the EV. Home charging has been predominantly slow, single phase charging (IEA, 2022), where the power rating is between 3 and 7 kW. Faster AC charging, using 3 phases and higher voltages (Bahrami, 2020), facilitates charging outside, as well as V2G operation.

Semiconductor power electronics, acting as switches, are a core component of AC/DC and DC/DC converters. They enable high efficiency energy conversion thanks to their switching speed and their capability to handle higher power (Batarseh and Harb, 2018). However, Si devices are now approaching their theoretical performance limit (Nawaz and Ilves, 2016). In response, wide bandgap semiconductive materials, like SiC, gallium nitride, diamond, and others, have been developed as alternatives to Si. They enable operation at higher voltages, higher temperatures and higher frequencies than Si. SiC outperforms Si, with strong performance in terms of power density, thermal management, and on-resistance (Galioto et al., 2026).

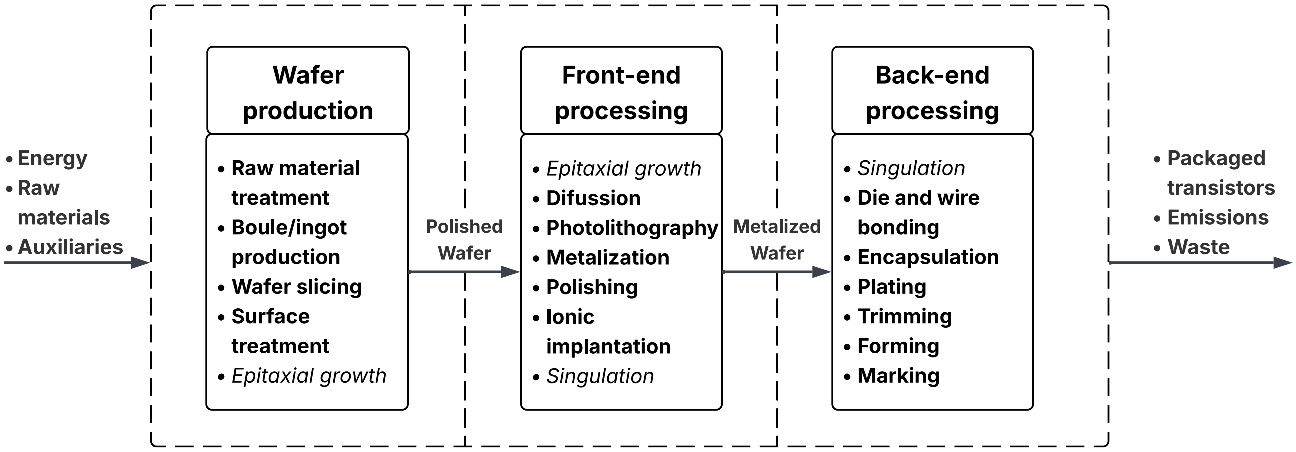

Figure 1 Production process model for transistor manufacturing.

The manufacturing of Si and SiC power electronics follows similar steps (Wijesundara and Azevedo, 2011), shown in Figure 1. However, due to their different material properties, the processes in those production steps differ. The largest difference occurs in the wafer manufacturing stage. SiC is also not a naturally occurring material (other than as moissanite) and it must be produced from silicon and a carbon source. The boule production step is where the boule is grown from feedstock materials. For SiC, this is a time-consuming process that requires high temperatures and controlled pressures. Manufacturing SiC wafers is more energy intensive, with lower production yields (Díaz Triana et al., 2021) and smaller diameters.

Power electronic transistors discussed in this thesis are voltage-controlled switches. However, they differ not only in material, but in device structure and type. Si devices discussed in this thesis are insulated gate bipolar transistors, or IGBTs. On the other hand, SiC devices are metal oxide semiconductor field effect transistor, or MOSFET. Devices modeled are both viable for automotive applications.

The purpose of the electricity grid is to deliver the electrical energy generated to the end users. To efficiently accomplish this, different sections of the grid operate at different voltages, from hundreds of kV to the 400 V delivered to households. The grid can be divided into transmission and distribution grids. The transmission grid carries the energy over large distances, at voltages ranging from 220 to 400 kV. The distribution grid can be subsequently divided into regional and local grids (Svenska kraftnät, 2024). The operating voltage of the distribution grid is reduced with each step. What is also referred to in this work as the *low-voltage distribution grid* (or *low voltage grid*) is the las section of the local grid, which includes the transformers that carry out the last voltage reduction step, from 11 or 22 kV down to 400 V. This is likely the first section of the electricity grid to be impacted by EVs home charging.

3 Methods

This section summarizes the methodologies used in Papers 1, 2, and 3, as well as in the new work presented in this thesis. Subsection 3.1 provides a summary of the LCA framework, as it underpins the rest of the work done. Subsections 3.2 and 3.3 describe LCA-specific methodological choices and sources for data for Papers 1 and 2, respectively. Subsection 3.4 provides a description of the LCA-specific methodological choices made for the assessment of distribution transformers done in Paper 3. This subsection also provides a brief overview of the energy systems modeling performed in that paper. Finally, subsection 3.5 describes the LCA-specific methodological choices made in the original work done in this thesis.

3.1 LCA framework

Life cycle assessment (LCA) is a framework for estimating the potential environmental impacts of a product or service. This is done by compiling and quantifying processes and input and output flows that occur throughout the lifecycle of a product, from raw material extraction to end-of-life (EOL) treatment. Assessments that cover all these stages are referred to as “cradle-to-grave” studies. An alternative to these are “cradle-to-gate” studies, where the assessment typically ends at the gate of the production site, and the use phase and EOL treatment are not included. An LCA comprises four phases (Baumann and Tillman, 2004; International Organization for Standardization, 2006), illustrated in Figure 2. These are: goal and scope definition, inventory analysis, impact assessment, and interpretation.

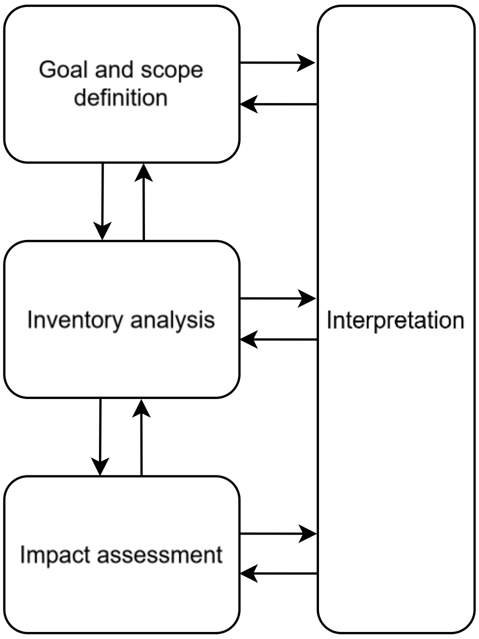

Figure 2. LCA framework, based on ISO standard 14040:2006 (International Organization for Standardization, 2006)

In the **goal and scope definition** phase, a decision is made on which products or “options” to include, the purpose of the study, and the study’s context (Baumann and Tillman, 2004). When defining the **goal**, decisions are made regarding the intended application, reasons for the study and its audience.

During the **scope definition**, a decision is made regarding the functional unit, system boundaries, impact categories, and data requirements for the study. The functional unit is determined from the intended function of the product system. It provides a reference to which all other flows relate. In being tied to a specific function, it allows comparison between other product systems with the same function. The system boundaries are set based on the technical, spatial and temporal limitations of the function and the study. The definition of foreground and background systems is part of the technical system boundaries. The foreground system is typically defined as those processes about which decisions may be taken as a direct result of the LCA study (Baumann and Tillman, 2004). The background system is thus defined as those processes which take place outside the direct influence of the decision makers (Baumann and Tillman, 2004). Another important decision taken in the scope definition is that of which impact categories are examined in the study and the methods by which they are assessed.

LCA studies are broadly catalogued into two different types, based on the choices made here. *Attributional LCAs* estimate how much of the world’s total environmental impact belongs to a specific product system. Attributional LCA uses average data for its inputs to calculate the average environmental impact of a production system (Ekvall, 2020). *Consequential LCAs* estimate how changes in the product system affect the world. Examples of these changes could be design alterations or shifts to alternative process routes. Consequential LCA uses marginal data to calculate the environmental burdens of an additional unit produced (Ekvall, 2020).

In the **inventory analysis** phase, data is collected and quantified for all relevant inputs and outputs of a product system (International Organization for Standardization, 2006). The inputs and outputs include material and energy, emissions, waste, and products.

The **impact assessment** phase describes the potential environmental effects of the inventoried flows. To do so, all flows are classified and characterized based on their contribution to the chosen impact categories. This results in a potential impact score, usually measured in equivalences to base impact, for a specific impact category. *Classification* and *categorization* are mandatory steps in the impact assessment phase. Additional optional steps exist, where category impact results are presented *normalized* to a specific reference. Afterwards, normalized results may be *grouped* and *weighted* into a single score. These optional steps require value judgements, which make the results more subjective.

The **interpretation** phase explains the impact assessment results by linking the findings to the inventory analysis and contributions of individual unit processes. Results should be aligned to the defined goal and scope. Interpretation is also done in tandem with the other phases. This makes LCA an iterative process, repeatedly reviewing, evaluating, and reworking the other phases of the assessment.

3.2 Methodological choices of paper 1

Paper 1 reports a cradle-to-grave, attributional LCA of the home charging equipment of an EV. This charging equipment consists of an OBC and the EVSE. Two existing designs for OBCs are modeled, one state-of-the-art bidirectional OBC and today's typical unidirectional OBC. Two theoretically constructed OBCs are modeled as well, to incrementally explain the effects of power rating and directionality in the OBC. Additionally, three EVSEs are modeled: two from existing unidirectional designs, one 7.4 kW and one 22 kW, and one bidirectional EVSE. This bidirectional EVSE was developed in dialogue with technical experts from Volvo Cars. In combination, these OBCs and EVSEs combine into four assessed charging equipment options:

- **UniSi-7.4**: today's typical unidirectional EV charging equipment. A unidirectional OBC with a rated power of 11 kW that uses Si IGBTs. This option also includes a unidirectional EVSE with a rated power of 7.4 kW.
- **UniSi-22**: a theoretically constructed unidirectional OBC. The UniSi-7.4 OBC's was scaled in size to reflect a power rating of 22 kW. This option includes a unidirectional EVSE with a rated power of 22 kW.
- **BiSi-22**: a theoretically constructed bidirectional OBC. Modeled from a state-of-the-art bidirectional OBC but replacing the transistors from SiC MOSFETs to Si IGBTs. This change in transistors affects cooling needs, so the housing and cooler are modeled equal to those of the UniSi-22 OBC. A 22-kW bidirectional EVSE is included in this option.
- **BiSiC-22**: a state-of-the-art bidirectional EV charging equipment. A bidirectional OBC with a rated power of 22 kW using SiC MOSFETs. A bidirectional 22-kW EVSE is included in this option – same as in BiSi-22.

Data for these models was collected from a variety of sources, including reference designs, scientific literature, conversations with experts, engineering judgements, datasheets, and company and industry reports. Specifically, information for today's typical OBC was collected from the International Material Data Sheet (IMDS) system ("Home - IMDS Public Pages - Liferay," n.d.) with the assistance of Volvo Cars. Information for the state-of-the-art OBC was taken from a reference design from Wolfspeed Inc. (Wolfspeed, Inc, 2023a, 2023b). Unidirectional EVSEs are modeled based on Raghavan et al. (2023). The 7.4 kW and the 22 kW unidirectional EVSEs have the same composition and mass, according to the manufacturer. Only the charging cable changes. Specific attention to detail was taken when modeling the production of power electronic transistor devices, dividing their production into three stages: wafer production, front-end processing, and back-end processing. New information for the front-end processing stage was collected from STMicroelectronics' environmental report of the Catania site for the year 2022 (STMicroelectronics, 2023).

The function of all equipment options is to provide the EV battery with the total energy needed by the EV to drive 200,000 kilometers over a 15-year lifetime. This translates to a functional unit of 40 megawatt hours charged by an EV battery. All equipment options are assumed to fulfill the same charging operation during their use phase. Variations in this stage are only due to the specific efficiency of each modeled option.

The technical boundaries of the system are defined so the foreground system covers manufacturing of electric and electronic devices, assembly of OBC and EVSE, use phase, and EOL. The background system contains the energy supply, material extraction, and production of some components and auxiliaries. This background system is modeled using the Ecoinvent database, specifically the cut-off version 3.9.1 (Wernet et al., 2016). Raw material extraction and material production are modeled to represent global average production. The assembly of the OBC and EVSE, the use phase and EOL take place in Sweden. The study is set in the present day, and components are assumed to have a lifespan of 15 years.

Two impact categories are assessed: climate change impact and material resource scarcity. They are chosen as the use phase efficiency is an important difference between assessed options, and electronic production is both energy intensive and uses a large variety of resources that risk becoming scarce. For climate change impact, the midpoint indicator for Global Warming Potential method from the IPCC 2021 is used, with a 100-year time horizon and units in kilograms of CO2-equivalents (Intergovernmental Panel On Climate Change, 2023). For material resource scarcity, the Crustal Scarcity Indicator (Arvidsson et al., 2020) midpoint indicator is used, with units of kilograms of Si-equivalents.

A sensitivity analysis was conducted to assess the relevance of the carbon content of the electricity supply mix on the overall results. Results of this analysis are presented exclusively for climate change impact. In addition to the base case, low-carbon scenario, two supplementary electricity mixes were assessed, representing a medium- and high-carbon intensity mix. These were the average European electricity supply mix, and the average Poland mix, respectively.

3.3 Methodological choices of paper 2

Paper 2 reports a cradle-to-gate attributional LCA of two alternative SiC wafer production routes. The output of both routes is the same: a 150 mm diameter polished SiC wafer for electronic device manufacturing. The production routes differ in the raw material processing and boule production steps. The first route produces SiC through the Acheson process, grinds it, and then uses it to grow a boule using physical vapor transport (PVT). This is referred to as the “Acheson-PVT” route and was modeled using the unit process data compiled in Paper 1, drawn from literature data. The alternative route is a newer process, where the production of SiC and boule growth occurs in the same process, called high temperature chemical vapor deposition (HTCVD). This is referred to as the HTCVD route and was modeled with data gathered from environmental permits for an existing production site in Sweden and complemented with data from literature.

The function of the assessed systems is to produce 150 mm diameter SiC polished wafers for electronic manufacturing. Therefore, the functional unit chosen is one 150 mm diameter SiC polished and cleaned wafer, with a thickness of 300 μm and a mass of 17 grams delivered at the factory gate.

The foreground system of the system is set to include feedstock production, both SiC production via the Acheson process as well as silane production via hydrochlorination of silicon and disproportionation of trichlorosilane. The boule growth, via PVT or HTCVD are also included in the foreground, as well as subsequent slicing, lapping and beveling, polishing, and cleaning. The background system includes the energy supply, material extraction, and production of auxiliaries. These are taken from the Ecoinvent database (Wernet et al., 2016) cut-off version 3.12. As a base case, production of wafers is modeled to be representative of typical real-world locations. The HTCVD route is assumed to take place in Sweden, in alignment with the data gathered for the process. Silane is assumed to be produced in Germany. The Acheson-PVT route is modeled taking place in USA, as one of the first and largest SiC electronic manufacturers (Wolfspeed Inc.) has large production facilities there. The study is set in the present day.

To provide a thorough comparison of the impacts caused by the two routes, all impact categories in the Environmental Footprint 3.1 (Andreasi et al., 2023) package are used, along with their suggested midpoint indicators. These indicators allow for a good understanding of different impacts on the environment, human health, and material resource use. A contribution assessment of the impacts is done to determine the main impact drivers.

A scenario analysis is performed on the production supply mix used in both production routes. “Production supply mix” is a term used to describe the average supply of electricity, heat, production auxiliaries and waste treatment for a country or region. Different carbon intensities of the production supply mix are assessed in 4 different scenarios, where complete production is assumed to take place in a single country. The modeled countries are Sweden, Germany, USA and China. Sweden is assessed as a low-carbon intensity energy mix, where SiC production already takes place. Germany, USA and China are countries with large semiconductor industries and energy supply mixes of varied carbon intensity. A fifth scenario is added to represent a broad and more varied regional energy mix, represented with an average European energy mix.

3.4 Methodological choices of paper 3

Two separate modeling methods are used in conjunction in Paper 3. Using energy systems modelling, the first step models the low voltage distribution grid and estimates the impacts that a fleet consisting of 100% EVs would have on it, in terms of reinforcement to the modeled grid. The second step is an LCA of the distribution transformers needed for the reinforcement, providing a climate impact for the reinforcement necessitated by each charging strategy.

The distribution grid was modeled based on the REGAL model, by Lundblad et al. (2024). The model creates a synthetic representation of the low-voltage distribution grid of Sweden consisting of 104,853 1x1 km^2 “grid cells”. A 100% EV light vehicle fleet is modeled, with three different possible charging strategies. These strategies are: *direct*, i.e., charging directly when the EV arrives home; *cost-minimized*, where charging happens based on an electricity spot price; and *mixed*, a mix of 70% of the fleet direct charging and the remaining 30% following a cost minimized strategy. The load of the EVs is added to the household load. With this, the model simulates the thermal and voltage exceedances to operational limits of the low-voltage grid. The exceedances are translated into a reinforcement need for that grid cell, in terms of an increase in transformer capacity.

The second step is a cradle-to-gate attributional LCA of the distribution transformers used for reinforcing the distribution grid. The transformer capacities modeled, in kVA, are: 50, 70, 100, 150, 200, 315, 400, 500, 600, 700, 800, 900, 1000, 1125, 1250, and 1500. All transformers are assumed to be aluminium-wound and have an operational voltage of 11 kV. Data was collected from a variety of environmental product declarations for distribution transformers of different capacities and combined to form the composition of an average transformer. This was multiplied by the mass of distribution transformers of each capacity, taken from a manufacturer's product catalogue. Linear interpolation was used to calculate the masses of transformers when sought after capacities were not found in the catalogue.

The function of the assessed system is to produce aluminium-wound distribution transformers needed. Therefore, the functional unit chosen is one aluminium-wound transformer of a given capacity with an operational high voltage of 11 kV produced.

The foreground system includes production of the major components and transformer manufacturing. Transportation or installation of these transformers is not included in the model. The background system includes production of the energy supply, raw material extraction, and production auxiliaries. These are taken from the Ecoinvent database (Wernet et al., 2016) cut-off version 3.11. Production of the transformers is modeled as taking place within Europe, while the production of commodity raw materials (steel, aluminium, etc.) is modeled with global market averages. Production is assumed to take place in the present day.

The environmental impact is calculated for the climate change impact category, using the Global Warming Potential indicator for 100 years (GWP100) from the IPCC 2021 (Intergovernmental Panel On Climate Change, 2023). The number of transformers of each capacity needed as reinforcement for each strategy are multiplied by their respective climate change impact. All impacts for a given strategy are added together, resulting in the total climate change impact of the reinforcement of the Swedish low-voltage electricity grid for that charging strategy.

3.5 Methodological choices of the thesis work

Additional work presented in the main section of this thesis consists of a cradle-to-gate attributional LCA of a power electronic transistor. It builds on the work of Papers 1 and 2, and presents results for three different transistors, covering stages from the raw material acquisition to a packaged device. The transistors modeled are one Si IGBT, one SiC MOSFET produced following the Acheson-PVT route, and one SiC MOSFET produced following the HTCVD route. Data for the SiC polished wafer production is taken from Paper 2, and the front-end and back-end processing are modeled with the unit processes of Paper 1, as is the complete Si IGBT model. The diameter is 150 mm for SiC wafers and 200 mm for the Si wafer, corresponding to common commercial sizes.

The function of the system is to produce an Si IGBT or an SiC MOSFET intended for automotive use. The functional unit is one power electronic transistor produced.

The technical boundaries of the assessment are set so that the foreground system includes the wafer manufacturing, the front-end processing, and the back-end processing stages. Also included is the feedstock production for the SiC of both production routes. The background system contains the production of the Si wafer, energy supply and auxiliaries, raw material extraction, and waste treatment processes. Data for the background system was taken from the Ecoinvent database (Wernet et al., 2016) cut-off version 3.9.1.

The impact assessment was performed for the climate change impact category, with the Global Warming Potential with 100 years horizon (GWP100) indicator from the IPCC 2021 (Intergovernmental Panel On Climate Change, 2023), in kilograms of CO_2-equivalents. Results for each assessed routes are then added to the total impact of their corresponding OBC, based on the modeled options in Paper 1. The original impact of the transistors as modeled in Paper 1 was removed to avoid double counting. The impacts of the Si IGBTs are added to the BiSi-22 OBC, while those of the SiC MOSFETs are added to the BiSiC-22 OBC.

4 Results

Results presented here are a selection of those presented in papers 1, 2 and 3, as well as new research done to answer the research questions in this thesis. To answer RQ1, subsection 4.1 presents Paper 1 results from the life cycle impact assessment of the EV charging equipment options and the sensitivity assessment of the electricity supply mix. Subsection 4.2 is based on work from Paper 2 to answer RQ2, presenting the impacts and main drivers of two SiC wafer manufacturing routes. Tied to this, subsection 4.3 answers RQ3 with new work presented in this thesis. A synthesis of the models of Papers 1 and 2 is made, calculating the production impact of three different packaged transistors, as well as their respective effect on a bidirectional OBC. Subsection 4.4 uses Paper 3 to address RQ4, presenting the effects that different charging strategies have on the low voltage distribution grid, the reinforcement required as a consequence of said effects, and the environmental impact derived from this reinforcement. More information and additional results can be found in the respective papers.

4.1 EV charging equipment: impacts of power rating, bidirectionality and transistor technology

Table 1 shows the climate change and resource scarcity impacts of the four assessed EV charging equipment options. Impacts are divided into the production of the OBC and EVSE, the use phase, and the EOL treatment. The state-of-the-art charging equipment (BiSiC-22) is shown to have lower climate change impact than today's current equipment (UniSi-7.4). The impact of the OBC increases for the constructed options UniSi-22 and BiSi-22, representing power scaling and a bidirectional design. Climate change impact decreases from option BiSi-22 to BiSiC-22 but remains higher than that of option UniSi-7.4. This higher OBC impact is offset by that of the EVSE and – to a lesser extent – by its performance during the use phase.

Table 1. Climate change and resource scarcity impacts (in kilograms of CO2-equivalents and tons of Si-equivalents, respectively) of all assessed charging equipment options. The burden of each stage of the system's life cycle is shown, along with a total cradle-to-grave impact. Results taken from Paper 1.

	Climate change impact (kg of CO2-equivalent)				Resource scarcity impact (tons of Si-equivalent)			
	UniSi-7.4	UniSi-22	BiSi-22	BiSiC-22	UniSi-7.4	UniSi-22	BiSi-22	BiSiC-22
OBC	226	273	363	303	177	197	339	333
EVSE	453	457	344	344	783	802	618	618
Use phase	85	85	117	66	43	43	58	33
EOL	9	10	11	11	0	0	0	0
Total	771	824	834	724	1,003	1,042	1,015	984

Regarding the material resource scarcity impacts, the state-of-the-art and the current charging equipment have similar results. The scarcity result of the OBC increases from 156 tons of Si-equivalents in the UniSi-7.4 option to 176 and then to 339 tons of Si-equivalents, for the UniSi-22 and BiSi-22 options, respectively. The result of the BiSiC-22 OBC is reduced slightly, to 333 tons of Si-equivalents, but the remains twice as high as that of today's current OBC. The EVSE and the improved performance during the use phase offset these OBC impacts, resulting in the two charging equipment options having a similar scarcity result. The EOL phase has minor relevance across all assessed options and impact categories.

Figure 3 shows the contribution to climate change and resource scarcity impacts of the OBC components of UniSi-7.4 and BiSiC-22. The housing and cooler contribute with almost 50% of the climate change impact for today's current OBC. This contribution is reduced for the state-of-the-art OBC. The assembled PCBs and the inductors have an increased contribution. Regarding resource use, the assembled PCBs are the largest contributors in both OBCs. They contribute to approximately 45% and 65% of the resource scarcity impacts of the current and state-of-the-art OBCs respectively. These contributions are driven by the integrated circuit devices included in them. The mounting process and the inductors are both relevant for the current OBC. The contribution share of the mounting process drops for the state-of-the-art OBC, while that of inductors increases. Transistors contribute 4% and 6% of the total climate change impact of the current and state-of-the-art OBCs and their contribution to the resource scarcity result is 2% and 1%, respectively.

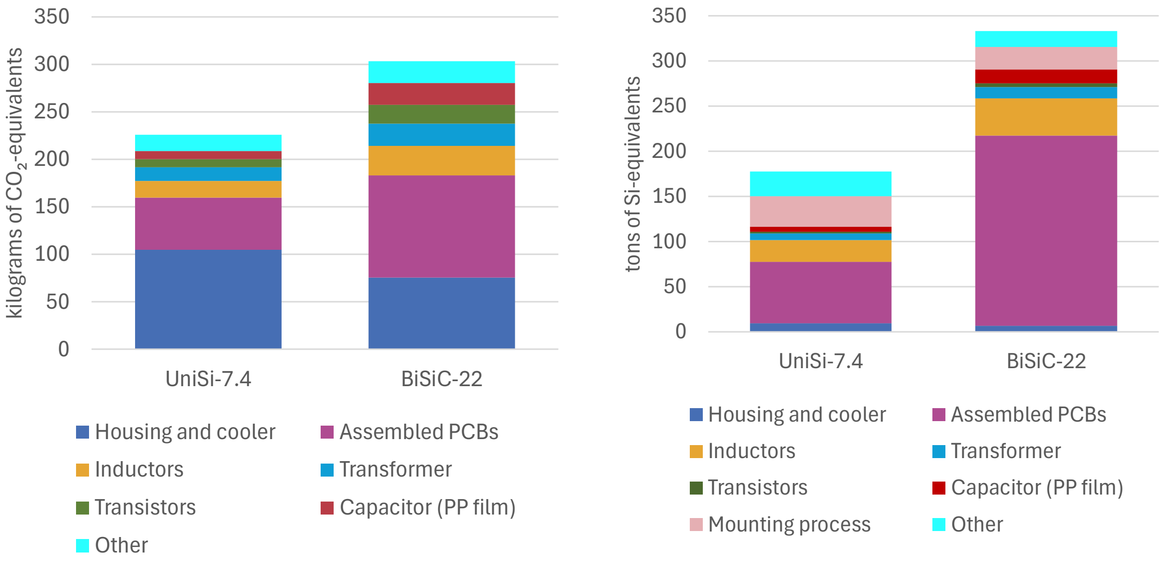

Figure 3. Component contribution to climate change and resource scarcity impacts of the unidirectional Si 7.4 kW and the bidirectional SiC 22 kW OBCs. Results taken from Paper 1.

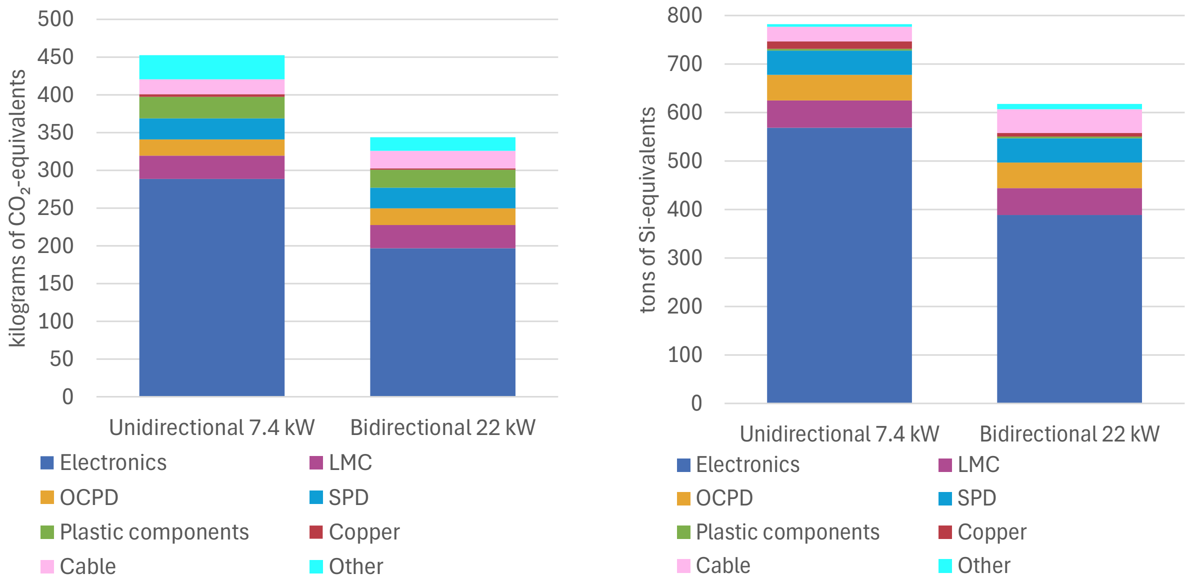

Figure 4. Component contribution to climate change and resource scarcity impacts of the unidirectional 7.4 kW and the bidirectional 22 kW EVSEs. Results taken from Paper 1.

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Figure 4 shows the contribution to climate change and resource scarcity impacts of the components of the current and state-of-the-art EVSEs. Electronic components are the largest contributors to both impact categories and for both assessed EVSEs. The added protection, measuring and controlling devices have similar contributions between the two EVSEs. The contribution of the cable is larger in the state-of-the-art EVSE, for both impact categories.

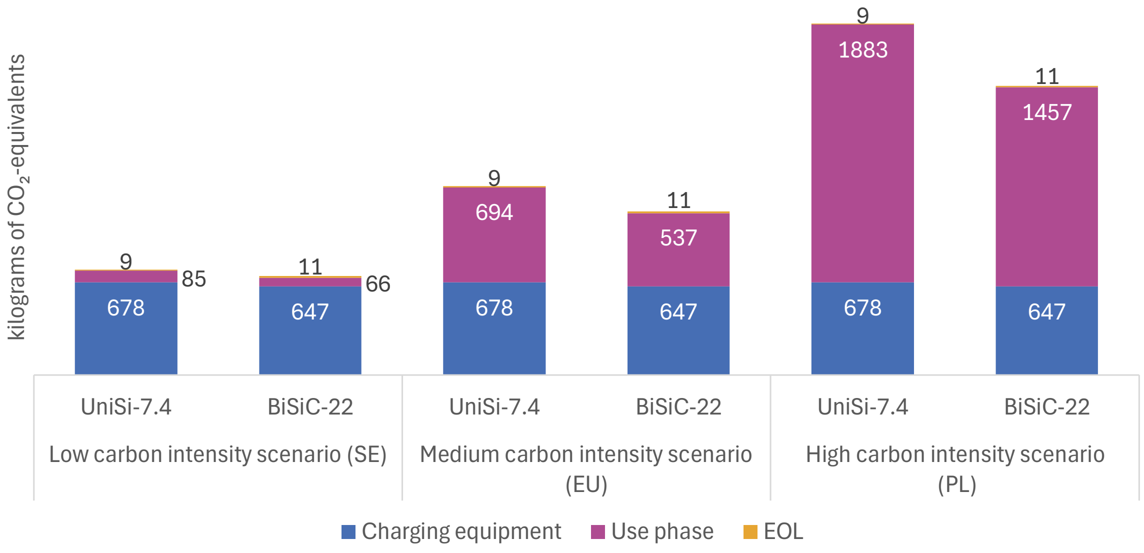


Figure 5. Climate change impacts the assessed charging equipment when using a low, medium or high carbon intensity electricity supply mix.

Figure 5 presents the results of the three scenarios of the sensitivity analysis of the electricity supply mix of the use phase. It shows the climate change impacts of the equipment production, the use phase, and the EOL treatment for today's current and state-of-the-art charging equipment. For medium and higher carbon intensity electricity mixes, the use phase becomes the dominant source of impacts. The contribution of the equipment for UniSi-7.4 goes from 88% of the impact in a low carbon scenario, to 49% in a medium carbon scenario, and down to 26% in a high carbon scenario. For the BiSiC-22 charging equipment, it goes from 89% to 54% and then down to 31%.

4.2 Impact potential of SiC production routes

Table 2 shows the impact assessment results of both assessed production routes for the base case scenario. The HTCVD route is shown to result in lower impacts across all assessed categories. The difference is an order of magnitude larger for categories such as climate change impact, non-renewable energy resource use and freshwater eutrophication. For material resource use, the impact of the Acheson-PVT route is over three times that of the HTCVD route. This is assessed with the abiotic depletion potential indicator, in line with EF3.1, instead of the crustal scarcity indicator used for assessing the same impact category in Paper 1.

Table 2. LCIA results of both Acheson-PVT and HTCVD routes for producing one polished SiC wafer for all impact categories in the Environmental Footprint 3.1. Results taken from Paper 2. Column "Acheson-PVT/HTCVD" added for this thesis.

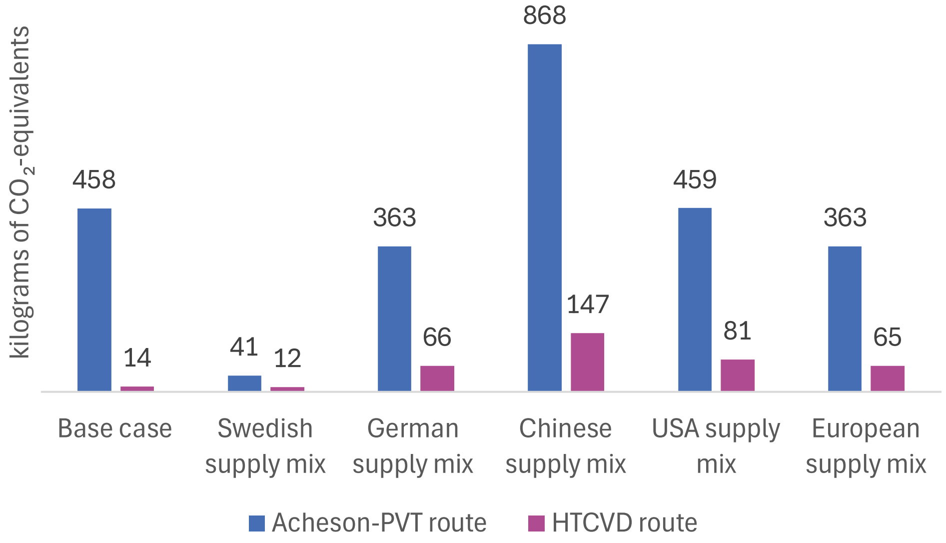
Impact category	Acheson-PVT	HTCVD	Units	Acheson-PVT/ HTCVD
Acidification	1.18	0.07	mol H+-Eq	16
Climate change	458	14	kg CO2-Eq	32
Ecotoxicity: freshwater	1096	96	CTUe	11
Energy resources: non-renewable	8799	815	MJ, net calorific value	11
Eutrophication: freshwater	0.33	0.01	kg P-Eq	34
Eutrophication: marine	0.26	0.02	kg N-Eq	15
Eutrophication: terrestrial	2.11	0.16	mol N-Eq	13
Human toxicity: carcinogenic	7E-08	2E-08	CTUh	4
Human toxicity: non-carcinogenic	3E-06	2E-07	CTUh	13
Ionising radiation: human health	175	50	kBq U235-Eq	3
Land use	949	222	Dimensionless	4
Material resources: metals/minerals	7E-04	2E-04	kg Sb-Eq	4
Ozone depletion	3E-06	7E-07	kg CFC-11-Eq	4
Particulate matter formation	8E-06	8E-07	disease incidence	9
Photochemical oxidant formation: human health	1.28	0.05	kg NMVOC-Eq	28
Water use	97	70	m3 world Eq deprived	1

For all these categories, a contribution assessment shows that electricity use is the main source of impacts. For the Acheson-PVT and HTCVD routes it accounts for: 97% and 55% of the climate change impact, 99% and 63% of the freshwater eutrophication, respectively. These impacts are largely driven by the fossil fuels used in their respective electricity supply mixes. For material resource use, electricity use is responsible for 85% and 53% of the impacts, for the Acheson-PVT and HTCVD respectively. However, these impacts are mainly driven by copper use.

Figure 6 shows the climate change impact, in kilograms of CO2-equivalents, for the scenario analysis. If the same market mix of energy and other process inputs are supplied to both routes, the HTCVD route has lower impacts than the Acheson-PVT route. A high carbon electricity mix can increase the climate change impact of both production routes by an order of magnitude. In a low-carbon scenario, production following the Acheson-PVT route leads to lower impacts than the HTCVD route using medium- or high-carbon intensity mixes.

Notably, the electricity supply mix is a decisive factor for the impact of both routes. For the Acheson-PVT route, electricity use contributes between 75% and 98% of the impact. For the HTCVD route, the contribution of electricity use ranges between 84% to 91%, excluding the Swedish scenario. For this scenario, electricity use contributes with 43% of the climate change impact; other main contributors are hydrochloric acid production and treatment of spent sawing slurry.

Figure 6. Climate impact, in kilograms of CO2-equivalents, for all production steps of a polished SiC wafer taking place in Sweden, Germany, China, USA and European average. Results shown for the Acheson-PVT route and HTCVD with mass allocation of silane production. Results taken from Paper 2.



4.3 HTCVD-route SiC MOSFETs: how do they compare?

Figure 6 shows the climate change impact of producing one encapsulated power transistor. These transistors can be either an Si IGBT, an SiC MOSFET following the Acheson-PVT route, or an SiC MOSFET following the HTCVD route. The total impact of these devices ranges from 1.03 to 1.43 kilograms of CO_2-equivalents, corresponding to the SiC HTCVD route MOSFET and the SiC Acheson-PVT route MOSFET respectively. The largest sources of impact for all devices are the inputs grouped for auxiliaries and processing energy. The semiconducting chip is the second largest driver of impacts. The SiC HTCVD route chip has the lowest impact, followed by that of the Si IGBT and then by the SiC Acheson-PVT route one.

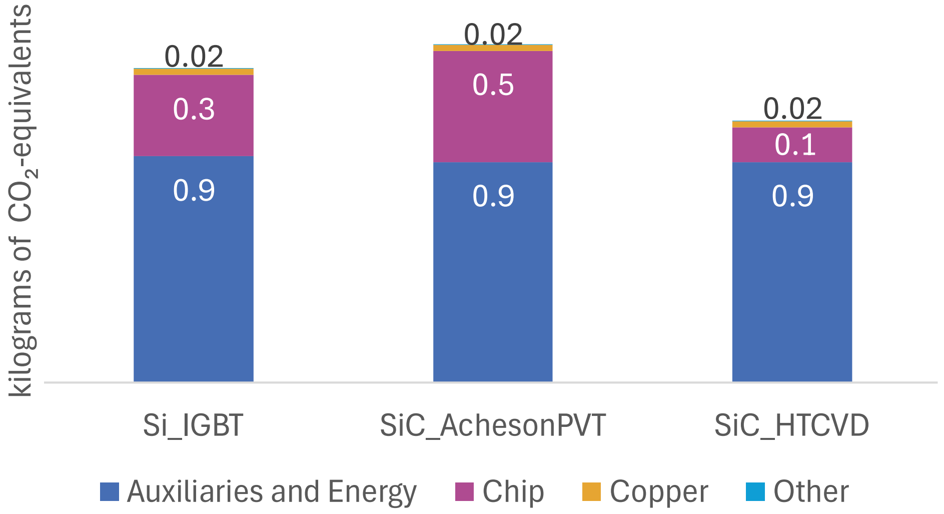


Figure 7. Climate change impact (in kilograms of CO_2-equivalents) of packaged transistor, for an Si IGBT and of two SiC MOSFETs, one produced following the Acheson-PVT route and one following the HTCVD route.

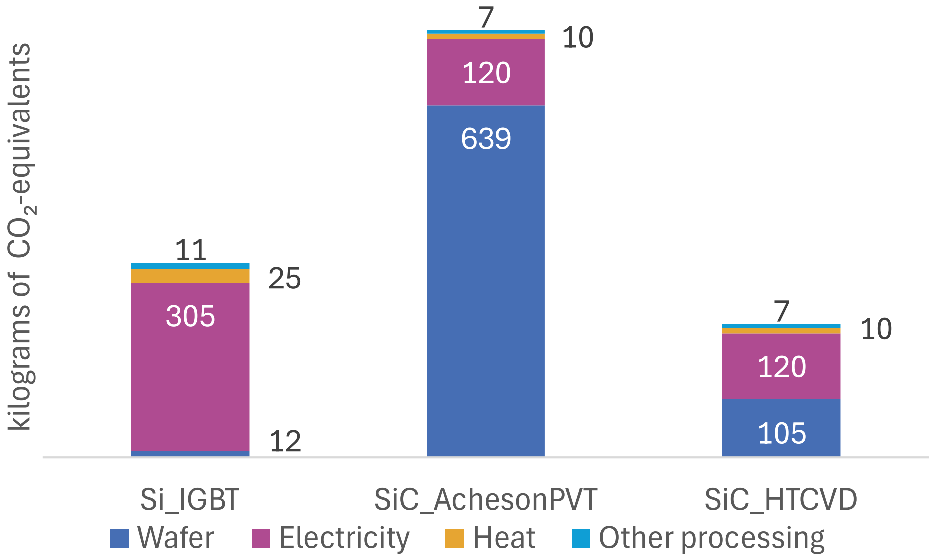


Figure 8. Climate change impact (in kilograms of CO_2-equivalents) for a metalized wafer, after the front-end processing stage, for an Si IGBT and of two SiC MOSFETs, one produced following the Acheson-PVT route and one following the HTCVD route.

Figure 7 shows the climate change impact for manufacturing one metalized wafer, either 200 mm Si or 150 mm SiC wafer. This corresponds to the impact of the wafer production and the front-end processing. For the Si metalized wafer, the main source of impact is the electricity used in the front-end processing, while the contribution of the polished wafer is significantly lower. For SiC, the impact of the polished wafer is significantly higher; it contributes to 82% and 44% of the climate impacts for the Acheson-PVT route and the HTCVD route metalized wafers, respectively. Electricity for the front-end processing contributes to 15% and 49% of their respective climate change impact.

Table 4 shows the climate change impact that the assessed transistors have on a bidirectional OBC. It shows total impact of the transistors as well as their share of the impact of the OBC. Using MOSFETs from the HTCVD route leads to the lowest climate change impact for a bidirectional OBC. The impact is larger for the OBC using Si IGBTs, as it requires a larger cooler and housing than its counterparts using SiC MOSFETs. This makes the relative contribution of the Si IGBTs the lowest of the three options, despite their total impact score being 20% higher than that of the HTCVD route MOSFETs in absolute numbers.

Table 3. Impact of a Si IGBT or a SiC MOSFET produced following the Acheson-PVT route or the HTCVD route, in a bidirectional OBC. OBC impacts are taken from Paper 1, specifically Option (3) for the bidirectional 22kW Si IGBT IBC, and Option (4) for the bidirectional 22 kW SiC MOSFETs.

	Bidirectional 22 kW		
	Si IGBT	SiC Acheson-PVT	SiC HTCVD
Transistor count	14	14	14
Impact per transistor	14	14	14
Total transistor impact	1.3	1.4	1.1
Total OBC impact	18	20	15
Share of impact from transistors	362.65	303.51	299.10
Transistor count	5.0%	6.4%	5.1%

4.4 Environmental impact of low voltage grid reinforcements

Table 5 shows the estimated consequences of the different charging strategies according to the REGAL model. These consequences are shown in terms of number of grids where the transformer capacity is exceeded at least once, the percentage of the total grids where there are exceedances, the mean and maximum exceedance, the number of transformers and total capacity added as a reinforcement to the low-voltage grid, and the total climate change impact of this strategy. A direct charging strategy leads to the largest number of exceedances. Reinforcing the low-voltage grid for this strategy requires the most installed capacity and transformers, leading to the largest climate change impact. A cost-minimized charging strategy has the opposite effect, resulting in the lowest number of exceedances, lowest number of transformers installed, and lowest climate change impact. Following a mixed charging strategy results in a middle case between the other two strategies, both in terms of number of exceedances and total climate impact change. However, this strategy has the lowest maximum exceedance and the lowest need for reinforcement capacity. Its total results are closer to those of the cost-optimized charging strategy. A more detailed breakdown of different amounts of transformers needed for the reinforcement can be found in Paper 3. Notably, a large number of 50 kVA transformers is needed by both direct charging and mixed strategies, compared to those needed by the cost-optimized strategy.

Table 4. Consequences of different charging strategies in terms of number of exceedances, the share of the total grid where exceedances were registered, mean and maximum exceedance in terms of capacity, and the number and total capacity of transformers added as reinforcement. Results taken from Paper 3. Row for total climate change impact was added in this thesis, compared to Paper 3.

	Direct charging	Cost-minimized charging	Mixed charging
Number of grids where the transformer capacity is exceeded	36,927	7,195	18,613
Percentage of grids where the transformer capacity is exceeded	35.2 %	6.9 %	17.8 %
Mean exceedance of rated transformer capacity	10.5 %	24.7 %	11.1 %
Maximum exceedance of rated transformer capacity	338 %	374 %	317 %
Number of transformers added to reinforce the grid	21,344	7,394	12,744
Total capacity needed to reinforce the grid [MVA]	5,776	4,063	3,969
Total climate impact of the charging strategy [kton CO_2-eq]	150	90	100

Table 5 shows the contribution of the components of an average transformer to its climate change impact. The windings, both high voltage and low voltage, are responsible for over 54% of the climate change impact of an average transformer. The core is responsible for 22%, followed by the tank (8%), the stainless-steel components (8%), and the mineral oil used for cooling (3%).

Component	Contribution to climate change impact of average transformer
HV Winding, aluminium	33.3%
Core, GOES	21.8%
LV winding, aluminium	21.4%
Tank, low alloyed steel	8.2%
Stainless steel components	7.8%
Mineral oil	2.5%
Plastic components	1.9%
Manufacturing Process	1.0%
Copper lugs and other components	1.0%
Paper	0.5%
Porcelain	0.1%
Cardboard	0.1%

Table 5. Component contribution to climate change impact for an average aluminium-wound transformer. Results taken from Paper 3.

Figure 9 shows the climate impact caused by reinforcing the low-voltage grid, depending on the charging strategy followed. The direct charging strategy has the highest climate change impact, followed by the mixed charging strategy and then the cost-optimized strategy. 50 kVA transformers have the highest contribution to climate change for the direct and mixed strategies, contributing with 27% and 19% respectively. For the cost-optimized strategy, 50 kVA transformers represent under 3% of the total impact.

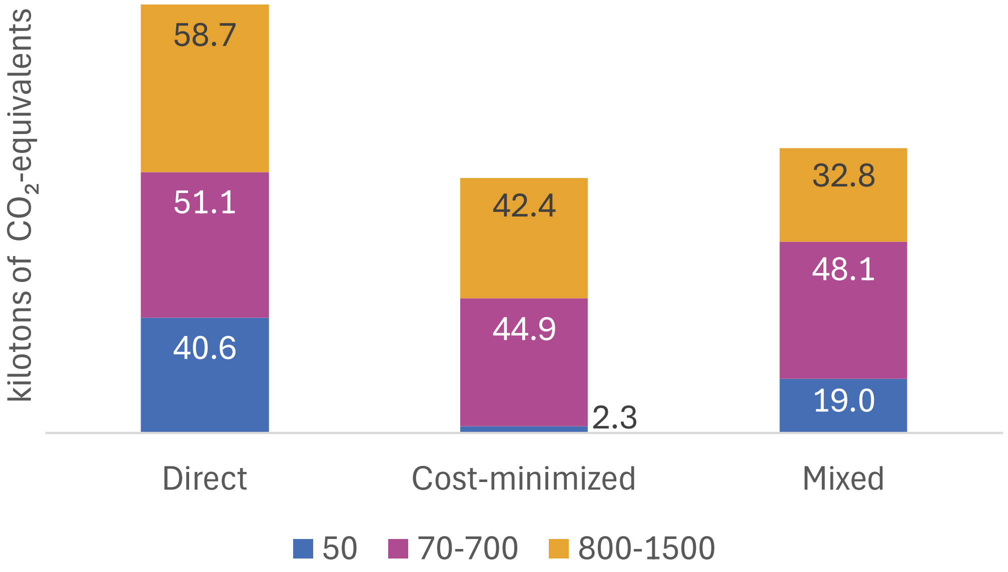


Figure 9. Total climate change impact of the reinforcement to the low-voltage grid required by each assessed charging strategy, and the contribution to it of transformers with capacities of 50 kVA, 70-700 kVA, and 800-1500 kVA, in kilotons of CO2-equivalents. Results taken from Paper 3.

5 Discussions

5.1 Answering research questions

RQ1: *What are the environmental burdens of the EV charging equipment needed for performing V2G, and how do they compare to the burdens of current equipment?*

The state-of-the-art bidirectional EV charger has lower climate change impact than today's typical charger. This is despite having a considerable increase in power rating, and a need to accommodate bidirectionality. The state-of-the-art OBC increases the environmental burden of the EV charger, while the EVSE lowers it enough to offset the increases from the OBC.

For the OBC, the power rating increase comes with a higher cooling need, larger connectors and generally bigger devices inside the OBC, all of which drive the impact up, as seen in the UniSi-22 option. Furthermore, the changes to allow the bidirectional flow of energy add more transistors and integrated circuit devices, further increasing the impact of option BiSi-22. Integrated devices also make for the largest single source of resource scarcity impact, because of the gold contained in them. However, the use of SiC MOSFETs instead of Si IGBTs in the state-of-the-art bidirectional OBC helps reduce the overall increase in impact of the OBC. This effect is indirect, as replacing Si IGBTs for SiC MOSFETs reduces the need for cooling due to their improved thermal performance. Thus, the OBC requires a smaller housing and cooler. Even so, the climate change impact and resource scarcity impact of the BiSiC-22 OBC are 37% and 113% higher than that of the UniSi-7.4 OBC.

The BiSiC-22 wallbox has a lower mass compared to the wallboxes of the unidirectional EVSEs assessed. This mass reduction is likely a result of EV charging technology maturing, allowing for a modern design and a better definition of the device's requirements; not only a consequence of bidirectionality. It includes a reduction of the electronic components, which leads to lower climate change impact and material resource use, since electronics are the largest contributor to both indicators.

Impacts in the use phase come from the energy losses during operation of the EV charging equipment. They are driven by the OBC operational efficiency, as the EVSE efficiency is the same for all modeled options. These losses have a higher burden when the electricity supply mix has a higher carbon content. The impact of the losses of the state-of-the-art bidirectional EV charger is slightly lower than that of today's typical charger if the electricity supply mix has a low carbon content. In the high carbon intensity scenario, the use phase becomes the dominant source of impacts and relevance of the equipment significantly decreases.

SiC MOSFETs appear to offset any impacts from their production, due to their reduced cooling needs and their improved operational efficiency. The latter is particularly relevant when the electricity supply mix has medium or high carbon content.

RQ2: *How does the environmental impact of SiC wafers vary depending on the production route used?*

The HTCVD route results in lower environmental impacts across all categories Electricity use is the largest contributor to the impacts of SiC wafer production, contributing up to 98% of the impacts for the Acheson-PVT route and 88% for the HTCVD route. A contribution analysis of climate change impact, freshwater eutrophication, and material resource use all highlight the electricity use as the main source of impacts. The better results of the HTCVD route can largely be explained due to it using 84% less electricity than the Acheson-PVT route. The boule production step is responsible for a large portion of this energy demand. Improving the speed at which the SiC boule grows could reduce the energy consumption of SiC wafer production significantly, reducing the overall wafer impact.

Compared to the base case scenario, the Acheson-PVT route can have eleven times smaller climate change impact if using a low-carbon intensity electricity supply mix. On the other hand, shifting to a high-carbon intensity energy mix can lead to approximately 90% higher climate change impact for this production route. For the HTCVD route, there is an order of magnitude in the difference between the impacts for the low- and high-carbon intensity energy mix. The impacts of producing an SiC polished wafer can vary by a factor of 70, depending on the production route followed and the energy supply mix used.

The choice of electricity supply is a powerful lever for mitigating the impact of the production of SiC polished wafers. Their impact can be drastically reduced by changing the electricity supply to renewable energy. This should be prioritized in existing Acheson-PVT production facilities over switching to the HTCVD route, as it will lead to better environmental outcomes, and likely be more economically feasible. For setting up future production, however, the HTCVD route is recommended.

RQ3: *What is the environmental impact of SiC transistors following these different production routes, how do they compare to Si transistors, and what is their impact in the OBC of EVs?*

The semiconducting chip in a power electronic transistor is not the main contributor to its environmental impact. At a packaged transistor level, the largest impact comes from the energy and auxiliaries used during the back-end processing stage. The chip is the second largest source of impact. However, since the masses of packaged devices are very similar, the chip is the main source of variation in impacts.

Upstream, after front-end processing, the differences between assessed options are larger. The metalized wafer from the Acheson-PVT route has the highest impact, twice as large as that of the Si or the SiC HTCVD route metalized wafers. For Si, the impacts of the wafer production stage are less relevant than those of front-end processing. The opposite is true for SiC metalized wafers. Electricity use in the front-end processing stage is the largest contributor of impacts for Si, and second largest for the SiC. Overall, electricity use is the largest source of impacts for both Si and SiC transistors. Switching the electricity supply in all production stages to renewable energy is a viable impact mitigation strategy throughout the production of power electronic transistors, regardless of the type.

The material properties of SiC contribute to reducing the environmental burden of SiC devices. As a wide band gap semiconductor, SiC has properties that enable the use of smaller chip sizes. Smaller chip sizes result in SiC singulation yielding over 75% more chips than the Si singulation step. This is despite SiC wafers being smaller in diameter than Si wafers. SiC's material properties also allow for smaller packaged devices. SiC devices are currently used in standardized package sizes that are based on Si performance. As stated by Diaz Triana et al. (2021), once SiC devices have a larger presence in the market, packaging designed for their performance may allow for a smaller mass. A reduction in the mass could result in lower climate change impacts from the back-end processing stage. It may also lead to a lower material resource use, since other components in the packaged transistor could be reduced, such as the copper lead frame and heatsink.

Transistors can contribute directly and indirectly to the impact of an OBC. The direct contribution of transistors to the OBC's impact is relatively low, regardless of technology or production route. The variation in impact share between devices and between OBCs is also low. However, the indirect contribution can be significantly larger. As seen for the bidirectional OBC using Si IGBTs, the total OBC impact is larger than for both SiC alternatives, in large part due to the larger cooling need. This increased need leads to Acheson-PVT SiC MOSFETs outperforming Si IBGTs. SiC devices produced following the HTCVD route outperform the other two options, and lead to lower climate change impacts and improved performance per device and for bidirectional charging equipment of EVs.

RQ4: *What are the environmental impacts of reinforcing the low-voltage distribution grid to support charging of an EV fleet and how do different charging strategies affect this?*

A 100%-EV fleet will require reinforcing the low-voltage distribution grid, regardless of the charging strategy assessed. New distribution transformers installed as reinforcement lead to climate change impacts ranging from approximately 90 thousand tons up to 150 thousand tons of CO_2-equivalents, corresponding to the cost-optimized and direct charging strategies, respectively. A large share of the impact of direct and mixed strategies comes from the large number of 50 kVA transformers added. For the direct strategy specifically, the need for only these transformers outcounts the total number of transformers for the other two charging strategies. 50 kVA transformers are also the main difference in the climate change impact of the mixed strategy compared to the cost optimized. Special attention in the reinforcement strategies should be directed to avoid installing a large amount of 50 kVA transformers.

The impacts a 100% EV fleet has on the low-voltage distribution grid may be reduced or exacerbated by V2G operation. The additional charging and discharging of energy to the grid could cause further exceedances in the transformers. This is also the result of charging strategies that focus on spot price for optimization. Other pricing mechanisms, like power tariffs, or alternative pricing signals could result in different charging patterns, and therefore in different reinforcement needs.

In the study, an assumption is made that any exceedance must be avoided and thus equipment in a grid where a small exceedance occurs must be reinforced. In practice, a certain level of exceedance can be allowed, at the discretion of the grid operator. Additionally, all reinforcements are not likely to take place simultaneously, but over a long period of time. Other measures taken in the meantime could mitigate some of these reinforcement needs. V2G can be one such measure.

Impacts from the reinforcement of the grid are relevant for any implementation of V2G. The combination of environmental assessments and energy systems modeling allows us to assess the environmental consequences of the interactions between the EV fleet and the low-voltage distribution grid in terms of grid reinforcement and equipment.

5.2 Future research

To the best of my knowledge, no other work has performed LCA to establish the environmental impacts taking place with cars and charging equipment capable of performing V2G. These are environmental aspects which are independent from actual V2G operation, and corresponds to the burden of enabling V2G. It can be thought of as part of a "fixed" burden of V2G. Future work can continue the assessment of the equipment and its role in V2G. For example, an assessment of the role that the battery and its state of health play in V2G is an urgent topic. Battery degradation due to V2G is likely dependent on the specific implementation and can be conceptualized as a "variable" environmental burden for V2G operation.

An additional aim of the project is to assess the multifunctionality aspect of V2G. This presents a methodological question regarding how to consider the two different operations of an EV – driving and discharging to the grid. In a next step, this project's aims to assess different methodological practices in LCA for dealing with multifunctionality. This could be done by performing a comparison of partitioning through allocation, both economic and physical properties, and system expansion. This comparison could also reflect on the effect these different methods have on how V2G is assessed.

Another project aim is to assess the environmental impacts of V2G in operation and its effects in the energy system. There are myriad V2G applications and combinations of services that a vehicular fleet can perform. The combination of energy systems modeling with LCA, as was done for RQ4, can be useful for assessing the interactions between a fleet of EVs and the grid, quantifying the environmental performance of said interactions. Therefore, a study will be done to extend the work done in Paper 3 to include different applications of V2G and their consequences on the low-voltage distribution grid.

6 Conclusions

After assessing the environmental burden of EV charging equipment, the state-of-the-art bidirectional equipment is found to have a lower climate change and similar resource scarcity impacts than today's typical unidirectional charging equipment. The state-of-the-art OBC has a higher burden than its counterpart, due to its increased power rating and bidirectionality. However, this higher burden is offset by the improvements on the EVSE and the improved efficiency of SiC transistors in the use phase.

Regarding the environmental impact of SiC wafer production, the HTCVD route for production of a polished SiC wafer has lower environmental impacts compared to one produced with the Acheson-PVT route across all assessed categories. Electricity use is the principal impact driver for both production routes. This makes the carbon content of the electricity supply mix a key lever for decreasing the impact of SiC wafers.

Concerning power electronic transistor production, SiC MOSFETs produced with the HTCVD route have a lower environmental impact than both those produced with the Acheson-PVT route as well as their Si counterparts. Using HTCVD-produced SiC MOSFETs instead of Si IGBTs can lead to a lower impact for the OBC, both directly and indirectly. The production of these SiC MOSFETs has 17% lower impact than that of Si devices. At the OBC level, the direct improvement is less noticeable due to the relatively low contribution of transistors to overall OBC impact. On the other hand, the indirect benefits that SiC devices have in terms of decreased cooling need and increased operational efficiency result in SiC MOSFETs being a better alternative than Si IGBTs for these applications.

In regard to the environmental impacts of reinforcing the low-voltage distribution grid, the charging strategy followed by an EV fleet was found to play a significant role. All assessed charging strategies required reinforcement; however, following a cost optimized strategy results in five times fewer exceedances and in 40% less climate change impact than following a direct charging strategy. Interestingly, a fleet following a mixed charging strategy results in 34% less climate change impact than following a direct strategy, while needing only 30% of the fleet to optimize charging based on the electricity spot price.

This thesis pieces together some of the environmental impacts that can be expected of any V2G implementation. These impacts can be thought of as a "fixed" environmental burden of V2G, set by the charging equipment and the reinforcement of the low voltage grid. Any energy and emission savings resulting from a given V2G implementation must mitigate these "fixed" burdens. In future work we can apply these findings when assessing other aspects of V2G, such as the role of the EV battery and its state of health. These findings can also be used in assessments of the role of V2G in the electricity system, and its effects on renewable energy penetration.

7 References

Andreasi, B.S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., Ardente, F., 2023. Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method [WWW Document]. JRC Publications Repository. https://doi.org/10.2760/798894

Arvidsson, R., Söderman, M.L., Sandén, B.A., Nordelöf, A., André, H., Tillman, A.-M., 2020. A crustal scarcity indicator for long-term global elemental resource assessment in LCA. Int J Life Cycle Assess 25, 1805–1817. https://doi.org/10.1007/s11367-020-01781-1

Babrowski, S., Heinrichs, H., Jochem, P., Fichtner, W., 2014. Load shift potential of electric vehicles in Europe. Journal of Power Sources 255, 283–293. https://doi.org/10.1016/j.jpowsour.2014.01.019

Bahrami, A., 2020. EV Charging Definitions, Modes, Levels, Communication Protocols and Applied Standards. https://doi.org/10.13140/RG.2.2.15844.53123/11

Batarseh, I., Harb, A., 2018. Power Electronics. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-68366-9

Baumann, H., Tillman, A.-M., 2004. The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application, Edition 1:8. ed. Studentlitteratur, Lund.

Chen, J., Craig, M.T., Michalek, J., Bruchon, M., Vaishnav, P., 2025. Negative Electric Vehicle Emissions: Vehicle-to-Grid Can Incentivize Enough Wind and Solar Investment to Reverse EV Charging Emissions. Environ. Sci. Technol. 59, 21090–21101. https://doi.org/10.1021/acs.est.5c06944

Díaz Triana, A., Schmidt, S., Glaser, S., Makoschitz, M.L., 2021. A "life cycle thinking" approach to assess differences in the energy use of SiC vs. Si power semiconductors: e·nova 2021, International Conference. e-Nova 2021.

Ekvall, T., 2020. Attributional and Consequential Life Cycle Assessment, in: José Bastante-Ceca, M., Luis Fuentes-Bargues, J., Hufnagel, L., Mihai, F.-C., Iatu, C. (Eds.), Sustainability Assessment at the 21st Century. IntechOpen. https://doi.org/10.5772/intechopen.89202

Fernandes, C., Frías, P., Latorre, J.M., 2012. Impact of vehicle-to-grid on power system operation costs: The Spanish case study. Applied Energy, Smart Grids 96, 194–202. https://doi.org/10.1016/j.apenergy.2011.11.058

Galioto, G., Vitale, G., Sferlazza, A., Lullo, G., Giaconia, G.C., 2026. Wide and Ultrawide Bandgap Power Semiconductors: A Comprehensive System-Level Review. Electronics 15, 835. https://doi.org/10.3390/electronics15040835

Home - IMDS Public Pages - Liferay [WWW Document], n.d. . IMDS Public Pages. URL https://public.mdsystem.com/en/web/imds-public-pages (accessed 10.3.25).

IEA, 2022. By 2030 EVs represent more than 60% of vehicles sold globally, and require an adequate surge in chargers installed in buildings [WWW Document]. IEA. URL https://www.iea.org/reports/by-2030-evs-represent-more-than-60-of-vehicles-sold-globally-and-require-an-adequate-surge-in-chargers-installed-in-buildings (accessed 10.10.25).

Intergovernmental Panel On Climate Change, 2023. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157896

International Organization for Standardization, 2006. Environmental management – Life cycle assessment – Principles and framework.

Kempton, W., Letendre, S.E., 1997. Electric vehicles as a new power source for electric utilities. Transportation Research Part D: Transport and Environment 2, 157–175. https://doi.org/10.1016/S1361-9209(97)00001-1

Kumar, M., Panda, K.P., Naayagi, R.T., Thakur, R., Panda, G., 2023. Comprehensive Review of Electric Vehicle Technology and Its Impacts: Detailed Investigation of Charging Infrastructure, Power Management, and Control Techniques. Applied Sciences 13, 8919. https://doi.org/10.3390/app13158919

Lundblad, T., Taljegard, M., Mattsson, N., Hartvigsson, E., Johnsson, F., 2024. An open data-based model for generating a synthetic low-voltage grid to estimate hosting capacity. Sustainable Energy, Grids and Networks 39, 101483. https://doi.org/10.1016/j.segan.2024.101483

Musil, F., Harringer, C., Hiesmayr, A., Schoenmayr, D., 2023. How Life Cycle Analyses are Influencing Power Electronics Converter Design, in: PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management. Presented at the PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 1–9. https://doi.org/10.30420/566091368

Nawaz, M., Ilves, K., 2016. Replacing Si to SiC: Opportunities and challenges, in: 2016 46th European Solid-State Device Research Conference (ESSDERC). Presented at the 2016 46th European Solid-State Device Research Conference (ESSDERC), pp. 472–475. https://doi.org/10.1109/ESSDERC.2016.7599688

Noel, L., Kester, J., Sovacool, B.K., Zarazua de Rubens, G., 2019. Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility, 1st ed. 2019. ed, Energy, Climate and the Environment. Springer International Publishing : Imprint: Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-04864-8

Noori, M., 2015. Development of Regional Optimization and Market Penetration Models For Electric Vehicles in the United States. Electronic Theses and Dissertations.

Ozpineci, B., Tolbert, L., 2011. Smaller, faster, tougher. IEEE Spectrum 48, 45–66. https://doi.org/10.1109/MSPEC.2011.6027247

Raghavan, S.S., Nilsson, E., Nordelöf, A., 2023. Unit Process Inventory Data for Residential Electric Vehicle Charger Life Cycle Assessment (No. E2023:002), Report / Division of Environmental Systems Analysis, Chalmers University of Technology. Chalmers University of Technology.

Safayatullah, M., Elrais, M.T., Ghosh, S., Rezaii, R., Batarseh, I., 2022. A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications. IEEE Access 10, 40753–40793. https://doi.org/10.1109/ACCESS.2022.3166935

Sithara S. G. Acharige, Md. Enamul Haque, Mohammad Taufiqul Arif, Nasser Hosseinzadeh, Kazi N. Hasan, Aman Maung Than Oo, 2023. Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations. IEEE Access 11, 41218–41255. https://doi.org/10.1109/ACCESS.2023.3267164

Sovacool, B.K., Kester, J., Noel, L., Zarazua de Rubens, G., 2020. Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review. Renewable and Sustainable Energy Reviews 131, 109963. https://doi.org/10.1016/j.rser.2020.109963

STMicroelectronics, 2023. Dichiarazione ambientale 2022 Sito di Catania [WWW Document]. URL https://www.st.com/content/ccc/resource/corporate/company_promotion/site_brochure/group0/2b/fa/3c/22/17/05/4e/01/EMAS-Declaration-Catania-2022/files/st-catania-emas-environmental-declaration-2022.pdf/_jcr_content/translations/en.st-catania-emas-environmental-declaration-2022.pdf (accessed 9.18.24).

Svenska kraftnät, 2024. Sveriges elnät [WWW Document]. URL https://www.svk.se/om-kraftsystemet/oversikt-av-kraftsystemet/sveriges-elnat/ (accessed 4.27.26).

Veldman, E., Verzijlbergh, R.A., 2015. Distribution Grid Impacts of Smart Electric Vehicle Charging From Different Perspectives. IEEE Trans. Smart Grid 6, 333–342. https://doi.org/10.1109/TSG.2014.2355494

Wang, Z., Jochem, P., Yilmaz, H.Ü., Xu, L., 2022. Integrating vehicle-to-grid technology into energy system models: Novel methods and their impact on greenhouse gas emissions. Journal of Industrial Ecology 26, 392–405. https://doi.org/10.1111/jiec.13200

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wijesundara, M.B.J., Azevedo, R., 2011. Silicon Carbide Microsystems for Harsh Environments, MEMS Reference Shelf. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4419-7121-0

Wolfspeed, Inc, 2023a. 22kW Bi-directional High Efficiency AFE Converter [WWW Document]. URL https://www.wolfspeed.com/products/power/reference-designs/crd-22ad12n/ (accessed 12.19.24).

Wolfspeed, Inc, 2023b. CRD-22DD12N 22kW Bi-directional High Efficiency DC/DC Converter [WWW Document]. URL https://www.wolfspeed.com/products/power/reference-designs/crd-22dd12n/ (accessed 12.19.24).

Xu, L., Yilmaz, H.Ü., Wang, Z., Poganietz, W.-R., Jochem, P., 2020. Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies. Transportation Research Part D: Transport and Environment 87, 102534. https://doi.org/10.1016/j.trd.2020.102534

Zhao, G., Baker, J., 2022. Effects on environmental impacts of introducing electric vehicle batteries as storage - A case study of the United Kingdom. Energy Strategy Reviews 40, 100819. https://doi.org/10.1016/j.esr.2022.100819