Wide Band Gap Technology: Energy and environmental related Life Cycle Assessment (LCA).

4E Power Electronic Conversion Technology Annex (PECTA)

October 2023

Technology Collaboration Programme
by iea

Power Electronic Conversion Technology Annex - 2023

The report was commissioned by the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E) – Power Electronic Conversion Technology Annex (PECTA).

It was formally approved by the Management Committee of PECTA, consisting of Roland Brueniger, Adriana Díaz, Christian Holm Christiansen and Peter Bennich.

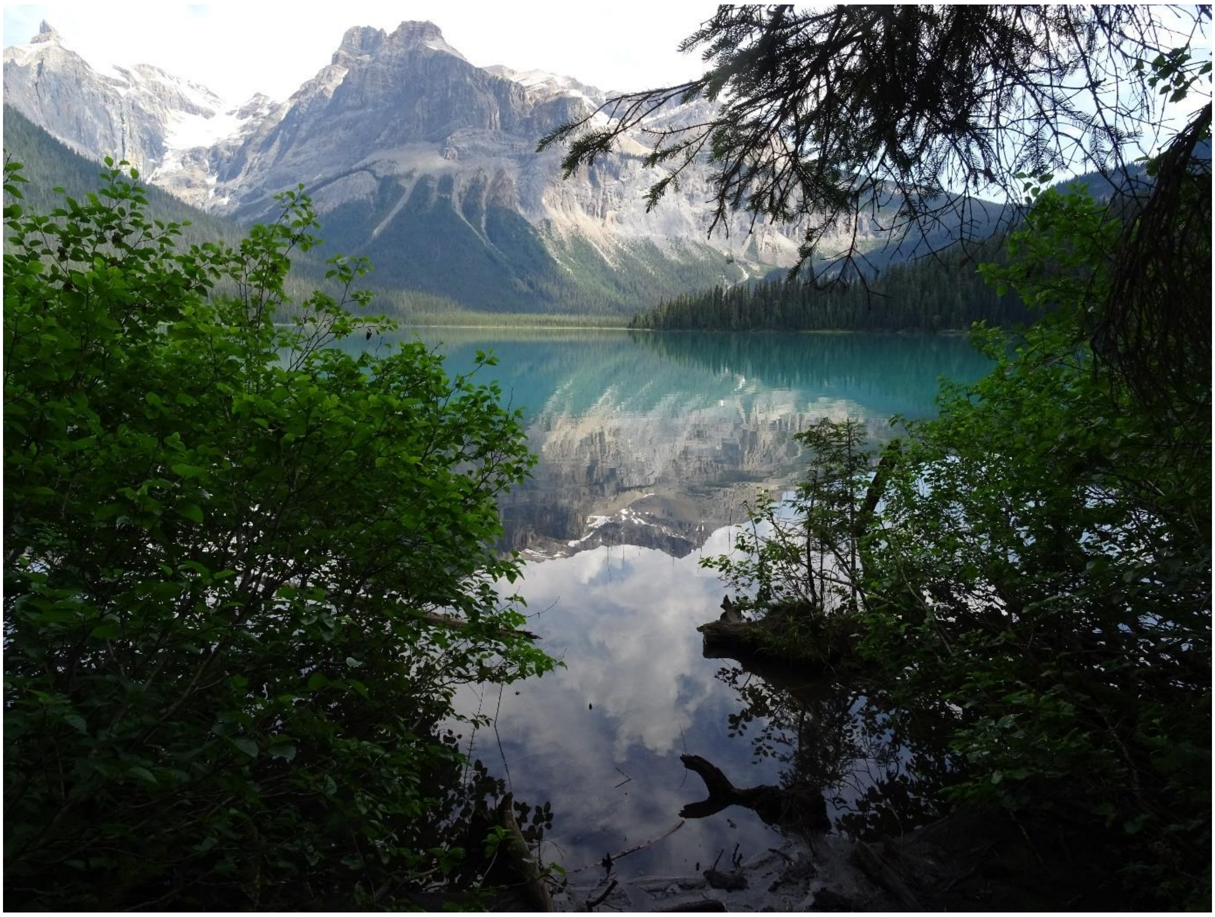
Main authors:

DI Sebastian Glaser, DI Philipp Feuchter, Dr. Rainer Pamminger, Dr. Adriana Díaz

Abstract:

This report reflects the results of the work: Energy and environmental related Life Cycle Assessment (LCA) of PECTA, the Power Electronic Conversion Technology Annex, during the period 2020 to 2023. It explores the energy and material aspects and environmental impacts of selected applications incorporating WBG technology. The report introduces the main guiding research questions, presents the methodology for the analysis, and discusses the results and key findings in three areas. The report concludes with thoughts about the next steps and the PECTA outlook for the next 5-year term.

The core of the methodology presented relies on the concept of "life cycle thinking," which encompasses the pathway of energy and resources from the extraction of raw materials to manufacture, along the distribution and use, until the EoL of devices and products. The work has been completed with inputs from industry and academia experts. This report also discusses the need for data, information, and indicators along the value chain, in light of the development of energy efficiency policies for the adoption of WBG technologies. The report also includes three publications (conference papers) released during the work, with the aim of broadly disseminating the PECTA work results. This report is meant to be a useful resource for practitioners of government officials in the development of energy efficiency policies and programs.



About the IEA 4E Power Electronic Conversion Technology Annex (PECTA):
Power electronic devices incorporating Wide Band Gap (WBG) technologies are maturing rapidly and offer enormous opportunities for improved energy efficiency. 4E´s PECTA assesses the efficiency benefit of utilizing the emerging WBG technology, keeps participating countries informed as markets for Wide Band Gap technologies and devices develop, and engages with research, government, and industry stakeholders worldwide to lay the basis for suitable policies in this area. Further information on PECTA is available at: https://pecta.iea-4e.org.

About the IEA Technology Collaboration Program on Energy Efficient End-Use Equipment (4E):
The Technology Collaboration Program on Energy Efficient End-Use Equipment (4E TCP) has been supporting governments to coordinate effective energy efficiency policies since 2008. Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.
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The main 4E collaborative research and development activities include the

- Electric Motor Systems Annex (EMSA)
- Solid State Lighting (SSL) Annex
- Electronic Devices and Networks Annex (EDNA)
- Power Electronic Conversion Technology Annex (PECTA)

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Executive Summary

Electronic products of our modern society rely on electronic conversion devices, which handle a wide range of power levels, from milliwatts to gigawatts. New Wide Band Gap (WBG) based power electronics technologies promise higher energy efficiency and faster switching with an overall smaller size of the components compared to conventional silicon-based ones. This is indeed advantageous from an efficiency perspective in the use phase, regardless of the benefits or disadvantages along other life cycle phases, e.g., manufacturing, distribution, and End-of-Life (EoL). This report investigates five different environmentally relevant aspects of this modern technology along the product's life cycle, looking at energy, GHG emissions, resource use, system design, and circularity. In addition, considerations for assessing these environmentally relevant aspects are discussed in terms of missing information and improvement opportunities.

The methodological approach of the research was mainly based on desk research and interviews with experts from academia and industry but also a case study was carried out. Insufficient environmental indicators in available databases, unspecific assessment methods and product information implied that assumptions and estimations were made, leading to uneven coverage and findings for the two investigated WBG technologies, Gallium Nitride (GaN) and Silicon Carbide (SiC). For the manufacturing process of SiC wafers an overall higher energy-demand by a factor of seven compared to the traditional Silicon based wafers was estimated. The yield of wafer processing was 15% lower, compared to the traditional technology, leading to an increased amount of production losses. The production of SiC is still not fully mature, but it is expected to be more efficient in the future. The higher energy efficiency in the use phase, and the smaller size of the SiC die can result in a lower energy profile and material savings due to size reductions of the system's components, e.g., up to 50% smaller components for cooling and up to 30% size reduction of the overall conversion system. These size reductions further lead to lower greenhouse gas (GHG) emissions in the production and use phase, but also in the distribution phase (e.g., shipping of WBG-based products to costumer).

The research on the EoL process shows that appropriate recycling and reuse practices for WBG technology are broadly missing, with some opportunities available at pilot scale. Missing product information that would facilitate material selection and recovery, and challenges of reliability for reuse of components are key factors hindering the circularity of these components. As the two main WBG materials investigated are rated as critical raw materials in Europe, e.g., Gallium has an import reliance of 98%, a circular approach is of high importance to reduce the risk of supply disruption in the European Union. A few legislative measures, e.g., CRM Act, ESPR and the EN4555x standards, are already in place or in draft state to help tackle these challenges.

These PECTA work results will be continuously used and expanded with the planned research in the next term of PECTA, looking more deeply at GHG and resource aspects of WBG technology.

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Insight 2	Methodology	PCRs for power electronics
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Abbreviations and units

AI	*Artificial Intelligence*
CAD	*Computer Aided Design*
CRM	*Critical Raw Material*
EEPS	*electronic and electrical products and systems*
EoL	*End-of-Life*
EPD	*Environmental Product Declaration*
ESPR	*Ecodesign For Sustainable Products Regulation*
EV	*Electric Vehicle*
GaN	*Gallium Nitride*
GHG	*Greenhouse Gas Emissions*
GWP	*Global Warming Potential*
HEMT	*High Electron Mobility Transistor*
IoT	*Internet Of Things*
kWh	*kilo Watt hours*
LCA	*Life Cycle Assessment*
LCC	*Life Cycle Costing*
MOSFET	*Metal-Oxide Semiconductor Field-Effect Transistor*
MW	*Megawatts*
PCB	*Printed Circuit Board*
PCR	*Product Category Rules*
PECTA	*Power Electronic Conversion Technology Annex*
PV	*Photovoltaic*
SBTs	*Science Based Targets*
Si	*Silicon*

SIA	*Semiconductor Industry Association*
SiC	*Silicon Carbide*
SMD	*Surface Mount Device*
WBG	*Wide Band Gap*
WEEE	*Waste from Electrical and Electronic Equipment*

Contents

1. Background

Semiconductors are essential components of electronic devices, which in turn are the building blocks in our modern, digitalized energy and communication systems, playing a significant role in the electrification process of many sectors such as transport and industry. In the age of computers, smartphones and smart appliances, demand for semiconductors continues to increase.

The Semiconductor Industry Association (SIA) indicated that the industry shipped a record 1.15 trillion semiconductor units in 2021. The dollar value of these units was $555.9 billion. The future might involve even more of the same. The age of artificial intelligence (AI) and smart manufacturing depends on simple semiconductors that enable cheap computing power [1].

Computers, mobile phones, refrigerators, washing machines, air conditioners, and other appliances around in the home and in office equipment operate thanks to semiconductors. As a result, semiconductor chips constantly evolve to respond to rising standards, mainly demanding instant, multifunctional, and durable services [2].

In the context of climate change and international commitments to reach significant reduction of greenhouse gas emissions (GHG), a 2022 insight article of McKinsey & Company indicated that some of the semiconductor industry's most important end customers, have committed to reaching net-zero emissions for their full value chain, and have set aggressive timelines for achieving their goals. Some semiconductor companies have also responded by setting their own GHG emissions goals. For instance, Infineon plans to reduce GHG emissions by 70% in 2025, compared with its 2019 baseline, and aspires to reach carbon neutrality for emissions directly under its control by the end of 2030. Intel recently committed to net-zero GHG emissions in its global operations by 2040 and has targeted achieving 100 percent use of renewable electricity as an interim milestone in 2030. Several semiconductor players have also committed to science-based targets (SBTs), including STMicroelectronics, NXP, and UMC. Over the next few months or years, more semiconductor companies are expected to commit to ambitious and actionable emissions targets [3].

From the side of most governments, it is imperative to take action to cut GHG emissions. The prospects of energy savings from using wide bandgap (WBG) semiconductors needs to be further explored. Recent estimates from PECTA showed that globally more than 130 TWh could be saved annually through the application of new WBG power conversion technology mainly for drives, but also for data centres, photovoltaics (PV), EV (EV)charge stations, laptop chargers and renewable energy generation, as shown in Figure 1. Considering, that PVs and EV charge stations are expended to massively expand in the next decades, up to 270 TWh for PVs and 33 TWh for EV charge stations could be saved annually.

Semiconductors incorporating WBG technology allow higher blocking voltages, faster switching speeds and increased operating temperatures, which enable smaller and lighter systems [4].

These are strong motivations in PECTA to assess the energy efficiency potential and impact of the use of WBG semiconductors and create awareness among policy makers of this technology. PECTA is conducting further detailed analysis on the potential energy savings for different applications and the respective readiness level, to highlight when policy intervention is most needed and propose specific policy options [4]. This PECTA work in particular aim to inform policy makers on ways to promote the integration of WBG technology into power electronic systems, within the framework of sustainable energy policies.

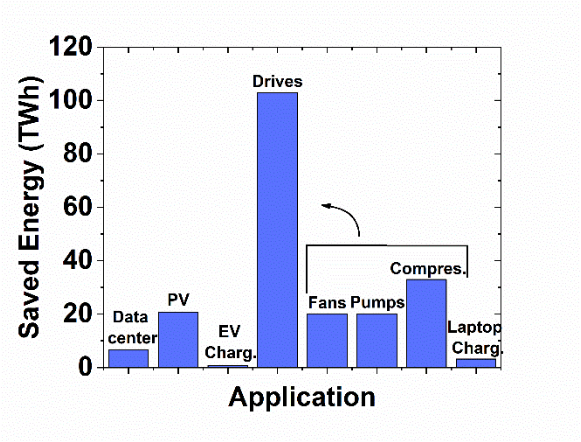

Figure 1: Large energy efficiency potential from incorporating WBG semiconductors in selected applications [5].

This report brings together the main results of research work conducted from October 2020 to October 2023, which included extensive literature and desk review of relevant sources, as well as the exchange of information with experts to whom the authors express their gratitude and appreciation, for their open collaboration spirit, and for their valuable contributions. The handling of all aspects of WBG semiconductors is, in light of its likely further expansion, an ongoing, changing, and dynamic challenge, therefore this report and the research work do not claim to be an ultimate compilation of all the information possibly available until today.

The report is presented as a structured documentation of the available but dispersed information, which has been extracted and summarized with the view to make it accessible and useful to the PECTA members and policy-makers as mentioned before. The following chapters in this report discuss the concept of PECTA (in Chapter2), and its main three areas of research and results (in Chapters 3, 4 and 5); followed by the conclusions and outlook in Chapter 6. Appendices and references are provided at the end of this report.

2. Overview of the PECTA work: “Energy and environmental related Life Cycle Assessment.”

In the first phase of PECTA from 2019 to 2020 [6], the estimations completed on the efficiency potential did not include the energy consumption for the production of the WBG devices or the disposal of these semiconductor devices, and their materials (Si, SiC, GaN) as well as the passive, and cooling materials.

Other impacts of WBG to the environment, focusing on GaN and SiC, were not yet fully investigated in comparison to the use of classic Si based technology for the same applications. Additionally, the effects of using WBG devices on the entire system design were neither put in focus nor compared to the impacts of semiconductor production. These trade-offs needed to be evaluated, and these were areas of interest for the PECTA work “Energy and environmental related Life Cycle Assessment (LCA).”

The idea of this PECTA work was not to start conducting full LCAs, which would demand extensive resources from PECTA. Instead, the Task experts follow an approach based on Life Cycle Thinking, to compile the available literature information and data from already completed LCAs, to structure this information to answer key questions on the new WBG based technologies. The work focused on SiC and GaN semiconductors, aiming at completing reliable and robust analysis of their environmental aspects and impacts, exploring the trade-offs along their life cycle, and with respect to the classic Si based technology for power conversion. In some cases, selected streamlined life cycle assessments were completed, as discussed in the following chapters. Life cycle in this context refers to the stages in a product´s life, from the extraction of raw materials to the production, its distribution, use and EoL, as shown in Figure 2.

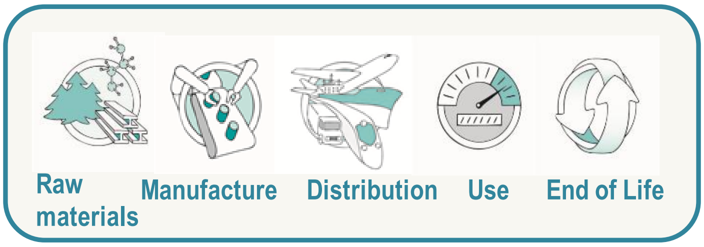

Figure 2: Stages of the life cycle of a product [own illustration].

The three principal areas cover first the production (manufacture) of WBG (Area 1). While the potential for energy efficiency gains is widely researched, the relation to the energy use during manufacturing processes remains insufficiently studied. This aspect is relevant for SiC semiconductors, as there are differences in their production processes compared to Silicon semiconductors. The work was structured along the life cycle stages that are most important in terms of their energy inputs, and the stages where significant differences exist between Si and SiC technologies.

The research regarding the WBG application, namely the use of WBG power semiconductors in products is closely related to the effects in product design and product performance (Area 2). In order to study this, the system boundaries were extended accordingly and the applications, their production, transport, and use were analyzed. In addition, the effects on the product design were quantified, and the associated environmental impacts were assessed on the basis of a selected environmental impact indicator (Global Warming Potential - GWP) and discussed along the life cycle stages up to the use.

Finally, the End-of-Life (EoL) of the WBG semiconductor devices and materials were investigated, concerning resources use, availability of critical materials and potential for recycling and reuse activities (Area 3).

These three areas were the priority in the working period of this PECTA work (2021 to 2023).

The concepts and results from Areas 1, 2 and 3 are presented in the following chapters, including specific insights aligned to on or more of the following 6 key aspects: Energy, GHG emissions, Resource use, Circularity, Methodology and Design. These aspects are explained as follows:

Energy	The generation of energy always has an impact on the environment and consumes resources. It is therefore important to take a closer look at energy consumption as a relevant environmental aspect. Energy is required along the stages of the life cycle of (WBG) power electronic semiconductors, from the manufacture to the EoL. As any kind of electrical power conversion involves losses, an additional "own" energy demand is also present in WBG applications.
GHG emissions	GHG emissions contribute to the environmental impact category Global Warming Potential (GWP). GHG emissions occur along the life cycle stages of products, and this is why they are analyzed to the possible level of detail for the case of WBG power semiconductors.
Resources use	WBG power semiconductors, but also electronic components and appliances in general, contain resources, either embedded directly, consumed during in the manufacturing processes or along the other life cycle stages. Resources might regarded as critical due to their material scarcity and/or supply risks due to political-economic (in)stability.
Circularity	One meaning of circularity is *the* fact of constantly returning to the same point or situation. In this report it means keeping the value of processed resources in products longer, and enabling their recovery, reuse or recycling as recommended strategies to lower the environmental impacts of products. These strategies for "closing the loop" at the level of materials or products are studied as contributing to "circularity". The challenge is however realizing such closed loops, for which the relevant factors are the technologies available, the product design, a (suitable) legal framework, and the business models that make circular models economically viable in the first place.
Methodology	Suitable environmental assessments require an agreed methodology to evaluate the environmental performance, but also datasets with specific environmental information, and robust product information (e.g., bill of materials, content declarations, and detailed product specifications). The environmental assessment of new, emerging technologies such as WBG is extremely difficult to carry out, because these three components: methodology, datasets and product information are not readily available, or are not fully accesible due to other reasons (e.g., internal company proprietary information on products).

Design	Design is the way in which products are planned and made. Therefore the design choices are relevant from an energy and resource use perspective. Early decisions in the design process greatly influence the resulting environmental impacts of the product. Moreover, the features of components (e.g., size, thickness) are likely to influence other components, and/or on the overall system design. This is why it is important to also look holistically at the design choices and their effects along the life cycle.

3. Overview of and insights from the manufacture of WBG devices

3.1. Overview

The environmental impact of semiconductors along their life cycle is complex, as semiconductors can be incorporated into thousands of products. In this work, which we call Area 1, we focused on the manufacturing of the product that shall fulfil specific functions over a period of time. The performance of many electronic components and products, might not be seen in isolation, but embedded into a "system." The research covered the following questions:

- How energy intensive are the current manufacturing steps required to produce selected WBG devices?
- How do the typical production steps for Si based devices compare with the production of WBG devices?
- How is the relationship or the proportion of the energy involved in manufacturing of WBG and Si based semiconductors (one-time activity), to the energy in the use phase (recurrent activity)?

As shown in the example in Figure 3, the manufacturing processes are followed by the integration into specific products, and the use of such applications. In Area 1 the distribution and EoL stages were not considered, as these are covered in other Areas this PECTA work.

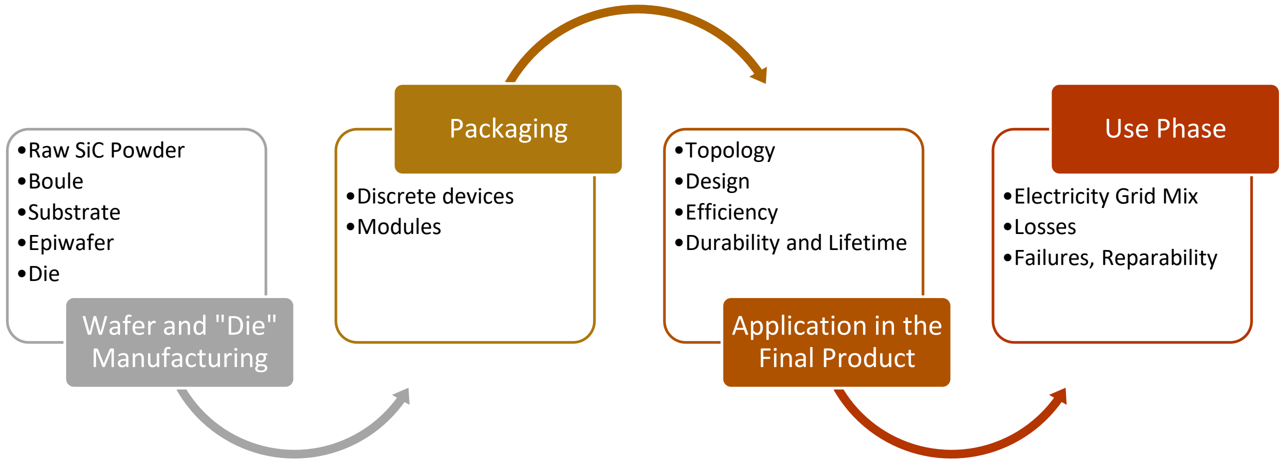

Figure 3: Overview of the life cycle stages of manufacturing and use for SiC power semiconductors [own illustration].

This task involved conducting extensive desk research and literature review, interviewing selected experts, and consolidating information and data analysis in a technical model of the energy demands for manufacturing for selected conditions and applications.

The details on the methodology and the discussion of results are documented in a first paper [7], which was presented at the e·nova 2022 conference and published on the PECTA website. This paper is included in **Appendix 1**. The important contributions or insights of Area 1 are discussed in the following section, with reference to the paper and with additional analysis prepared for this final report.

3.2. Insights from Area 1

We considered environmental aspects and impacts related to materials (SiC, GaN and Si) and their production, but especially we focused on gaining insights on the energy related aspects. As this work was the first to be launched, we also gained insights on the methodologies available for evaluating the environmental aspects and impacts of power semiconductors, which are explained first in this section.

3.2.1. Insights on the methodology to evaluate environmental impacts

Insight 1: Despite the considerable interest and efforts over the past decades to adopt life cycle assessment (LCA) as a methodology to help decision-makers better understand the environmental aspects and impacts of products and services, the publicly available and detailed LCAs for semiconductors in general are not abundant, and those LCAs available were performed over a decade ago. The need of more up to date LCAs has not only been recognized by PECTA experts, but also by other researchers who begin to publish more up to date LCAs (some of which were not yet available at the time investigation or were not fully applicable for WBG technologies). The paper in **Appendix 1** includes some of the well known LCA references for power electronics.

Insight 2: The stronger development of WBG semiconductors has not triggered a simultaneous development of product category rules (PCR) for conducting LCAs of WBG semiconductors, and as such both, LCAs and Product Environmental Declarations (EPDs) for semiconductors are practically missing.

As the name says, Product Category Rules (PCR) set the requirements to follow and comply with when evaluating certain type of product by means of a LCA according to ISO 14040/ISO 14044 [8]. The PCR defines the system boundaries, the data requirements, the methodology and indicators to report and to be declared, e.g., in Environmental Product Declaration (EPD) according to ISO 14025 [9]. Usually, the PCRs are developed in a participatory stakeholder engagement process [10][1], with experts from e.g., companies, industry/trade associations, and practitioners, similar to the development of other national and international standards.

In the absence of specific PCRs for (WBG) semiconductors, the practitioners like us in, rely on the ISO 14044 as framework to conduct an LCA. This ISO standard is broad enough for conducting LCAs of many different types of products, which is in principle positive, but leaves room for making approximations and assumptions that could limit the use and validity of results.

Insight 3: A more detailed definition of the specific and unique variables that determine the environmental impacts of the semiconductors, including those incorporating WBG, is needed. At this time, the International EPD system®, a known program for releasing Environmental Product Declarations [11][2], indicates that a PCR for Electronic and electric equipment and electronic components (non-construction) is being developed, and the preliminary publication is set for December 2023 [12].

This document will provide Product Category Rules (PCR) for the assessment of the environmental performance of electronic and electric equipment, and electronic components (non-construction), and the

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[1] Ideally such as process also follows specific requirements, such as those set in ISO 14027:2017 Environmental labels and declarations - Development of product category rules.

[2] The International EPD System is the world's first and longest operational EPD program, originally founded in 1998 as the Swedish EPD System by the Swedish Environmental Protection Agency (SEPA) and industry. Third-party verified EPDs based on ISO 14025 and EN 15804 are published against a commercial fee. In addition, supplemental environmental communication services are provided.

declaration of this performance by an EPD. The product category corresponds to UN CPC divisions 43-48, 84 [13] and HS codes - category 85 - Electrical machinery and equipment and parts thereof [14].

In the non-exhaustive list of products under the scope of this PCR, electric vehicle conductive charging, and power electronic converter systems and equipment are included, as well as electric accumulators, audio, video and IT products, electrical appliances for household and similar purposes, electricity metering equipment, low-voltage switch gear and control gear assemblies, and servers. Parts and accessories of computing machines (e.g., laser printer cartridges) are currently in the scope of the 2014 “Parts and accessories of computing machines”. After expiration of this PCR, computing products will also be covered by the new PCR [12].

Additionally, the International Electrotechnical Commission (IEC), who do not operate an EPD platform, developed a standard (IEC 63366) which defines PCR rules for performing a LCA of electrical and electronic products and systems (EEPS) in the context of environmental declarations. The standard IEC 63366 is currently in draft status and is expected to be approved by March 2024 [15].

Insight 4: This first step towards an “accepted and acceptable” standard (a PCR in this case) is taking a horizontal approach, to set the requirements in one main PCR, for conducting LCAs and preparing EPDs for a wide variety of end-use electronic products but also electronic components. Any electronic and electric equipment that classifies as construction product is excluded from the scope of this PCR, and more specific requirements might be set by complementary PCRs (c-PCRs), allowing EPDs based on functional units [11]. This broad scope of products poses challenges in the evaluation of life cycle stages, but also because electronic elements that are integrated into different final applications might need to be assessed differently along all life cycle stages. Likewise, for the large variety of end-use products covered, detailed information and plausible scenarios might need to be clearly defined and justified in the LCA, especially if a comparative assertion between products is intended.

3.2.2. Insights on energy related aspects of WBG manufacture

Insight 5: The comparison of the energy demand for the WBG and Si semiconductors manufacture, including the corresponding Front-end wafer production, Front-end wafer processing and Back-end packaging was done taking as reference the production of 6” wafers. From this analysis the main, interrelated variables which play an important role influencing the energy demand are the boule growth, the process yield and die size ratio.

Insight 6: Growing the SiC boule is an energy intensive process of the front-end wafer production. Current reliable data on energy demand for the fabrication of the Si ingot was not readily available. With inputs from industry experts, it was estimated that the energy demand for growing SiC boules is 20 to 40 times higher per usable wafer area than for growing Si ingots.

Regarding the cutting of the Si ingot and the SiC boule into wafers, more energy per usable wafer area (referring to a 6” wafer) is also needed in the case of a SiC wafer, with an estimated ratio of 1[Si]:7,22[SiC]. Compared to Si ingots, SiC boules are much harder to cut, and there are significant “kerf losses” in this energy intensive cutting process. Also, the smaller diameters of the SiC wafer and a smaller usable height (thickness) compared to Si contribute to higher energy demand for the same usable wafer area considered.

Insight 7: SiC wafer processing steps are very similar to Si wafer processing steps. However, one important difference is the processing yield, which is still lower for SiC wafers (due to crystal defects or process errors) than for the more established Si wafer Front-end processing. The expert estimation for the overall front-end yield is 75% for SiC, and 90% for Si.

Insight 8: Energy intensity and efficiency in the use of material (yield) in the production of the conventional Si and the SiC technologies showed differences. The losses have an influence on the energy “burden” for producing a die, notably the material losses for the growth of the SiC boule, the kerf losses from wafer cutting, and the processing losses due to faulty dies. As the manufacturing technology for SiC matures, it is expected that these losses will be reduced, the “energy profile” of manufacturing WBG power semiconductors will improve and new production technologies are arriving.

Insight 9: Higher energy consumption in power semiconductor production can be compensated during use phase. We studied the application in photovoltaic inverters: PV inverters already have a very high efficiency; so an improvement through the use of WBG technology only achieves small efficiency increases of about 2% [6]. Calculated over the long service life of about 20 years, 20000 kWh/ year, and 400000 kWh over its entire life are saved for the case of a 1MW PV installation.

Moving from the manufacture to the design of applications using WBG technology, the next chapter focuses on Area 2, where the effects on the product design, and the associated environmental impacts are discussed.

4. Overview of and insights from Area 2, Design Aspects and Environmental Impacts

4.1. Overview

The research in Area 2 focuses on WBG power semiconductor application, in particular on chargers for electronic devices (notebooks and cell phones), which have been selected as a case study and are show in Figure 4.

Design aspects were investigated, also regarding the overall performance - the effects of incorporating GaN components for energy conversion on the product design, and the resulting environmental impacts along the life cycle of the chargers.

Relevant questions addressed in Area 2 were:

- What is the impact on product design through the use of WBG power semiconductors?
- What is the influence of WBG technology on the product's different life cycle stages in terms of (selected) environmental impacts?
- Which life cycle stages are relevant in terms of (selected) environmental impacts, i.e., contribute significantly to the overall result?
- How does the use of WBG power semiconductors shift this relevance?
- Can the use of WBG technology achieve a significant reduction of (selected) overall environmental impacts?


[redacted]

Figure 4: Laptop chargers investigated, on the left a 60W Si-based charger (reference), and on the right a 60W GaN-based charger [16]

To answer these questions, the authors contacted experts from academia and industry to discuss the effects of WBG on the product design level. A functional structure of a power converter was used to describe the impact of using GaN transistors. A streamlined Life Cycle Assessment (selected environmental impact indicator Global Warming Potential, GWP) was completed for a conventional 60W Si-based laptop charger (reference product), and a 60W GaN-based laptop charger. The inventory data were obtained from product teardowns (bill of materials) and power measurements carried out in another PECTA work, recently presented in a paper at the EPE 2023 Conference [17]. Selected results of the streamlined LCA were published in two papers [16, 18], which are included in **Appendix 2** and **Appendix 3**. The second [16] was presented at the 2023 CARE Conference.

4.2. Insight from Area 2

The focus has been expanded from the manufacturing of the semiconductor devices to the subsequent phases, such as the production of a product that uses WBG technology, and also the distribution and use phase of the product. Insights were gained through a broader perspective on the more complete life cycle. What is the impact on product design? What is the influence of WBG technology on the different life cycle phases? Which phases are relevant in terms of (selected) environmental impacts? How does the use of WBG power semiconductors shift this relevance?

4.2.1. Insights on energy related aspects of manufacturing of WBG applications

Insight 10: The electrical and physical properties of WBG materials result in lower wafer area per chip for the same functionality, i.e., the energy (and the environmental impact) in manufacturing becomes lower per chip, see Table 1.

Table 1: Estimated Die size reduction for SiC and GaN according to different sources [own adaption].

WBG technology	Die size reduction
SiC - MOSFET	about 50% [6] about 56% [19] up to 77% [20]
GaN - HEMT	about 58% [20]

4.2.1.Insights on design aspects of applications incorporating WBG power semiconductor.

With WBG power semiconductors, a higher switching frequency can be realized within the topology of the charger, which, very simplified, leads to smaller components. But even without an increase in the switching frequency, the application of WBG power semiconductors can lead to a more optimal design.

A functional structure of a power converter was chosen as the basis to present the impact of adopting WBG on the design. This functional structure serves to describe all kind of power converters (regardless of their topology or applied semiconductor technology). This structure is appropriate to discuss the results from desk research and to analyse the design of a 60W laptop charger – the selected case study in Area 2. Results from desk research, from expert interviews and the laptop chargers are shown in Table 2.

Table 2: Estimated effect from WBG on the design of Si and GaN laptop chargers studied [own adaption].

Function block [21]	Effect on the design	Estimated change in size [22]	Relative weight contribution in laptop chargers [in %, otherwise absolute in g]
Input filter	The power electronic filters can be smaller due to smaller passive components as a higher switching frequency can be chosen in the WBG applications design but can also increase in size due to more EMI noise.	+10% up to -50%	• In the Si Reference charger: 3,5% • In the WBG charger: 6,4%
Power processing unit	E.g., the size of a transformer (selected case study are flyback converter) is influenced by the switching frequency, in theory by the factor 1/f.	up to -20% (core)	• In the Si Reference charger: 29,40% • In the WBG charger: 29,50% (Both chargers have almost the same switching frequency.)
Energy buffer	According to experts, the use of WBG power semiconductor should not have a significant impact on the energy buffer [22].	No impact	• In the Si Reference charger: 6,8% • In the WBG charger: 8,2%
Cooling system	The size is related to the efficiency of the device, the more energy is lost during energy conversion, the larger the heat sink must be to dissipate the heat.	up to -50%	• In the Si Reference charger: TO-220 housing, and conventional Aluminium heatsink: 19,60g • In the WBG charger WBG charger with a GaN chip: SMD housing and a steel plate heatsink. EMC shielding: 8,15g
Output filter	Same effects as for the input filter, discussed above.	up to -50%	• In the Si Reference charger: 1,8% • In the WBG charger: 0,3% (USB-C’s output filter)
Remaining blocks	e.g., fuses, or controller are not affected	No impact	-
Overall design	Significant size reductions can be achieved.	up to -30%	• Si Reference charger: 171,4g, without socket and USB-C cable • WBG charger: 153,1g

Insight 11: Effects on the design of a product through the application of WBG power semiconductors are very difficult to predict accurately and systematically for a broad spectrum of power converters. In general, it seems that for the chargers a size reduction is indeed achieved by increasing the switching frequency (see Table 2), but beyond size reduction, other design goals that can be achieved through the application of WBG technology can be manifold. In order to assess whether the use of WBG technology is preferable from an environmental point of view, the product must be considered along its entire life cycle, to include advantages and disadvantages caused through WBG effected product designs.

4.2.1.Insights on GHG emissions of use of WBG applications

After the manufacture of the WBG power semiconductors, there are further life cycle stages in which the products cause environmental impacts, and which are possibly influenced by the use of WBG technology. These are:

- Application, namely the manufacturing of products in which WBG technology is used
- Distribution of such products
- Use of such products

GHG emissions in the production phase

Insight 12: A smaller required chip area proportionally reduces the material consumption and the environmental impact of the chips in production (without chip packaging). In a recent industry study, GWP values for a Si IGBT Module of 26,4kg CO2-eq, and 11 kg CO2-eq for a SiC MOSFET Module [23] were reported, which point out to the effect previously assumed.

GHG emissions through WBG application

According to industry, around 30% reduction of GHG emissions can be achieved in the material- and manufacturing stages of a 60W charger with WBG technology [24]. The analysed case study though did not show such a significant difference (4,33 kg CO_2-eq for the WBG charger and 4,43kg CO_2-eq for the Si Reference charger).

Insight 13: The effect on the design and the associated GWP savings are difficult to generalize, as these are strongly related to the topology selected and the implementation of such topology, and comparison between individual products are difficult to be made.

GHG emissions in the distribution phase

Insight 14: A reduction in the weight of the charger, for example by increasing the power density through the use of WBG technology, can reduce the environmental impact (e.g., GHG emissions) in the distribution phase. The lighter weight is even more relevant the longer the distances these devices (with WBG technology) are transported.

GHG emissions in the use phase

Insight 15: The more energy is processed by the power converter during the total lifetime of the application, the more absolute losses occur. A significant increase in energy efficiency through the use of WBG technology, especially for intensive energy using products, brings the greatest leverage and enables the improvement from the perspective of lower environmental impacts. For the 60W WBG charger studied, the Global Warming impact in the use phase becomes dominant at around 2300 charging cycles, for a scenario of operation with the electricity mix of Austria. In the case of scenario of use with the Chinese electricity mix, the GHG emissions in the use phase are dominant already at 700 charging cycles.

Insight 16: If a significant improvement in efficiency is no longer possible, or it is only through the use of numerous additional components in the design, it is important to carefully consider whether such an improvement does not turn out to be disadvantageous over the entire life cycle.

Since it is not only energy and greenhouse gas emissions that have an impact on the environment, the next chapter takes a closer look at where the materials for WBG technology come from and what happens after a WBG device is used.

5. Overview of and insights from WBG resources and End-of-Life perspectives

5.1. Overview

In addition to the aspects of energy and greenhouse gas emissions associated with WBG technology and applications, there are two other aspects that were investigated in the work we called Area 3. First, the use of critical raw materials in this new type of power electronics and second, the End-of-Life (EoL) of WBG power electronics. The results are summarized in a published paper [18], which was presented at the EPE conference in 2023. The paper is included in **Appendix 3**.

Critical raw materials are materials that face a specific economic importance and are at risk of a supply disruption. Depending on the field of application (e.g., batteries, fuel cells, motors, power generators) and on the origin country or region of the major supplies, a material can become critical. [25]

At the end of a product's life, there are different opportunities for further processing its materials. These can be disposed of, incinerated, recycled, or reused (repaired, refurbished, remanufactured). Ideally the design of a product but also the conditions and infrastructure at the EoL are fit for closing the loop of the materials (Circularity), avoiding their value getting dispersed or lost.

The research in Area 3 focused on answering the following questions:

- Are WBG materials critical for the EU?
- What are the typical EoL treatment routes and opportunities to close the loop for materials in WBG technologies?
- What are (main) regulatory aspects of electronic containing WBG concerning their criticality and waste treatment?
- What are the relevant information policymakers shall be aware of?

5.2. Insights from Area 3

5.2.1. Insights on resource use aspects of WBG

Insight 17: The primary materials in SiC and GaN, namely Silicon metal and Gallium respectively are both rated as critical by the European commission [25].

Only a minority of the abundant Silicon reserves is pure enough to be economically further purified to metallurgical or electronical grade Silicon. As the purification process is an energy intensive process, Silicon metal is mainly produced in countries where the material supply is pure enough, and there is access to cheap energy (e.g., coal-based energy in China or hydropower energy in Norway) [25].

The EU would have Silicon reserves with the necessary purity [26], but still relies on imports from non-EU countries, mainly Norway, Brazil and Russia, for around 74% of the Silicon metal supply. For the global supply of Silicon metal, China dominates 76% of the market [27]. Additionally, China has an unused production overcapacity, to produce more than twice of the current global demand, which puts the market under pressure [28]. The demand of Silicon metal is forecasted to grow 2-fold until 2050 from today's demand, with Silicon metal mainly being used for the Aluminium and chemical industries, photovoltaic, and electronic sectors.

Gallium is currently produced as a by-product of the Aluminium and Zinc production. Only 5 to 7% of the available Gallium potential in the Bauxite ores is used further to refine Gallium, the rest ends up in the red mud[3]. For Gallium, the reserves are abundant enough to cover the demand of the next decades. However, no documented reserves and no production exist in the EU, as the last refining factory closed in 2016 [29]. The import reliance on Gallium counts for 97% in the EU, mainly coming from China, USA, and Ukraine. China dominates 94% of the global Gallium market. The demand for Gallium is forecasted to grow 17-fold until 2050 from today's demand , and Gallium is mainly being used in photovoltaics, lighting and integrated circuits [30, 31].

<u>Insight 18:</u> Unless the demand of Gallium or Silicon is consistent, or decreasing, a full substitution with secondary raw material is rather difficult, even if a recycling rate of 100% would be achieved, as depicted in Figure 5 (In practice, recycling would never be 100% efficient, due to collection and sorting losses, but also due to thermodynamic barriers). In addition, the materials that are used today, might only be available years later as secondary raw material, as they are in use for a given time. The use time depends for instance on the type of product, and on it is reusability. Even if the demand would be consistent, it could not be met with secondary raw material for the first years, until a consistent supply from EoL materials is also available.

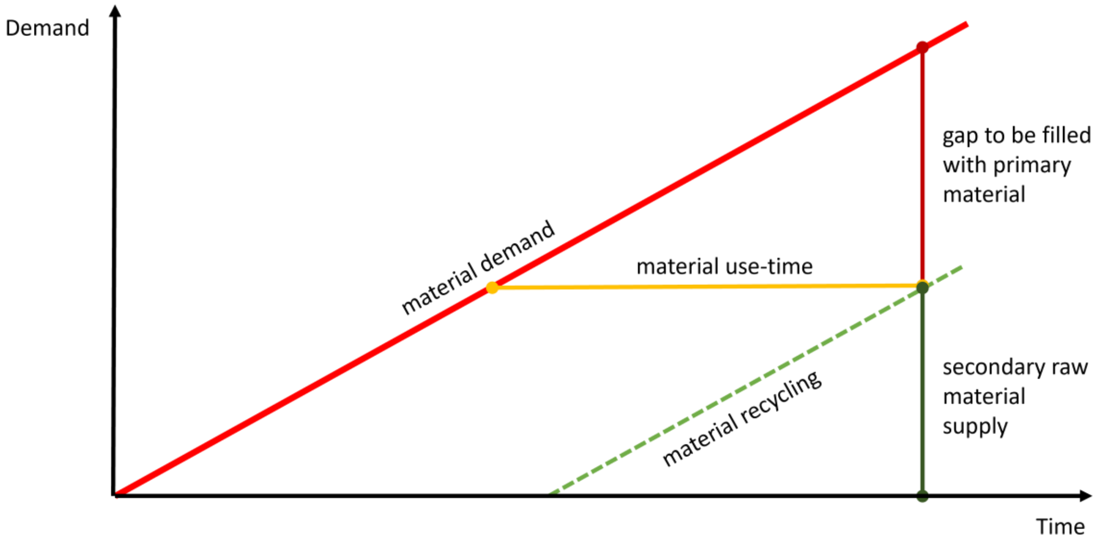

Figure 5: Demand/Recycling issue [own illustration]

<u>Insight 19:</u> For Gallium that is used in integrated circuits no substitution is available that provides the same or a better performance. Silicon and Germanium can be used for a limited number of application but with a lower performance level. For lighting application, organic light emitting diodes (OLED) can be used as an equivalent, but their price is more than twice that of Gallium based light applications. For Silicon metal no substitutions are known that can be used without serious loss of performance, or increase of cost [27, 30].

<u>Insight 20:</u> Early 2023 the EU presented a regulation, called "Critical Raw Materials (CRM) Act", which aims to strengthen the supply chain of critical raw materials. The EU has set measures to reduce the dependency on CRMs, by asking for at least 10% of strategic raw materials[4] to be sourced in the EU, at least 40% to be processed in the EU, at least 15% to be recycled in the EU, and a maximum of 65% of a strategic raw material supplied by only one country. Beside those targets, the EU will support CRM concerning projects (e.g., CRM explorations, approval of new mines, recycling of CRMs), and will focus on building-up a more resilient network of CRM suppliers [31].

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[3] Hazardous residual of Aluminium production

[4] Selection of CRMs that are strategically important for the EU, including Gallium and Silicon metal.

With the EU regulation called “Chips Act” the EU also sets measures to reduce the dependency on non-EU countries for semiconductors, by improving the knowledge and production capacities for microchips within the EU [32].

5.2.1. Insights on circularity aspects of WBG

<u>Insight 21:</u> In the EU the WEEE collection rate counts for only 46%, globally this rate only counts for 17% [33]. This means that more than half of the electronic waste is not properly collected nor recycled or reused. The not collected products are probably exported illegally to other countries (Numerous reports from electronic waste dumps in countries in Africa are available, [34]), and there are treated under conditions harmful to the environment and to people, e.g., through rudimentary incineration in open spaces, to recover copper, gold, and other precious metals.

In the EU, the collected WEEE generally enter a mechanical separation and sorting facility, to separate the removable parts (e.g., batteries, housing, cables). Afterwards, the remaining materials are shredded and sorted into fractions of base and precious metals (e.g., Steel, Aluminium, Copper) and polymers. For base and precious metals are treated in pyrometallurgical and hydrometallurgical recycling processes, while polymers are generally incinerated.

<u>Insight 22:</u> For technology materials such as GaN and SiC, no industrial recycling stream exists that recovers these materials at commercial scale. The Printed Circuit Boards (PCBs) that might contain GaN and SiC are commonly sent to pyrometallurgical processes to recover the Copper, but the other technology metals usually end-up as slags, dusts, or as impurities in the recovered metal, unless they occur in large quantities and an established sub-process is available for their specific recovery.

The separation of technology metals from other parts of the product might need a lot of effort which is not always profitable. Materials like Gold, Silver, and Palladium might be favoured for recovery over technology metals that are used in small amounts and/or do not have a high economic value. Therefore, there is a conflict between recycling of critical materials and recycling of the most profitable materials. This leads to products in recycling streams targeted for their most valuable materials. Also, as some economically valuable materials are recovered in different but dedicated recycling routes, that technically do not allow the recovery of other materials. A full recycling of all materials is practically impossible, especially if some of the targeted materials are not separated in advance to the recycling processes.

<u>Insight 23:</u> No methods exist so far for recycling old scrap[5] to recover SiC. There are few technologies to recycle the from kerf-losses from the SiC wafer production process. This industrial waste is of higher SiC concentration and purity compared to old scrap [35, 36]. In the case that old scrap containing SiC would be recycled, it would need to be concentrated to a higher content, and any impurities would need to be removed, which would again demand energy, and this could then reduce the economic viability of such process.

Hydrometallurgical technologies exist at pilot scale to recover GaN. According to [37], recycling of old scrap containing GaN is already done in China at a large scale. Moreover, the recycling of Gallium from GaN containing LED waste could be economically and technically feasible through leaching processes [38]. Whether the use of acids for the leaching process could lead to other environmental impacts and health issues would need further investigation.

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[5] Old scrap is scrap that comes from products which have been already in use and have reached their EoL.

Insight 24: A promising process for the homogenization and concentration of technology metals such as Gallium from WEEE, was recently developed by Fraunhofer UMSICHT. This technology called iCycle® would enable an economically feasible recycling [39].

Insight 25: According to PECTA experts [19], the WBG components are currently not built for a second use. Depending on their application they last as long as they should. A challenge in this regard is the reliability of power electronics, as further discussed in Insight 29. To realize the implementation of circularity in power electronics one approach could be to develop a three-dimensional (3D) schematic design, that also includes assembly considerations on a super-system, system, and sub-system level. Currently one dimensional (1D) schematic designs are the most common, but this leads to a dimensional incompatibility of circular design criteria [40].

As smaller die sizes can be realized with WBG technology, for a given design size the available space could be taken to add easily dismountable connections, e.g., screws or plug-in connectors, that usually need more space than a glued or soldered connection.

To reuse power electronic components it is beneficial to know the *residual functional value* of the components as described in [41]. According to the calculated residual functional value, which considers the environmental footprint of the component, the remaining lifetime of the component, and the environmental burden for the reuse processes, it can be estimated if a reuse of the component is meaningful from an environmental point of view, or not.

Insight 26: A challenge regarding the recycling process might be the trend towards a more integrated design of PCBs with embedded semiconductors. Embedded semiconductors are more difficult or even impossible to separate from other materials, and this makes a homogenization and concentration of these materials even more difficult. It is not evident that the more integrated designs would also involve more durable component which could be used for a longer time, and/or be reused. This needs further investigation.

Insight 27: Since a few years, the sustainability topic also is in the agenda of some companies of the power electronic sector. Some companies already developed a circularity framework as part of their science-based target (SBTs) strategy, and includes the three main aspects of *rethink, reduce, and recirculate*. At the beginning of such sustainability journeys companies also need to create partnerships for circular products with suppliers and other stakeholders. Examining in more detail such examples would be beneficial to study strategies and impacts in terms of closing the loop of critical materials [42].

Insight 28: A barrier in the adoption of WBG materials is still their reliability, especially for the case that components and devices incorporating WBG would be designed for reuse. Usually reliability tests for semiconductors? are performed at much higher temperatures than normal operational temperatures, to accelerate the aging process and reduce the testing time, because testing under real conditions would take weeks or years. Still, these testing conditions could trigger failure mechanisms that are not necessarily matching real life situations. The challenge is finding appropriate testing methods that are feasible to implements and fit for purpose. One important aspect would be to better understand the degradation processes that occur before failure mechanisms. Currently there is a knowledge gap in this field [43]. Modern technology, like the Internet of Things (IoT), Artificial Intelligence (AI), CAD software with reliability plug-ins, as well as offline and online logging systems could be used to understand and predict failure mechanisms, and to guarantee reliability of WBG products in the future. A working group in JEDEC is working on developing reliability test standards for WBG (Sic and GaN) semiconductors [44].

Insight 29: The European standard series EN 4555x gives a framework on how to assess the durability of energy related products, and the ability of energy related products to be remanufactured, repaired, reused, upgraded, recycled, and recovered [45]. Also, a method to calculate and declare the amount of reused and recycled material and critical raw material in energy related products is included. Additionally, these standards define to whom, how and in which grade information on these aspects should be delivered. This basic framework is a solid base, but these standards may need to be further refined for the case of WBG applications, to define more closely the criteria, which are rather broadly defined and possibly too general at this time.

Insight 30: The new EU Ecodesign for Sustainable Products Regulation (ESPR), which focuses on electronic products, but also much broader on products like vehicles or other industrial products, enters into force in 2025, and will replace the current EU Ecodesign Directive [46]. Other than the Ecodesign Directive, the ESPR looks beyond the product's energy efficiency, to optimize the product's circularity and transparency of used materials. Specific measures will be defined for each product group under the scope of the regulation. As the ESPR also regulates subcomponents, power electronics could be regulated specifically other to electronics in general.

A digital product passport is also planned as one measure of the new ESPR, which aims for a more detailed and easily accessible product information and transparency i.e., providing information on materials content, recycled content, recyclability, and the Carbon footprint. The EN 4555x standards will help to define the framework for this product passport. It is expected that this regulation will move companies to re-designing their products towards sustainability soon [47].

Insight 31: The different EoL routes involve different impacts and magnitudes, associated to the energy demand, GHG emissions, toxicity, and wastes generated. In terms of the WBG components, it is also important to consider the reverse logistics associated to these EoL routes, the final WBG materials available and the remaining product value.

Table 3 presents a qualitative assessment and comparison of the EoL routes for WBG components. The red coloured fields stand for disadvantageous; orange stands for semi-disadvantageous and green stands for advantageous, compared to the other technologies.

Medium in this context means for example that the energy demand for the Reuse process is estimated to be higher than for the "low" graded incineration process, due to more complex collecting, sorting, repairing, and testing operations required for preparing a product for reuse. If a field is rated as "high," it means that it is comparably higher than for other EoL processes. For example, the remaining product value after the reuse process is estimated to be higher than the remaining product value after a recycling process. Complex reverse logistics need more rigorous separation and collection systems, and a more complex supply chain than semi-complex or easy reverse logistics. A WBG material will be lost in incineration processes or in the WEEE recycling, but it could be returned if recycled in a specific WBG, or if it would be reused.

Table 3: Qualitative comparison EoL process for WBG components in terms of selected aspects [own adaptation].

EoL process	Likely involved processes (according to state of the art)	Energy demand	Process toxicity	WBG material	GHG emissions	Generation of waste	Remaining product value	Reverse logistics
Recycling of WEEE with WBG	Collection Crushing Sorting Pyro-/Hydrometallurgy	medium	medium	lost	medium	medium	low	Semi-complex
Specific process for recycling WBG	Separate collection Crushing Annealing Leaching Purification	high	high	returned	high	low	medium	semi-complex
Reuse	Separate collection Sorting and dismantling Refurbishing /Repairing/Remanufacturing Testing	medium	low	returned	medium	low	high	complex
Incineration	Collection Incineration	low	high	lost	high	high	low	easy
Disposal	(Collecting) Disposal	low	high	lost	high	high	low	easy

6. Conclusion and Outlook

Wide band gap-based semiconductors are a promising technology for more efficient and smaller devices, and this served as the motivation to explore various environmental aspects and impacts along the life cycle of selected applications and case studies based on Silicon Carbide and Gallium nitride. This research addressed specific aspects considered of interest for policy makers, in a framework that describes the energy, greenhouse gas emissions, resources use, circularity and design, as well as the methodologies to assess such aspects.

A key challenge to perform an environmental assessment for WBG technologies is the lack of existing LCAs, databases, PCRs and EPDs, leading still to results that are uncertain because scenarios considered also include many assumptions. This issue has already been recognized by other researchers who are beginning to develop standards and data for evaluating the environmental performance of power electronics.

With respect to the stage of the life cycle of power electronics, data collected analyzed in this research indicates that the production of WBG materials such as SiC has a higher energy demand compared to conventional Silicon production. Nevertheless, due to the higher efficiency of WBG, the WBG die can be produced in a smaller size, and more dies per wafer can be cut. This leads to a lower energy demand per die, which nearly balances out the higher energy demand for the WBG material production in the first place.

The higher energy efficiency and the smaller size of WBG-based semiconductors lead to design advantages and further saving on materials used, reduced energy and GHG emissions during the manufacturing, distribution (e.g., shipping of WBG-based products to costumer) and use phases. This was discussed in the case study carried out to compare two 60W laptop chargers, with GaN and conventional Si technology.

On the resource aspects of WBG, the research of available literature and information from experts revealed that both Gallium and Silicon metal, the base materials for GaN and SiC, are rated as critical raw materials by the European Commission, due to their main supply by non-EU countries, therefore with some potential risks for disruption of the supply.

Currently no viable commercial EoL recycling technology is available for supplying these materials as secondary streams in the concentration and quality needed for most common technical applications. Some promising recycling concepts exist at a pilot scale, with yet unknown environmental impacts, but with the potential to improve over time.

Recent developments of regulations and standards (e.g., in the EU the ESPR and the standards EN4555x) are a first step on the way towards more circular electronic components in the future. Industry and academia have already started to consider this evolving environmental policy and market contexts, and the implications for the (WBG) semiconductor sector. As the production of WBG material becomes more mature, it is expected that processes will become more efficient and lead to further energy, material and GHG emissions reductions.

The use of components incorporating WBG materials should be guaranteed as long as possible. For a meaningful reuse of these components, the challenge is realizing a product design for circularity, in testing the components for their reliability, and managing the reverse logistics of EoL products. With the regulations on critical raw materials, and product design and information, there is a momentum to further develop the methodological approaches for life cycle assessments and reliability testing, and to take better decisions on environmentally focused designs.

In the next term of PECTA, this research will be even more focused on greenhouse gas emissions (GHG) as well as the use and fate of resources. A closer look will be given at gathering more precise and robust data along the life cycle, to carry out environmental assessments of selected applications. Especially the environmental impacts of WBG recycling, e.g., leaching processes, remain unclear and need to be assessed.

The focus will also be set on optimized reverse logistic scenarios, targeted disassembly processes of WBG components, reliability testing and design of reusable components. In terms of calculating the residual value of reusable components, Life cycle costing (LCC) might also be path to explore in the next research period. Also, a design-decision tool could be developed to support the product design process of the power electronics industry towards a more sustainable and circular product design. As with this task, the goal will continue to be providing evidence and insights for policy makers, as well as informing a broader audience from academia, industry, and the public.

Appendices

Appendix 1

Paper 1 - Diaz, A.; Schmidt, S.; Glaser, S., "A “life cycle thinking” approach to assess differences in the energy use of SiC vs. Si power semiconductors," 2021.

Appendix 2

Paper 2 - Glaser, S.; Diaz, A.; Makoschitz, M., "Design aspects and environmental impacts of using Wide Band Gap based semiconductor technology in consumer chargers," 2023.

Appendix 3

Paper 3 - Glaser, S.; Feuchter, P.; Diaz, A., "Looking beyond energy efficiency - Environmental aspects and impacts of WBG devices and applications over their life cycle," EPE - PECTA, 2023.

References

[1] Singh, A., "*Why Semiconductors Are a Really Big Deal,*" 2023; Available from: https://www.fairobserver.com/business/why-semiconductors-are-a-really-big-deal/ (accessed on 12.10.2023).

[2] Nanou, E., "*8 Reasons Why Semiconductors Are Important to Modern Living,*" 2023; Available from: https://www.makeuseof.com/why-semiconductors-important/ (accessed on: 12.10.2023).

[3] Burkacky, O., "*Sustainability in semiconductor operations: Toward net-zero production,*" 2022; Available from: https://www.mckinsey.com/industries/semiconductors/our-insights/sustainability-in-semiconductor-operations-toward-net-zero-production (accessed on: 12.10.2023).

[4] IEA, "*The Energy Efficiency Potential and Application Readiness of Wide Band Gap Technology,*" 2020; Available from: https://www.iea-4e.org/wp-content/uploads/publications/2020/12/4E-Policy-Brief-PECTA-1-271120.pdf (accessed on: 12.10.2023).

[5] Spejo, L. B.; Nonis, E.; Schulz, N.; Minamisawa, R. A., "*Energy saving potential of WBG-commercial power converters in different applications,*" 2023.

[6] Markoschitz, M.; Krischan, K.; Bergmann, P.; Diaz, A.; Brüninger, R., "*Wide Band Gap Technology: Efficiency Potential and Application Readiness Map,*" 4E Power Electronic Conversion Technology Annex (PECTA), 2020.

[7] Diaz, A.; Schmidt, S.; Glaser, S., "*A "life cycle thinking" approach to assess differences in the energy use of SiC vs. Si power semiconductors,*" 2021.

[8] International Organization for Standardization (ISO), *Environmental management — Life cycle assessment — Principles and framework. ISO14040:2006*, 2006.

[9] International Organization for Standardization (ISO), "*ISO 14025:2006 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures.*"

[10] International Organization for Standardization (ISO), "*ISO 14027:2017 - Environmental labels and declarations — Development of product category rules,*" Available from: https://www.iso.org/standard/66123.html (accessed on: 12.10.2023).

[11] The International EPD System, "*Global EPD programme for publication of ISO 14025 and EN 15804 compliant EPDs,*" Available from: https://www.environdec.com/about-us/the-international-epd-system-about-the-system (accessed on: 12.10.2023).

[12] The International EPD System, "*PCR Library,*" Available from: https://www.environdec.com/pcr-library (accessed on: 12.10.2023).

[13] United Nations, "*Central Product Classification (CPC)* " 2015; Available from: https://unstats.un.org/unsd/classifications/unsdclassifications/cpcv21.pdf (accessed on: 12.10.2023).

[14] International Trade Administration, "*Harmonized System (HS),*" Available from: https://www.trade.gov/industry-classification-systems (accessed on: 12.10.2023).

[15] The British Standards Institution (BSI), "*BS EN IEC 63366 Product category rules for life cycle assessment of electrical and electronic products and systems,*" 2024; Available from: https://standardsdevelopment.bsigroup.com/projects/2021-00211#/section (accessed on: 11.01.2024).

[16] Glaser, S.; Diaz, A.; Makoschitz, M., "*Design aspects and environmental impacts of using Wide Band Gap based semiconductor technology in consumer chargers,*" 2023.

[17] Zhu, H.; Jafar, A.; Machtinger, K.; Makoschitz, M.; Matioli, E., "*Measurement of WBG-based power supplies,*" EPE - PECTA, 2023.

[18] Glaser, S.; Feuchter, P.; Diaz, A., "*Looking beyond energy efficiency - Environmental aspects and impacts of WBG devices and applications over their life cycle,*" EPE - PECTA, 2023.

[19] Geissbühler, F.; Giovanelli, M.; Minichiello, L., "*Life Cycle Assessment Si- & SiC-Halbleiter, Projekt P3,*" Fachhochschule Nordwestschweiz, Hochschule für Technik, 2022.

[20] Beheshti, M., "*Widebandgap semiconductors: Performance and benefits of GaN versus SiC,*" Texas Instruments, Analog Design Journal, 2020.

[21] Iannuzzo, F., *Modern Power Electronic Devices*. 2020: Institution of Engineering and Technology.

[22] PECTA Industry and Academic Advisory Board, "*Expert Interviews,*" 2022.

[23] Musil, F., "*How Life Cycle Analyses are Influencing Power Electronics Converter Design,*" PCIM, Fronius International GmbH, Keynote, 2023.

[24] Navitas Semiconductor, *Sustainability Report 2021*. 2021.

[25] European Commission, "*Study on the Critical Raw Materials for the EU 2023 - Final Report,*" 2023.

[26] Mrotzek-Blöß, A.; Nühlen, J.; Pflaum, H.; Rettweiler, M.; Kroop, S.; Reh, K.; Franke, M., "*Recyclingpotenzial von Technologiemetallen und anderen kritischen Rohstoffen als wichtige Säule der Rohstoffversorgung (Recyclingpotenzial Technologiemetalle),*" Kurzstudie im Auftrag des Bundesministeriums für Wirtschaft und Energie (BMWi), 2015.

[27] European Commission, "*Factsheets updates based on the EU factsheets 2020 - Silicon Metal,*" 2022.

[28] Gregoir, L. & Van Acker, K., "*Metals for Clean Energy: Pathways to solving Europe's raw materials challenge,*" 2022.

[29] Liedtke, M. & Huy, D., "*Rohstoffrisikobewertung - Gallium,*" DERA Rohstoffinformationen 35: 86 S., 2018.

[30] European Commission, "*Factsheets updates based on the EU factsheets 2020 - Gallium,*" 2022.

[31] European Commission, "*Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020,*" 2023.

[32] European Commission, "*Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 (Chips Act),*" 2023.

[33] United Nations University, "*Share of electronic waste documented to be collected and properly recycled worldwide in 2019, by region,*" 2020; Available from: https://www.statista.com/statistics/1253099/ewaste-collection-recycling-rates-worldwide-by-region/ (accessed on 17.05.2023).

[34] Andeobu, L.; Wibowo, S.; Grandhi, S., "*Informal E-waste recycling practices and environmental pollution in Africa: What is the way forward?,*" Int J Hyg Environ Health, 2023. **252**: p. 114192.

[35] Hossain, S. T.; Johra, F. T.; Jung, W.-G., "*Fabrication of Silicon Carbide from Recycled Silicon Wafer Cutting Sludge and Its Purification,*" Applied Sciences, 2018. **8**(10).

[36] Sergiienko, S. A.; Pogorelov, B. V.; Daniliuk, V. B., "*Silicon and silicon carbide powders recycling technology from wire-saw cutting waste in slicing process of silicon ingots,*" Separation and Purification Technology, 2014. **133**: p. 16-21.

[37] Yang, Y.; Leng, G.; Chen, B.; Huang, Z., "*Techniques of recycling gallium from e-waste* " The Chinese Journal of Process Engineering, 2021.

[38] Swain, B.; Mishra, C.; Kang, L.; Park, K. S.; Lee, C. G.; Hong, H. S., "*Recycling process for recovery of gallium from GaN an e-waste of LED industry through ball milling, annealing and leaching,*" Environ Res, 2015. **138**: p. 401-8.

[39] Hense, P.; Nieberl, M.; Reh, K., "*Recycling von Elektroaltgeräten – Potenziale, Herausforderungen und Lösungsansätze,*" 2019.

[40] Fang, L.; Lefranc, P.; Rio, M., "*Barriers for eco-designing circular Power Electronics Converters,*" Procedia CIRP, 2023. **116**: p. 287-292.

[41] Rahmani, B.; Rio, M.; Lembeye, Y.; Crebier, J.-C., "*Design for Reuse: residual value monitoring of power electronics' components,*" Procedia CIRP, 2022. **109**: p. 140-145.

[42] Danfoss, "*Circularity Framework,*" Available from: https://www.danfoss.com/en/about-danfoss/company/sustainability/circularity/ (accessed on: 20.10.2023).

[43] Iannuzzo, K. Z. C. H. C. F., "*Reliability for WBG, results of a Pre-Scoping Study,*" EPE Conference 2023, Aalborg 2023.

[44] JEDEC Committee, "*SiC/GaN Power Electronic Conversion Semiconductor Standards (JC-70.1/JC-70.2),*" 2023; Available from: https://www.jedec.org/committees/ (accessed on: 12.10.2023).

[45] CEN-CENELEC, *EN 4555x Standards*, 2020.

[46] Europäische Kommission, "*Richtlinie 2009/125/EG des europäischen Parlaments und des Rates vom 21. Oktober 2009 zur Schaffung eines Rahmens für die Festlegung von Anforderungen an die umweltgerechte Gestaltung energieverbrauchsrelevanter Produkte,*" 2009.

[47] European Commission, "*Proposal for a regulation of the european parliament and of the council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC,*" 2022.

Appendix 1

Paper 1 - Diaz, A.; Schmidt, S.; Glaser, S., "A “life cycle thinking” approach to assess differences in the energy use of SiC vs. Si power semiconductors," 2021.

4E Power Electronic Conversion Technology Annex PECTA.

Task B: Energy and environmental related Life Cycle Assessment (LCA).

Paper publication: *A "life cycle thinking" approach to assess differences in the energy use of SiC vs. Si power semiconductors.*

By: Díaz Triana, A., S. Schmidt, S. Glaser, M. Makoschitz.

This paper presents the outcomes of the work from Area 1 of PECTA Task B, Energy and environmental related Life Cycle Assessment, conducted between January and September 2021. See more information under: https://www.iea-4e.org/pecta/tasks/.

The scope is the production of Wide Band Gap (WBG) semiconductors and the assessment of environmental aspects is focusing on the energy use for the different manufacturing processing steps. This investigation is especially relevant for Silicon carbide (SiC) semiconductors, as there are some key differences in production processes compared to (conventional) Silicon semiconductors. Through interviews with academic and industry expert and extensive literature research, this paper presents the main differences of the SiC semiconductors production chain.

The paper has been accepted and published in the proceedings of the international **e.nova 2021 Conference** "*Green Deal, Energy - Building - Environment*".

The oral presentation has been re-scheduled (due to Covid) from November 2021 to June 2022.

1

A "life cycle thinking" approach to assess differences in the energy use of SiC vs. Si power semiconductors.

Díaz Triana, A.[1]; S. Schmidt[2]; S. Glaser[2]; M. Makoschitz[3]

Corresponding contact: diaz@ecodesign-company.com

1 *ECODESIGN company engineering & management consultancy GmbH, Vienna, Austria*
2 *TU Wien Vienna University of Technology, Engineering design and product development, Vienna, Austria*
3 *AIT Austrian Institute of Technology GmbH, Austria.*

ABSTRACT:

Wide Band Gap (WBG) semiconductors have the potential to provide significant improvements in energy efficiency over conventional Silicon (Si) semiconductors. While the potential for energy efficiency gains is widely researched, the relation to the energy use during manufacturing processes remains insufficiently studied. This question is especially relevant for Silicon carbide (SiC) semiconductors, as there are some key differences in their production processes compared to Si. Through expert interviews and literature research, this paper aims to identify the main differences of the SiC semiconductors production chain. These differences are set off against a typical end-use scenario, to better understand the proportionality of energy inputs vs. efficiency gains. Furthermore, the most important variables in this assessment are highlighted.

1. INTRODUCTION

The broader application of WBG semiconductors for power electronics carries the promise of large energy savings in a range of different applications. Some of the sectors with the highest expected energy efficiency gains enabled by WBG semiconductors are photovoltaic systems (inverters), consumer electronics (power supplies), data centers (uninterrupted power supplies), and the electric automotive sector (drive-trains and charging infrastructure (Makoschitz et al. 2020). While these energy efficiency improvements from using WBG components compared to Si-components are widely researched and often promoted by manufacturers, the environmental impacts along the entire life cycle (beyond the use phase) are far less understood. Moreover, to the best knowledge of the authors, there is currently no Life Cycle Assessment (LCA) data available specifically focusing on WBG semiconductors, related research is generally scarce, and (publicly) available LCA information of sufficient level of detail and quality is limited or outdated. Most of the current LCA research available in the field of semiconductors focuses on Si-based semiconductors, especially logic and other IC chips (Wernet et al. 2016)). These references mostly contain aggregated data, which does not allow for separate analysis of individual processes and of their materials and energy inputs and outputs.

From a life cycle thinking perspective two aspects seem highly relevant. First, ICs like semiconductor memories, processors or logic chips are highly **energy intensive** to manufacture due to their complex design. Often manufacturing requires hundreds of processing steps. Secondly, the industry is changing and innovating rapidly, and therefore it is also especially competitive and secretive. ICs are subject of a continuous process of miniaturization- also called "die shrink". Boyd states that this is leading to a *continuous shift of* ***relevance*** *from the manufacturing stage to the use phase* (Boyd 2012).

These aspects do not fully apply to **power** semiconductors, such as metal oxide semiconductor field-effect transistors (MOSFETs) and diodes, as they are relatively less complex to produce, and are also less affected by the same continuous process of miniaturization. Taking on from these preliminary considerations, the next section discussed the specific assessment methodology and scope developed in this study. The key words to keep in mind are "relevance" and "differences".

2. METHODOLOGY AND SCOPE

Available studies report that the electricity use in manufacturing is, after the use phase, the most important source of environmental impacts for Silicon based semiconductors (Williams et al. 2002; Yao et al. 2004). The approach of this paper is therefore to gain a better understanding of the differences in the energy demand (i.e., primarily electricity) along the whole life cycle for selected WBG power semiconductors.

This analysis started off by focusing on the two currently most widespread WBG semiconductor materials - Gallium nitride (GaN or Si/GaN) and Silicon carbide (SiC). However, initial research revealed that the detailed assessment of energy use and energy savings along the life cycle is particularly relevant for SiC semiconductors.

The methodology of this study is structured along the life cycle stages and the scope was set on understanding which **processes and/or life cycle stages were (most) relevant**, in two ways: (1) stages that are most important *in terms of their energy inputs*, and (2) stages where *significant differences exist between Si and SiC technologies*. This was achieved through literature review and by conducting targeted interviews with academic and industry experts; who are mostly contributors to IEA 4E PECTA[1]. Interviewed experts helped identify, verify and quantify key selected variables related to processes and their differences (PECTA AAG/IAG 2021, interview). Figure 1 shows an overview of the life cycle stages for SiC and Si-based power semiconductors in the scope of this study. A photovoltaic (PV) inverter was the end use application chosen for this paper given the relevant energy savings potential reported for the SiC-based (PV) inverters (Makoschitz et al. 2020).

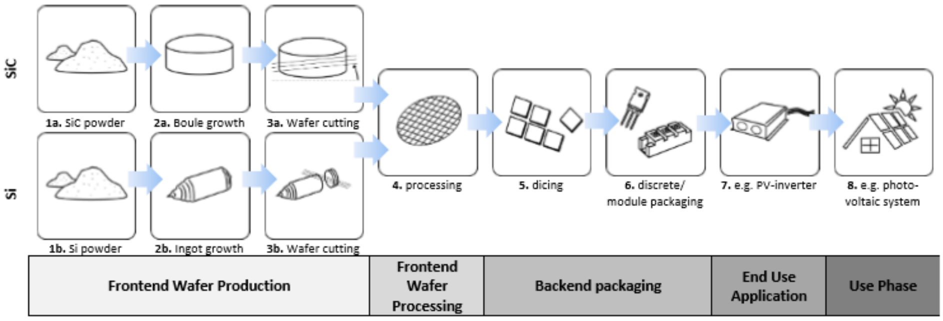

Figure 1: Life cycle stages of Si and SiC power semiconductors (Graphic: Schmidt, S. and S. Glaser (2021), own illustration).

RESULTS - DIFFERENCES ALONG THE LIFE CYCLE

The insights and results are discussed next for the processes and stages in Figure 1. It is important to mention that processes that are similar for both, Si and SiC, might have a substantial share of the overall energy demands. Still, the End of life stage of the electronic devices with SiC and Si is very similar at this point, and as such is not further investigated.

Front-End Wafer production: Si and most GaN semiconductors are manufactured using high purity industrial grade Silicon, by growing **Si ingots** through the Czrochalski process (Figure 1, 1b and 2b), with typical diameters of 8 to 12 inches (200mm and 300mm) (Prakash et al. 2011).

The substrate material for SiC semiconductors is also based on silica sand, with additional processing steps needed to obtain the SiC powder (Figure 1, step 1a). Usually, the Acheson process using physical vapor transport method (PVT) is applied. In this

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[1] PECTA is the **Power Electronic Conversion Technology Annex** of the IEA Energy Efficient End-Use Equipment Program (4E). Its goal is gathering and analysing information on new WBG power electronic devices to inform policy makers; see: https://www.iea-4e.org/pecta.

method, a graphite crucible is heated by induction coils to over 2300K in a furnace filled with a mixture of silica sand and carbon powder (Yang et al. 2018). The resulting SiC is ground into SiC powder and used as input material for **growing a "SiC boule"** (Figure 1, 2a). The Acheson process is estimated to require 7700 kWh electrical energy per ton of input material (Tanaka 2011); while the estimate for grinding is 1500 kWh/ton of SiC powder.

The input mass of SiC powder for growing a 6 inch (6") diameter SiC boule (usable height of 25mm) is about 30 kg; with a powder density of approx. 1,6g/cm³. The estimated (embedded) energy of the input SiC powder is **280 kWh/boule** (Figure 1, 1a) (PECTA AAG/IAG 2021, interview).

In this study the reference is the production of 6" wafers. Taking the boule height of 25mm, with a growth rate of 0,2mm/h, and a power rating of 130kW (Ellefsen et al. 2019) for the growth process, the resulting energy demand is **16250 kWh/boule**. The growth of the boules (Figure 1, 2a) with its associated electricity demand, is one of the key performance indicators for the semiconductor´s energy profile.

As indicated before, reliable data regarding the energy demand for growing Si ingots was not available for this study (Most LCA data contain aggregated process data). It was therefore estimated that the energy demand is **20 to 40 times** higher per usable wafer area for growing SiC boules than for growing Si ingots (PECTA AAG/IAG 2021, interview).

In each case, the ingot and the boule are then cut into wafers (Figure 1, 3a and 3b), which are polished and prepared for further processing. Compared to Si ingots, SiC boules are much harder to cut into wafers (Armstrong et al. 2017). The process is also accompanied by significant "**kerf losses**", which are currently estimated to **range between 50% to 75%** (PECTA AAG/IAG 2021, interview). These are significantly higher losses than those from cutting Si ingots into wafers. Assuming low kerf losses of 50%, for a usable height of 25mm and 500μm wafer thickness after cutting would result in 25 wafers/per boule. Taking 100 kWh for the operation of the slicing equipment (1kW*100hr/boule), the resulting energy demand is **665kWh/6" unpolished SiC wafer**.

(Prakash et al. 2011) provide a specific estimate for the energy input for Si wafer production, with an electricity demand of 2127 kWh/kg of polished Si wafer. Converting this energy input estimation of the 6" Si wafer to calculate an equivalent 6" SiC wafer (from a 128g weight; and 8" wafer), and further assuming mass losses of 40% (due to polishing from a thickness of 500μm to 300μm), this results in an energy demand of **92kWh/6" equivalent unpolished Si wafer**; for a ratio of 1:7,22 (**92kWh [Si]**: **665kWh [SiC]**). As the assumptions behind the datasets are nt fully known, and the datasets are possibly outdated, the results for Si wafers shall be used with caution.

Front-end wafer processing: "Wafer processing" (Figure 1, step 4) strongly depends on the complexity of the final chip. ICs like semiconductor memories, processors or logic chips are at the end of the complexity spectrum, often requiring hundreds of wafer processing steps, with a range of different high purity chemicals applied to create layers or so called "**mask levels**". Power semiconductors such as MOSFETs and diodes require far fewer mask levels compared to memories, processors or logic chips, e.g. SiC IGBTs (insulated-gate bipolar transistors) require about 11 to 12 mask levels (PECTA AAG/IAG 2021, interview).

Moreover, experts interviewed indicated that SiC wafer processing steps are very similar to Si wafer processing steps; therefore, these steps were not the focus of further investigation. However, one important difference is the processing yield. The yield is still lower for SiC wafers (due to crystal defects or process errors) than for the more established Si wafer front-end processing. The expert estimations for the overall front-end yield **is 75% for SiC, and 90% for Si** (PECTA AAG/IAG 2021, interview).

Back-end packaging: The back-end packaging processes follows the front-end processing and typically take place at a different manufacturing location. The dies on the processed wafer are cut into individual chips (Figure 1, step 5) and enclosed inside a protective package with external leads or connectors (Figure 1, step 6). There are about 20 families of different types of packages. The packaging type and the number of external leads are the most relevant variables for estimating the energy use of the back-end packaging process (Villard et al. 2015).

Due to the standardization of semiconductor packaging, the adoption of new packaging types is a slow process, which also depends on the device´s prevalence. As SiC devices are not yet widely common, they are usually packaged in the same types of packages as Si based devices. With SiC dies often being comparatively smaller than Si dies, using the same packaging type results in an overuse of packaging materials (PECTA AAG/IAG 2021, interview). Until new packaging standards are developed, it is plausible to consider the energy input for the back-end packaging process to be roughly the same for SiC as for Si semiconductors.

End-Use Application: The packaged chips or modules are incorporated into different end-use applications, e.g., in photovoltaic inverters (Figure 1, step 7). Key features of WBG devices play an important role. The higher switching frequencies and the lower energy conversion losses allow the design of compact and light weight end products with WBG semiconductors, consequently also using less materials. In the case of industrial transformers and power supplies with SiC, the **overall product size is reduced in the range of 25% to 50%** compared to equivalent Si applications (PECTA AAG/IAG 2021, interview). Certainly, the extent and relevance of this effect depends on the end-use application, and must be investigated at product level to understand how they translate into energy impacts. This will be further investigated in PECTA in the near future.

Use phase: This is the last life cycle stage covered in this study (Figure 1, step 8). Many studies have quantified the energy efficiency gains enabled by the introduction of WBG semiconductors, gains which vary widely depending on the end-use application. (Warren et al. 2015) estimate an average energy efficiency improvement of 14,7% due to the introduction of SiC semiconductors in the automotive industry (hybrid electric vehicles), resulting from improvements at the inverter level, but also from overall system improvements. For (PV) inverters, average energy efficiency gains of 2% are estimated (Makoschitz et al. 2020). As established Si based inverters already have a high efficiency in the order of 96,8%, further improvements seem rather limited.

In Austria PV systems have typically (approx.) 1000 hours of full load per year (use intensity). Assuming 20 years of service (product life time), the **efficiency gains,** namely the energy saved (not used) for a 1 MW (industry scale) PV system with a WBG inverter **would be approx. 20000 kWh/year, reaching up to 400000 kWh savings over its entire life cycle.** This example shows that the use of a WBG application could "pay back" many times the energy input needed for its manufacturing, through the higher efficiency and intense use over a long service life. In another scenario, the energy efficiency gains for power supplies in consumer electronics e.g., laptops, tablets and smartphones, range between 3% to 9% (Makoschitz et al. 2020).

KEY VARIABLES OF THE ENERGY PROFILE

The **five** most important aspects and variables for assessing the energy profiles and its differences between SiC and Si power semiconductors are discussed as follows:

(1) Boule growth: The growth of SiC boules requires significantly more energy per usable wafer area due the energy intensive processes, the smaller wafer diameters, and a significantly smaller usable height (thickness).

(2) Process yields: A number of losses influence the energy "burden" of the die at the end of the production line, notably the material losses for the growth of the boule (and ingot), the kerf losses from wafer cutting, and the processing losses due to faulty dies.

(3) Die size ratio: WBG power semiconductors are able to fulfil the same function with a smaller die. As growing the SiC boule is the most energy intensive step in the manufacturing, the die size ratio is key for assessing its energy profile.

(4) Effects on the product design: Using WBG semiconductors allowing higher switching frequency might have a strong impact on product design, enabling for example a reduction of material use, size and weight in selected end-use applications.

(5) Use phase characteristics: it is plausible to state that the Use phase of SiC power semiconductors will be the stage that plays the most important role, as shown with the

(PV) inverter example. Key variables in this case are the energy efficiency gains, the use intensity, and the product´s lifetime.

In summary, while the aspects 1 and 2 will negatively impact the energy profile of SiC devices (i.e., higher energy demand); the variables and aspects 3, 4 and 5 are those where SiC devices will show substantial improvements and savings.

4. DISCUSSION

As LCA data for WBG semiconductors was not readily available for this study, the aim was to describe the life cycle stages, the related processes and most relevant variables, especially for assessing their energy inputs. This study presented estimates of the energy inputs for four manufacturing steps (including sub-processes) of SiC and Si based devices, and discussed the differences in each case as well as their magnitude in relation to the potential for energy savings, taking as example a (SiC based) PV inverter as end-use application. The front-end processing and back-end packaging processes are very similar for both SiC and Si semiconductors. The front-end wafer production shows though more differences in terms of energy use, due to the nature of materials and the maturity of the processes involved (i.e., level of process losses). Further exploring the impacts on the design and on energy improvements resulting from incorporating SiC in certain end-use applications remains an area of research interest.

In terms of the life cycle thinking perspective presented in this study, future work aims at gaining a deeper understanding of the contribution to the life cycle stages that showed more differences between technologies as well as higher impact, to identify effective levers for improvement - a difficult task in light of the sparse LCA data available. Taking as references other relevant (LCA) impacts already identified for Si based semiconductors, i.e., global warming potential, abiotic resources depletion, water eutrophication, raw water use, human eco-toxicity, and photochemical (Summer) smog (Villard et al. 2015); the focus could also be expanded to assess these (LCA) impact categories for SiC semiconductors. Finally, research on the energy and environmental impacts of GaN based semiconductors will be pertinent, as these mature and penetrate the market.

ACKNOWLEDGEMENTS

This work is supported by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, as part of the IEA Energy Efficient End-Use Equipment (4E) technology program: https://nachhaltigwirtschaften.at/de/iea/technologieprogramme/4e/iea-4e-tcp-pecta.php. Our gratitude goes to the PECTA experts interviewed, for their invaluable insights and data for this study. The views and information presented in this paper are the sole responsibility of the authors, and do not reflect the views or opinions of PECTA, 4E or the IEA.

REFERENCES

Armstrong K, Das S, Marlino L, 2017. Wide Bandgap Semiconductor Opportunities in Power Electronics, US Dept. of Energy. https://info.ornl.gov/sites/publications/Files/Pub104869.pdf

Boyd S, 2012. Life-Cycle Assessment of Semiconductors (1. Aufl.). Springer New York, New York, NY, Online-Ressource.

Ellefsen OM, Arzig M, Steiner J, Wellmann P, Runde P, 2019. Optimization of the SiC Powder Source Material for Improved Process Conditions During PVT Growth of SiC Boules. Materials (Basel, Switzerland), 12 (19), 3272.

Makoschitz M, Krischan K, Bergmann P, Diaz A, Brueninger R, 2020. Wide Band Gap Technology: Efficiency Potential and Application Readiness Map. 4E PECTA, https://www.iea-4e.org/wp-content/uploads/publications/2020/05/PECTA_Report_Total-V10final-May-2020.pdf.

(PECTA AAG/IAG - Academic and Industrial Advisory Groups), 2021. Expert Interviews on WBG semiconductors and Si based semiconductors. Interview, 2021.

Prakash S, Schischke K, Stobbe L, 2011. Schaffung einer Datenbasis zur Ermittlung ökologischer Wirkungen der Produkte der Informations- und Kommunikationstechnik. Ressourcenschonung im Aktionsfeld IKT, unpublished.

Tanaka H, 2011. Silicon carbide powder and sintered materials. Journal of the Ceramic Society of Japan, 119 (1387), 218–233.

Villard A, Lelah A, Brissaud D, 2015. Drawing a chip environmental profile. Journal of Cleaner Production, 86, 98–109.

Warren JA, Riddle ME, Graziano DJ, Das S, Upadhyayula VKK, Masanet E, Cresko J, 2015. Energy Impacts of Wide Band Gap Semiconductors in U.S. Light-Duty Electric Vehicle Fleet. Env. Science & Technology, 49 (17), 10294–10302.

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B, 2016. The ecoinvent database version 3 (part I): overview and methodology. The Int. Journal of Life Cycle Assessment, 21 (9), 1218–1230.

Williams ED, Ayres RU, Heller M, 2002. The 1.7 kilogram microchip: energy and material use in the production of semiconductor devices. Env. Science & Technology, 36 (24), 5504–5510.

Yang C, Liu G, Chen C, Hou Y, Xu M, Zhang Y, 2018. Numerical Simulation of Temperature Fields in a Three-Dimensional SiC Crystal Growth Furnace with Axisymmetric and Spiral Coils. Applied Sciences, 8 (5), 705.

Yao MA, Wildson AR, Mcmanus TJ, Shadman F, 2004. 2004 IEEE Int. Symposium on Electronics & the Environment.10-13 May, 2004, Scottsdale, AZ, USA. IEEE, Piscataway, NJ, 328 p.

Contact information:

Dr. Adriana Díaz
Schwindgasse 4/2; 1040 Vienna
Email: diaz@ecodesign-company.com

Appendix 2

Paper 2 - Glaser, S.; Diaz, A.; Makoschitz, M., "Design aspects and environmental impacts of using Wide Band Gap based semiconductor technology in consumer chargers," 2023.

4E Power Electronic Conversion Technology Annex PECTA.

Task B: Energy and environmental related Life Cycle Assessment (LCA).

Paper publication: *Design aspects and environmental impacts of Wide Band gap based semiconductor technology in chargers for electronic devices.*

By: S. Glaser, A. Díaz Triana, M. Makoschitz.

This paper presents the outcomes of the work from PECTA Task B, Energy and environmental related Life Cycle Assessment, conducted between January 2022 and February 2023. See more information under: https://www.iea-4e.org/pecta/tasks/.

This paper focuses on the effects of incorporating GaN components for energy conversion on the product design and the resulting environmental impacts along the life cycle, in particular for the case of consumer chargers for electronic devices such as notebooks and mobile phones.

The authors contacted experts from academia, research and industry to discuss the effects of WBG at the product design level, and conducted a streamlined Life Cycle Assessment to evaluate the Climate change impacts, using Global Warming Potential (GWP) as indicator.

The paper has been presented and is also published in the proceedings of the international **Going Green – CARE INNOVATION 2023 Conference**: https://www.careinnovation.eu/.

Going Green
CARE INNOVATION 2023
May 8 - 11, 2023
Parkhotel Schönbrunn
Vienna, Austria

DESIGN ASPECTS AND ENVIRONMENTAL IMPACTS OF WIDE BAND GAP BASED SEMICONDUCTOR TECHNOLOGY IN CHARGERS FOR ELECTRONIC DEVICES

S. Glaser[1], *A. Diaz*[2], *M. Makoschitz*[3]

1 TU WIEN, Vienna University of Technology, Vienna, Austria
2 ECODESIGN company engineering & management consultancy GmbH, Vienna, Austria
3 AIT Austrian Institute of Technology GmbH, Vienna, Austria

Abstract: In recent years, Wide Band Gap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN) have increasingly become an alternative to standard silicon semiconductors used in e.g., power converters. This paper is the outcome of selected work of Task B: "Energy and environmental related Life Cycle Assessment (LCA)", of the Power Electronic Conversion Technology Annex (PECTA) of the Technology Collaboration Program Energy Efficient End-Use Equipment by the IEA (4E). This paper in particular focuses on chargers for electronic devices such as notebooks and mobile phones, and concentrates on two main areas: 1) The effects of incorporating GaN components for energy conversion on the product design; and 2) The resulting environmental impacts along the life cycle of the chargers.

To answer these questions, the authors contacted experts from academia, research and industry to discuss the effects of WBG on the product design level. A functional structure of a power converter was used to describe the impact of using GaN transistors. A streamlined Life Cycle Assessment with the selected Climate change indicator Global Warming Potential (GWP) was completed for a conventional 65W Si-based laptop charger, taken as the reference product, and a novel 65W GaN-based multi charger. The inventory data for these chargers were obtained from power measurements carried out in PECTA (Task F), and their bills of materials (BOMs) were obtained from tearing down the two products.

In general, the effect of using GaN on the design of the charger brings the possibility to increase the switching frequency, which enables size and weight reductions of components. Depending on pre-defined customer specification also a higher energy efficiency can be achieved (e.g., if Si or GaN transistors are utilizing the same operating frequency). In turn, both have repercussions on the environmental impact of the charger.

For 500 to 1500 charging cycles the GWP due to WBG power semiconductor material also including the manufacturing phase (production of the WBG device itself) is compared with the reference Si-based charger. When the battery charger operates for 1500 charging cycles, the GWP of the materials and production of the WBG device must be lower than 3,50 kg CO2-eq. If the WBG charger would be used for only 500 charging cycles, the GWP of the materials and production of the WBG device should be lower than 1,64 kg CO2-eq.

The results of this study show, that a reduction of environmental impacts over the entire life cycle may be possible through the use of WBG technology.

1. INTRODUCTION

In recent years, wide bandgap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN) have increasingly become an alternative to power semiconductors based on pure silicon in power converters. The larger band gap allows power devices to operate at higher voltages, temperatures, and frequencies [1]. For power converters various topologies exists, but all are based on similar components like magnetics (transformer, filter inductors), capacitors, analogue or digital controllers, power semiconductors and heatsinks. Those components as well as the choice of the topology are affected by the application of WBG power semiconductors [2].

Research on WBG during the last years has mostly focused on either the benefits of WBG, for example the volume reduction or increased power density potential due to the application of GaN technology [3, 4], or on possible issues, like electromagnetic interference due to faster turn-on and turn-off capability and transients of WBG devices.

Recent publications show the increasing relevance of environmental performance of WBG power semiconductors and their application [5].

This study is part of Task B of PECTA. The objective is to develop a better understanding among governments and policy makers of the environmental aspects and impacts of WBG applications. The research is analysing the environmental impacts, in particular during the life cycle of electronic devices such as consumer chargers or PV inverter, by means of Life Cycle Assessment (LCA) and following ISO 14040, ISO 14044. To understand the environmental impact of using WBG power semiconductors in applications in more detail, consequences are investigated at device and component level.

As there are limited commercial datasets (e.g., from Ecoinvent [6], GaBi [7]) to assess the environmental impacts of semiconductor using WBG materials, the authors are using information from industry, research and academic experts as well as plausible assumptions to model these WBG power semiconductors and determine ranges for which the GWP of the materials and production of the WBG device leads to an overall reduction along the chargers life cycle, compared to standard Si-based power semiconductors.

2. GOAL

First, the effects on the charger's topology, enabled by the use of WBG power semiconductors, are of great interest. In particular, the impact on design, e.g., reduction (or increase) in value, volume or weight of components. With this knowledge, environmental savings in the material- and manufacturing phase can be discussed in detail later on.

Due to the WBG power converter's increased efficiency [5, 8, 9], less energy is required to achieve the same amount of battery capacity in a specified time frame, this means less environmental impacts in the use phase. GHG emissions and materials used can be further reduced due to the already mentioned size reduction of components (impact on design). On the other hand, the initial energy consumption during the manufacturing process must be specified, in order to prevent extensively diminished positive returns of technological effects from excess energy during production. Thus, the environmental impact from the production processes of the WBG power semiconductors must be investigated and considered in detail as well. A GaN-based battery charger is considered as attractive alternative, if the sum of all aforementioned impacting factors along the product life cycle is not higher than for the Si-based solution.

The goal of this study is to investigate the following questions:

a) How does energy efficiency impact the overall environmental performance of WBG based power converters?

b) Are the life cycle phases materials, manufacturing, and the use phase the only relevant ones in terms of (selected) environmental impacts (e.g., GWP)?

c) Can the use of WBG technology achieve a significant reduction of (selected) environmental impacts along the entire life cycle (e.g., GWP)?

3. SCOPE

Using WBG power semiconductors has important impacts on the product design due to SiC's or GaN's electrical and thermal properties compared to Silicon (Si). SiC power semiconductors are used in high power applications due to their voltage, current and temperature capabilities [10]. GaN power semi-conductors are used in high switching frequency applications, GaN can handle up to 1MHz and above [1, 11].

The scope of this paper is an end-use application that is already widely established in the market -the USB-C chargers for mobile phones and laptops with GaN power semiconductors. In such electronic consumer chargers GaN enables reductions of up to half the size and the weight, compared to standard silicon-based chargers [11-13]. In particular, the size of the main transformer, EMI filter components, active and passive components, and the cooling needs can be reduced [11, 14].

This paper investigates these design effects (e.g., reductions in size and weight) and the resulting effect on greenhouse gas emissions (GHG) in the material and manufacturing phases, especially in the use phase, and eventually also in the distribution phase (transport from a product's manufacturer to the end-user).

A key life cycle phase to look at is the use phase. Applying WBG power semiconductors can result in energy efficiency improvements.

The previous generation silicon based chargers (e.g., flyback topology) show an efficiency up to 90% at 65kHz [11]. With WBG power semiconductors up to 94% - 95% are possible [2]. With new topologies, magnetics, controllers and a switching frequency up to 1 MHz applied at 60W chargers, efficiencies up to 95% - 98% could be reached in the next generations of chargers [11].

Power converters could be considered use intensive devices. In other words, they show relevant environmental impacts in the use phase, aside from the impacts due to the materials incorporated and the device´s production (see Figure 4). The lower the efficiency of energy conversion and the longer the device is in operation, the higher the environmental impact in the use phase. Small improvements in this life cycle phase might result in better overall environmental performance.

4. METHODOLOGY

The methodology is composed of two main elements: 1) With expert interviews [2] and literature research the WBG device's impact on the charger's design is identified; a generalized functional structure of power converters is used for presenting these results, and 2) conducting streamlined life cycle assessments, which also involves creating life cycle models of the products in the scope.

4.1. Impact on design

To obtain information on the effects of using WBG on product design, the authors contacted academia, research and industry experts [2]. The views and information from these experts where combined with information from published references that discuss e.g., the relationship between a higher switching frequency of WBG power semiconductor and the size and number of needed components such as heat sinks, passive components of filters [3] or transformers [15].

For presenting the results of these interviews and literature research in terms of the impact of WBG technology on the design, and also to provide a general framework for the other results of the study, a functional structure of a power converter is used.

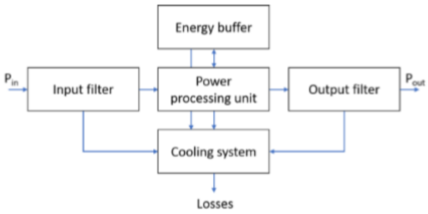

Figure 1: Functional structure of power converters, [adapted from [16]]

This functional structure of a power converter, is represented by 5 function blocks: the input filter, the energy buffer, the power processing unit, the output filter, and the cooling system [16]. The remaining components such as fuses, varistors, and controllers are only marginally influenced by the use of WBG power semiconductors.

The power processing unit converts the electrical energy from one form to another (e.g., AC to DC, DC to AC, converting different voltage levels, etc.), and the disturbances in one as well as the other side are filtered by the two filters. The energy buffer is required to enable the operating principle of the power processor´s topology. Considering the input and output power, losses related to power conversion occur throughout the whole system. These losses are dissipated to the environment in the form of heat, e.g., by the cooling system. These energy losses are also relevant from an environmental point of view, because they cause the environmental impacts in the use phase.

This functional structure, as shown in Figure 1, can be used to describe the chargers and, in general, all kind of power converters, regardless of their actual function, topology and applied semiconductor technology (Si or GaN).

The blocks in this functional structure are used for presenting the impact on design, for the analysis and discussion of results.

4.2. Streamlined life cycle assessment

The second pilar of the methodology in this paper is based on using the life cycle thinking approach, to analyse the relevant life cycle phases and quantify the environmental performance of the chargers.

A life cycle model was created for two types of consumer chargers. These are a 60W Silicon based charger, taken as the reference product, hereafter abbreviated as "60W Si-Ref"; and the 60W GaN based charger, referenced in the following as "60W WBG". The products are shown in Figure 2 and their data is included in Table 1.

Table 1: The 60W Si-Ref charger and 60W WBG charger analysed in this study

Charger	**60W Si-Ref**	**60W WBG**
Power semiconductor technology	Standard Si MOSFET	Pi SC1933C GaN InnoSwitch
Power density*, W/in^3	6,33	8,39
Total weight, g	171,40**	153,10

* Excluding socket
**Excluding USB-C cable

Figure 2: 60W charger Si-Ref on the left, and 60W WBG charger [17]

The bill of materials used to model the inventory of these chargers is based on real product data, obtained from disassembling the two products, identifying and weighing the parts and investigating the materials composition of the components (to the extent possible) and comparing them.

In particular energy in the use phase is considered, through energy efficiency data of these two products. More specifically the inventory modeled for the use phase includes data on the efficiency of these chargers when charging a laptop. Data were obtained from power measurements, carried out by PECTA experts in their laboratories [AIT, 2022].

All measurements were taken for different output voltages (5V, 9V, 12V, 15V, 20V) and under different load conditions (10%, 25%, 50%, 75% and 100% of the nominal rated power). Both the Si- and GaN-based charger are 60W PD devices. According to the manufacturers, the maximum output current of both devices is limited to 3 A. Therefore, the maximum output power per output voltage class is defined as follows:

- Output voltage: 5 V, Maximum Power: 15 W
- Output voltage: 9 V, Maximum Power: 27 W
- Output voltage: 12 V, Maximum Power: 36 W
- Output voltage: 15 V, Maximum Power: 45 W
- Output voltage: 20 V, Maximum Power: 60 W

Therefore, the maximum power of 60 W can only be supplied for batteries with a nominal voltage of 20 V (e.g., battery packs for laptops).

Measurement results of both, GaN- and Si-based power supply have been documented in Table 2 and Table 3 respectively.

Table 2: Measured efficiency of 60W WBG charger for different load and voltage levels [18]

60W WBG					
	5V	9V	12V	15V	20V
3A	91.8%	93.4%	94%	94.4%	94.4%
2.25A	91.9%	93.3%	93.8%	94.0%	94.3%
1.5A	91.6%	92.9%	93.4%	93.6%	93.7%
0.75A	89.7%	90.9%	91.5%	91.7%	91.7%
0.3A	84.9%	86%	86.6%	86.4%	86.1%

Table 3: Measured efficiency of 60W Si-Ref charger for different load and voltage levels [18]

60W Si-Ref					
	5V	9V	12V	15V	20V
3A	82.9%	87.9%	89.1%	89%	89.7%
2.25A	83.5%	87.4%	88.9%	89.6%	90.2%
1.5A	83%	87.1%	88.2%	89%	89.6%
0.75A	81.5%	85.3%	86.4%	87%	87.2%
0.3A	77.7%	82.2%	83.2%	83.1%	81.7%

For analysing the environmental aspects and impacts of the material-, manufacturing- and distribution phase one piece of each charger (60W Si-Ref and 60W WBG) is assessed. For analysing the environmental aspects and impacts of use phase, one charging cycle for a laptop is assessed. This approach provides information for the use phase to evaluate the GHG emissions for different scenarios, and to identify break-even points. The Global Warming Potential (GWP) indicator in kg of CO_2-eq was used in this assessment. The software SimaPro 9.3.0.3, the datasets by Ecoinvent 3.7.1 [19] and for and the method IPCC 2021 GWP100 V1.00 was used to calculate the GWP.

6. RESULTS

Following the functional structure in Figure 1, the impacts of incorporating WBG in the design is discussed for the input and output filters, the energy buffer, the power processing unit and the cooling system; in relation to the variables that play a key role.

A possible impact of WBG devices on the charger's design is realising a higher switching frequency within the charger's topology. According to experts, a moderate increase of the switching frequency by a factor 3 is possible for the consumer chargers using WBG technology without exceeding costs through the use of complex topologies [2].

However, the switching frequency does not necessarily have to be increased; with WBG power semiconductors at the same switching frequency, positive efficiency effects can be taken into account in the charger's design. In this study this is exactly the case, the 60W Si-Ref charger has a switching frequency of 60 kHz and the 60W WBG has 52 kHz.

6.1. Impact of WBG on Power electronic filters

The increase in frequency reduces the required volume and weight of the filters, because the value of the passive components is in theory inversely proportional to the switching frequency [3]. When the switching frequency increases by a factor 3, the size of filters is reduced to basically 1/3. Castellazzi [3] indicate though that at 4 times higher switching frequency, the filters size is only reduced by a factor of 2, due to different effects e.g., in the inductors (core losses etc.). Filters, like the input filter (common mode), could also increase in size, e.g., due to more EMI noise, to conform EMC compliance [2].

The relative contribution of the input filter is 3,5% for the 60W Si-Ref charger; and 6,4% for the 60W WBG charger. This means that the relative contribution of the input filter has almost doubled. In contrast, the weight of the output filter has decreased significantly. The relative contribution of the USB-C's output filter is 1,8% for the 60W Si-Ref charger, but only 0,3% for the 60W WBG charger.

6.2. Impact of WBG on the Energy buffer

According to experts, the use of WBG power semiconductor should not have a significant impact on the energy buffer [2]. In the case of the chargers with the flyback topology, the two DC capacities, the flyback input and flyback output capacities were considered.

This was confirmed in the case of the chargers, where no major impact on the energy buffer (capacitors) was detected in the two products disassembled. The relative contribution of the energy buffer is 6,8% for the 60W Si-Ref charger, and 8,2% for the 60W WBG charger, so very similar proportion in relation to the weight of the chargers itself.

6.3. Impact of WBG on the Cooling system

The size of the cooling system is related to the efficiency of the device, the more energy is lost during energy conversion, the larger the heat sink must be to dissipate the heat. If a high power density of the charger is to be achieved by a high switching frequency, the switching losses per unit time, and thus the total losses, will also increase [3, 4, 11]. The losses not only occur in the power semiconductor devices. In other components e.g., in the power electronic filters or the transformer also losses occur, that are dissipated as heat without the need of a heatsink. According to industry experts, a reduction of 50% of the heatsink size (for cooling the power semiconductor devices) can be achieved for the chargers [2].

The 60W Si-Ref charger uses power semiconductors with a TO-220 housing, and conventional aluminium heatsink, with 19,60g in weight. The 60W WBG charger with a GaN chip, has an SMD housing and a steel sheet heatsink (with 8,15g in weight), which seems also serving as EMC shielding. In this case, the weight and the material of the cooling system is reduced by more than half.

6.4. Impact of WBG on the Power processing unit

In general, a charger uses a transformer to process the power. In a flyback converter, the transformer serves as an energy storage. The higher the frequency, the more energy is transferred from the primary to the secondary side per time. Therefore, for the same amount of power, the necessary size of this energy storage decreases [11]. This means, that the size of this transformer is influenced by the switching frequency, in theory by the factor 1/f. In real terms a reduction of up to 50% [2] or even higher reductions [15] of the size could be achieved when using WBG.

However, for the two disassembled chargers the weight of the transformers is almost the same (60W Si-Ref 45,80g; 60W WBG 43,25g), which is not surprising, since they also have almost the same switching frequency. The relative contribution of the power processor as a whole result in 29,40% for the 60W Si-Ref charger; and 29,50% for the 60W WBG charger. Again, very similar proportion in relation to the weight of each charger itself.

6.5. Considerations

The effects on design estimated by experts [2], particularly on the size of key function blocks, are shown in Table 4.

Table 4: Estimated effect of WBG on the design of a charger [2]

Function block	**Change in size**
Input filter	+10% up to -50%
Power processing unit	up to -20% (core)
Energy buffer	No impact
Cooling system	up to -50%
Output filter	up to -50%
Remainder	No impact
Total	up to -30%

However, these individual functional blocks should not be considered as if they were alone and isolated from the effects of design on the rest. Table 4 is only showing an approximation and the possible ranges and trade-offs in size.

This paper mainly focuses on the impact on design by the use of WBG power semiconductors, more precisely, by their properties compared to e.g., a Si MOSFET. But there are many other factors impacting the design as well. For example, the impact of the component costs on the design cannot be dismissed. WBG power semiconductors are currently more expensive to procure than e.g., Si MOSFETs, but this cost disadvantage can be tried to offset by smaller passive components (inductors, capacitors) [2].

Another factor that cannot be neglected is the reliability and lifetime of GaN devices. Device manufacturers like Infineon give recommendations e.g., regarding spikes or peak switch voltage [20] to ensure a satisfactory lifetime of the devices. Such limits directly impact the design.

6.7. Impact of WBG on the product´s life cycle

A streamlined life cycle assessment was completed, to assess how the impact on design (e.g., changes in size of the functional blocks or properties like the charger's efficiency) due to the application of WBG influence the environmental impacts of the chargers along their life cycle.

Applying the estimations from Table 4 to the design of a 60W Si-Ref charger, shows that about 1,30 kg CO_2-eq could be reduced in the materials and manufacturing phases.

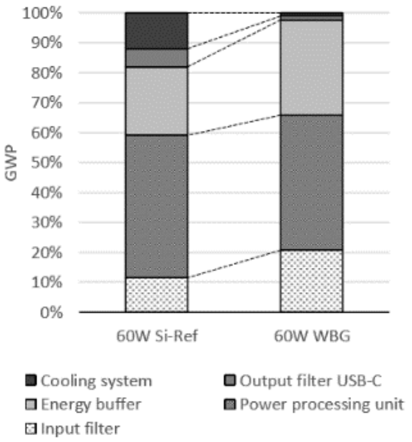

Figure 3: Environmental impact of material- and manufacturing phase for the 60W Si-Ref and 60W WBG chargers

6.7.1. Material- and Manufacturing phase

Figure 3 shows the GWP of the function blocks for the two 60W chargers, as % of the total GWP of materials and manufacturing. The WBG input filter shows +62,25% more GWP, and the energy buffer shows +25,17% more GWP than for the 60W Si-Ref, respectively. The GWP values are lower for the WBG USB-C output filter (-81,22%) and for the cooling system (-91,9%), than for Si-Ref. The 60W WBG power processing unit has a lower GWP (-14,50%) than the power processing unit for the 60W Si-Ref.

There are limitations and challenges in modelling the materials and manufacturing phases for the two 60W chargers with the available (environmental) datasets. This is the case for modelling the highly integrated power semiconductor Pi SC1933C GaN InnoSwitch, which was modelled as a controller.

6.7.2. Distribution phase

The dimensions and weight of the 60W Si-Ref charger and the 60W WBG charger were also considered for assessing the impact on their transport in the distribution phase of the life cycle.

The results in terms of the GWP are shown in Table 5 for a combined transport scenario for each charger. This combined transport scenario was calculated with distances of 4000km, 4000km and 900km for airplane freight, sea freight and lorry, accordingly.

As it can be seen, the smaller dimensions and lower shipping weight of the higher power density 60W WBG charger results in a lower GWP (-10,9%) in the distribution phase.

Table 5: Environmental impact (GWP) in the distribution phase of the two 60W chargers for selected transport scenarios

Charger	Transport	GWP
60W Si-Ref	0,69 tkm air 0,69 tkm sea 0,15 tkm lorry	0,55 g CO_2-eq
60W WBG	0,61 tkm air 0,61 tkm sea 0,14 tkm lorry	0,49 kg CO_2-eq

6.7.3. Use phase

The efficiency of the chargers during operation is not constant, as it depends on the charging current, which specifies the output power. A realistic load and charging scenario for a laptop was modelled, taking into account the power range during charging, and the resulting efficiency values.

The efficiency of the 60W Si-Ref charger is in the range from 70% to 88%, and for the 60W WBG from 83,5% to 94%.

The use phase was modelled with the electricity mix of Austria (0,329 kg CO_2-eq / kWh) for one charging cycle. The GWP is 3,59E-3kg CO_2-eq per charging cycle for the 60W Si-Ref, and 1,72E-3 kg CO_2-eq per charging cycle for the 60W WBG charger, respectively. The higher efficiency per laptop charging cycle of the 60W WBG charger results in a lower GWP (-52%) in the use phase per charging cycle.

7. DISCUSSION

7.1. GHG emissions at product level

A study by Navitas [5], focusing on 60W USB-C chargers, indicates that around 30% reduction of CO_2 emissions can be achieved in the material- and manufacturing phases through the use of WBG power semiconductors. The reductions are in the same range as those discussed with industry and academic experts, and reported in Table 4.

The contribution to the GWP in the materials and manufacturing phases for the two models analysed (see Figure 4) do not show such a significant difference, as both have approximately the same GWP (4,33 kg CO_2-eq for the 60W WBG charger and 4,43kg CO_2-eq for the 60W Si-Ref).

However, the 60W WBG charger includes a separate USB-A charging output, in addition to the USB-C. With about the same weight, size and resulting GWP, the functionality of the 60W WBG charger would be higher, compared to the 60W Si-Ref charger.

The declare unit considered was though one charging cycle of a laptop, which is only one type of function of the 60W WBG charger, and the one that gets 100% allocation of the GWP in the material- and manufacturing phase.

7.2. GWP Break-even analysis

To complement the analysis for the two chargers, a comparison of the GWP for given charging scenarios was completed. The results are shown in Figure 4, with the GWP values on the Y-axis and the number of laptop charging cycles on the horizontal X-axis.

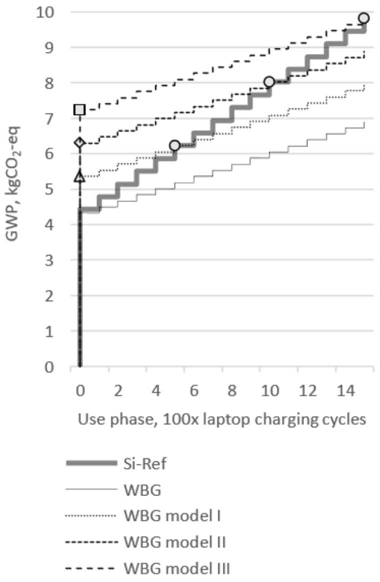

Figure 4: GWP break-even analysis for the 60W Si-Ref and the 60W WBG charger, including three additional (WBG) scenarios

The GWP of the material and manufacturing phases of the chargers is marked as initial value (vertical line at charging cycle “0”). The solid lines show the GWP of charging cycles (multiples of 100) for the 60W Si-Ref and the 60W WBG chargers. These are labelled Si-Ref and WBG, respectively.

Figure 4 shows three additional scenarios labelled WBG model I, WBG model II and WBG model III. These represent different ranges of WBG power semiconductor material and manufacturing phase impacts to achieve absolute GHG emission reductions, when compared to the 60W Si-Ref charger, for a given number of laptop charging cycles.

For charging cycles between 500 to 1500 the ranges of GWP due to WBG power semiconductor material and manufacturing phase (production of the WBG device itself) are compared with the reference Si-based charger. When the charger operates for 1500 charging cycles, the GWP of the materials and production of the WBG device must be lower than 3,50 kg CO_2-eq. If the WBG charger would be used for only 500 charging cycles, the GWP of the materials and production of the WBG device should be lower than 1,64 kg CO_2-eq.

In a study by Navitas [5] the impact on design and the corresponding CO_2 emissions reductions are attributed to the reduction of the size of the printed circuit boards and the electronic components (by 50% saving in the power semiconductors [5]).

The 3 WBG models I, II and III consider a worst case where the GWP of semiconductor production (the device itself) is initially higher than the GWP for the Si-Ref power semiconductor. Considering the GHG emission reductions reported in the Navitas study [5], the GWP values due to production could be lower than the ranges actually modelled for the WBG models I to III, with an even lower overall GWP along the life cycle of the 60W WBG charger.

7.3. GHG emissions at device level

Compared to Si power semiconductors, which are based on the material silicon (282.000 parts per million in earth’s crust [21]), the production of gallium nitride power semiconductors (GaN) requires the metal gallium (only 19 parts per million in earth’s crust [21]). GaN power semiconductors show the higher switching speed capabilities, lower resistance and a higher operating temperature compared to standard silicon power semiconductors [10]. Due to these advanced properties, WBG power semiconductor devices (e.g., GaN HEMTs) requires smaller wafer area than standard Si power semiconductors (e.g., Si MOSFET).

Taking a normalized value for the chips per wafer area for a silicon MOSFET, GaN is able to reach 2.4 and SiC even 4.3 [14] due to the superior properties of WBG materials (e.g., higher breakdown electric field, higher thermal conductivity etc.). This means that the dies can be much smaller for the same application, with further reduction in the environmental impact of the (semiconductor) die production. The Navitas study reports the environmental impacts due to materials, manufacturing and transport of WBG being up to 4 times lower compared to a Si power semiconductor (Si FET) with today’s production, and could be 10 times lower in the future as bigger wafer diameters are fabricated [5].

Not only the die of the power semiconductor could become smaller, also the manufacturing process to build up the device can be different, from a vertical structure (e.g., Si MOSFET) to lateral structure (current GaN devices e.g., GaN on Si HEMT), using less layers [22]. While current lateral GaN devices already show advantages over standard Si based power semiconductors, the full potential of GaN is only exploited by vertical structures (GaN JFET). Such devices could get up to 90% smaller [22] than pure silicon devices (e.g., Si MOSFET). Future environmental savings potential can be clearly derived from such further minimization of the active semiconductor structure.

8. SUMMARY

The guiding questions set out at the start of this paper are discussed as follows.

How does energy efficiency impact the overall environmental performance of WBG based power converters?

Figure 4 shows the importance of a higher energy efficiency in relation to the GWP indicator for the material and manufacturing phases of the life cycle of the two chargers investigated. The GWP break-even points occur at different number of charging cycles - the longer and intensively the WBG charger is used the more relevant its charging efficiency. A higher energy efficiency is a leaver to reach a lower, total GWP along the whole life cycle. In this study, the electricity mix of Austria (0,329 kg CO_2-eq / kWh) was taken into account for the use phase; with a different energy mix, the results change accordingly.

Are the life cycle phases materials, manufacturing, and the use phase the only relevant ones in terms of (selected) environmental impacts (e.g., GWP)?

Even when the two 60W chargers analysed show only a minor difference in weight and volume, the results discussed show that the use of WBG in the semiconductors has effects on the GWP of the material, manufacturing, and the use phases of the life cycle. This small differences also even have an effect on the GWP of the distribution phase (see Table 5). Chargers currently available in the market, with (high) power density of about 16 W/in^3 or higher, show higher reductions in terms of GHG emissions in the distribution phase.

By further increasing the power density, the reduction of GHG emissions in the distribution could be higher, but exhausting the power density potential must not take place at the expense of reducing efficiency in the use phase. More specifically, if the charger is designed to be more compact, at the expense of efficiency, lower GWP for the transport could be achieved, but the poorer efficiency would also have a detrimental effect in the GWP of the use phase. A small charger with low efficiency would become too hot during use, because the heat losses dissipated along the surface of the charger [4].

This also means that shifting the environmental burdens from one life cycle phase to another shall be avoided, which also means that the limits and interactions of these life cycle phases and the product features, (e.g., power density and efficiency) shall be well understood.

Can the use of WBG technology achieve a significant reduction of (selected) environmental impacts along the entire life cycle (e.g., GWP)?

Figure 4 shows that a reduction of GHG emissions over the entire life cycle is possible through the use of WBG technology for the selected WBG charger, especially in the use phase.

Previous work showed that GaN and SiC power semiconductors have a higher environmental impact per wafer in the materials and manufacturing phases when compared to Si [20]. Nevertheless, due to the outstanding properties of WBG semiconductors, the amount of the semiconductor material in the device itself (e.g., GaN HEMT) is lower than for Si power semiconductors. This brings also an attenuating effect on the environmental impact and could even lead to an actual reduction even in the material and manufacturing phase [5].

9. ACKNOWLEDGEMENTS

This work is supported by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology: https://nachhaltigwirtschaften.at/de/iea/technologieprogramme/4e/iea-4e-tcp-pecta.php. The energy and environmental related Life Cycle Assessment (LCA) aspects of power electronic circuits and devices using new WBG technology for selected applications is one of the current areas of work of the Power Electronic Conversion Technology Annex - PECTA (https://www.iea-4e.org/pecta/tasks), under the umbrella of the Energy Efficient End-Use Equipment collaboration program of the International Energy Agency -IEA - 4E; (https://www.iea-4e.org). Our gratitude goes also to the experts interviewed for this study, providing us their invaluable industry insights and their own data.

10. REFERENCES

[1] Infineon Technologies Austria AG. *Wide Bandgap Semiconductors (SiC/GaN)*. 02.08.2022]; Available from: https://www.infineon.com/cms/en/product/technology/wide-bandgap-semiconductors-sic-gan/.

[2] PECTA Industry and Academic Advisory Board, *Expert Interviews*. 2022.

[3] Castellazzi, E.G.A., *Tradeoff Study of Heat Sink and Output Filter Volume in a GaN HEMT Based Single-Phase Inverter*. IEEE TRANSACTIONS ON POWER ELECTRONICS,, 2018. **33**(6).

[4] Infineon Technologies Austria AG *A full-GaN solution for high power density chargers and adapters*. 2022.

[5] Navitas Semiconductor, *Sustainability Report 2021*. 2021.

[6] Ecoinvent Database v3.8 2022; Available from: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/.

[7] Sphera / GaBi extension database XI: Electronics 2022; Available from: https://sphera.com/.

[8] Vogel, D.B., *Das Energiepotenzial von WBG-Halbleitern ist enorm*, in *Energie Rundschau*. 2020.

[9] Ivkovic, M., *Three design freedoms enabled by SiC technology*, in *AVNET*. 2021.

[10] Ma, C.T. and Z.H. Gu, *Review on Driving Circuits for Wide-Bandgap Semiconductor Switching Devices for Mid- to High-Power Applications*. Micromachines, 2021.

[11] Navitas Semiconductor. *Gallium Nitride: The Next Generation of Power*. 28.07.2022]; Available from: https://navitassemi.com/gallium-nitride-the-next-generation-of-power/.

[12] GaN Systems. *GaN Systems Shrinks 140W Fast-Charger by 50%*. 06.02.2023]; Available from: https://gansystems.com/newsroom/140w-fast-charger-shrinks/.

[13] GaN Systems. *GaN: Taking Charge of Your Power Needs*. 06.02.2023]; Available from: https://gansystems.com/newsroom/taking-charge-of-your-power-needs/.

[14] Masoud Beheshti Texas Instruments, *Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC.* Analog Design Journal, 2020.

[15] Guy Moxey RichardsonRFDP and Woolfspeed, *A Designers Guide to Silicon Carbide Power*. 2020.

[16] Iannuzzo, F., *Modern Power Electronic Devices*. 2020: Institution of Engineering and Technology.

[17] Glaser, S., *own photo*. 2022.

[18] AIT Austrian Institute of Technology GmbH *Measurements were carried out in their laboratory by AIT under the supervision of M. Makoschitz*. 2022.

[19] Ecoinvent Database v3.7.1 2021; Available from: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7/.

[20] Infineon Technologies Austria AG *Reliability and qualification of high-voltage CoolGaN™ GIT HEMTs*. 2022.

[21] Franz, R., *How Will We Get the Gallium?*, in *Electronic Design*. 2016.

[22] Emilio, M.D.P. *Vertical GaN Devices – the Next Generation of Power Electronics*. 07.02.2023]; Available from: https://www.eetimes.com/vertical-gan-devices-the-next-generation-of-power-electronics/.

Appendix 3

Paper 3 - Glaser, S.; Feuchter, P.; Diaz, A., "Looking beyond energy efficiency - Environmental aspects and impacts of WBG devices and applications over their life cycle," EPE - PECTA, 2023.

4E Power Electronic Conversion Technology Annex PECTA

European Conference on Power Electronics and Applications
Aalborg DENMARK
EPE'23
September 4th > 8th, 2023
ECCE EUROPE
www.epe2023.com

Looking beyond energy efficiency - Environmental aspects and impacts of WBG devices and applications over their life cycle

S. Glaser (1), P. Feuchter (1) and A. Díaz (2)

1 TU WIEN, Vienna University of Technology; Lehargasse 6, 1060 Vienna, Austria
2 ECODESIGN company engineering & management consultancy GmbH; Schwindgasse 4, 1040 Vienna, Austria
Tel.: +43 1 58801 30751 (S. Glaser)
E-Mail: sebastian.glaser@tuwien.ac.at; philipp.feuchter@tuwien.ac.at; diaz@ecodesign-company.com
URL: www.ecodesign.at; https://www.ecodesign-company.com

Acknowledgements

This research has been conducted as part of the Task “Energy and environmetral related Life Cycle Assessment” of the Power Electronic Conversion Technology Annex -PECTA[1]. Authors are thankful to PECTA experts from the industry and academic advisory board for their contributions.
This research is partly funded by the Austrian Federal Ministry of Technology, Climate Protection, Mobility and Innovation (BMK).

Keywords

Wide bandgap; Silicon Carbide (SiC); Gallium Nitride (GaN); Environment; Life Cycle Analysis (LCA); End of Life (EoL); criticality; critical raw material (CRM);

Abstract

The environmental aspects and impacts of wide band gap (WBG) materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) in specific end-use electronic applications and products have not yet been fully investigated. The design trade-offs and comparison of WBG with classic Silicon based technology for the same applications, with a life cycle thinking perspective, are only starting to emerge. In general, policy-makers are unaware of the impacts and benefits of WBG semiconductor devices, and governments do normally have limited access to independent and well-founded expertise in this field. Therefore, it is challenging for policy makers to foresee and evaluate the future impacts and benefits of this technology. With increased knowledge and evidence it will be possible to consider appropriate policy responses.
This PECTA research is following a life cycle thinking perspective, which covers three relevant life cycle stages of WBG technology 1) the raw material supply and manufacturing of WBG components; 2) the design effects of WBG on applications and their use, and 3) the End of life (EoL) of WBG semiconductor devices, specially looking at fate, and availability (or criticality) of SiC and GaN. The different elements of the research methodology and selected results, especially

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[1] The Power Electronic Conversion Technology Annex - PECTA was launched in 2019 and aims at collecting and analysing information about new wide band gap (WBG) based power electronic devices; coordinating internationally acceptable approaches to promote WBG-based power electronics, and developing greater understanding and action amongst governments and policy-makers. More information is available under: https://www.iea-4e.org/pecta/about/.

considering the energy and greenhouse gas emissions (GHG), are discussed along these three relevant life cycle stages. Some additional information on impacts e.g., in the distribution phase are also included. Supporting the development towards a circular economy, recommendations for policy makers are presented. Results from this PECTA research are also more extensively documented in recent publications [1, 2].

1 Introduction

“Life cycle thinking” has moved from its origins in academic circles and in some companies, to become a powerful approach to design and develop sustainable products. Life cycle thinking in this context refers to the description of the stages or phases in a product´s life, from the extraction of raw materials to the production, distribution, use and End of life, as shown in Figure 1.

Figure 1: Life cycle stages of a product [3].

Life cycle thinking helps support the efforts of companies and organization in creating communications intended to inform different stakeholders. It is also an important approach in the policy development process. For example, under the Integrated Product Policy (IPP) of the European Commission, life cycle thinking and the use of Life Cycle Assessment (LCA) are considered to provide a solid framework for evaluating the potential environmental impacts of products along their entire life cycle. In some instances though, more consistent, robust data and agreement on LCA methodologies are needed, to continue using LCA as a tool for the evaluation of new technologies, products and systems.

This part of PECTA´s research is focusing on new wide band gap (WBG) semiconductor technology. WBG based semiconductors allow higher blocking voltages, faster switching speeds and increased operating temperatures, which enable smaller and lighter systems by a reduction of the size of active and passive components and cooling equipment. Moreover, WBG integrated power electronic systems come with an improved efficiency if operated with the same switching frequency as Silicon (Si) based devices. The most common argumentation about the benefits of using such WBG power semiconductors emphasizes the power-savings and energy efficiency gains, and the resulting reduction of greenhouse gas emissions. It has been estimated that a wide-spread adoptation in excess of 90% of such emerging power electronic systems utilizing WBG semiconductor devices would lead to a substantial annual decrease in electricity use worldwide. Some of the sectors with the highest expected energy efficiency gains enabled by WBG semiconductors are photovoltaic systems (inverters), consumer electronics (power supplies), data centers (uninterrupted power supplies), and the electric automotive sector (drive-trains and charging infrastructure). WBG power devices have a potential to provide a paradigm shift in performance and energy efficiency over the well established and mature Si power devices.

Silicon Carbide (SiC) and Gallium Nitride (GaN) are the most mature WBG materials so far. Considering each one separately, power electronic applications could in principle benefit from the low overall losses of SiC unipolar devices, from their higher operating temperature, switch/diode integration and from higher switching speed (albeit with certain adjustments to accommodate the new devices and their characteristics). SiC technology still shows limitations for its maximum adoption, particularly in terms of power density, high temperature, parasitic inductance and common mode noise at higher switching frequencies due to lack of suitable packaging for SiC devices. The role of GaN devices can be seen as complementary to Si and SiC, with most GaN devices not being suitable for higher voltage applications such as grid connected power electronics, due to their lower voltage rating and lower thermal performance

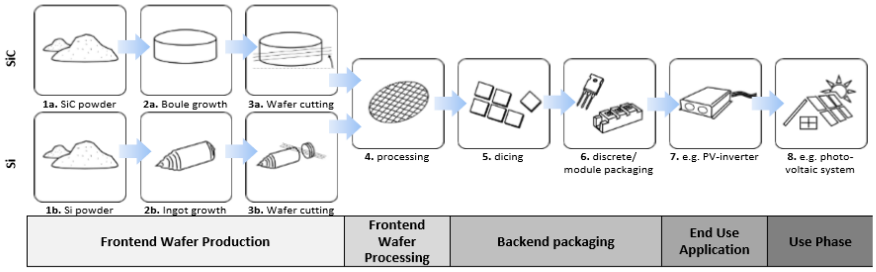

Figure 2: Life cycle stages of Si and SiC power semiconductors [1].

compared to SiC devices. However, the possibility of greatly reduced weight and volume means more integrated, compact hardware designs with GaN devices, better suited for consumer and mobile products, with significant growth across a range of sectors particularly power supplies and automotive applications [4].

LCA studies on WBG devices and electronic applications allow evaluating the trade-offs of these emerging technologies, as well as better management of compliance, coupled with innovation and differentiation, which are important to show the features and benefits from WBG in specific sectors. The future argumentation is setting the use of LCA to also demonstrate carbon neutrality, and this includes the evaluation of upstream and downstream scopes of the organizations i.e., the impacts along the supply chain and the logistics, the use, and EoL of the products. Energy and materials management also play a role in the transition towards more Circular business models, where materials are kept in cycles, maintaining the value of resource inputs and minimizing the generation of wastes.

2 Scope and methodology

The scope of this investigation lies on the energy demand and environmental impacts of using WBG technology for selected applications along important life cycle stages. That is, based on the life cycle thinking, authors examined in detail the stages of raw material supply and manufacturing, the design and use, and the End of life of WBG devices. The first step is the description of the life cycle stages of WBG, looking at the same time in more details to the data availability, to start the data collection process. Literature on LCA of electronic devices served as the basis, and in a more in-depth analysis, information was compiled for SiC and GaN. Literature research was performed by prompting peer reviewed research databases, web search and by further snowballing relevant literature.

Concerning the **raw material supply** of WBG afformentioned literature research was done to explain scarcity and criticality aspects as well as environmental aspects of sourcing these materials. Results are presented in section 3.1 of this paper.

Regarding the **manufacturing** of WBG semiconductors, more specifically, the differences between the energy demand in the production of SiC and the conventional Silicon semiconductors, the most important process paths in each case were analyzed and described for data collection, as shown in Figure 2.

Data on the energy demand and other process variables for the **front-end wafer production, front-end wafer processing, back-end packaging** and **the final application** were obtained from diverse literature sources, and from interviews with industry and academic expert [5]. Estimates of the differences in energy inputs for each process, and the magnitude of such differences in relation to the potential energy savings were caculated by modeling in Microsoft Excel the case of a SiC based PV inverter as end-use application [1]. A discussion of results for manufacturing is presented in section 3.2 of this paper.

As already mentioned, the use of WBG semiconductors allowing higher switching frequency might have a strong impact on product design, enabling for example, a reduction of material use, size and weight in selected end-use applications.

The scope of a second piece of PECTA´s research recently published [2] addressed the effects of using WBG devices on the design, size, performance and environmental impacts of power supplies (USB-C chargers) for electronic devices such as notebooks, mobile phones. Evaluating the effects and trade-offs is helpful to inform policy-makers in the field of energy efficiency and product policy. A discussion of results for this application and its use, is presented in section 3.3.

Due to reductions in weight, savings in the **distribution** phase were exemplary determined for different charger applications. The results, in terms of the impact indicator Global Warming Potential (GWP), are shown in Table 3 (in section 3.4), for a realistic transport scenario for various chargers. This transport scenario was calculated combining 4000 km airplane freight, 4000 km sea freight and 900 km lorry.

With regard to the **End of life**, different EoL routes for WBG have been investigated, as shown in Figure 3. The focus included aspects such as the current and possible future WBG recycling technologies, reuse potential, the challenges and advantages (for recycling and reuse), the existing legislation and gaps on legislation and reasons for WBGs reaching their end of life. Guiding questions were defined and adressed through the aforementioned literature research, and discussed with experts from academia and industry during structured interviews [5, 6]. Results are presented in section 3.5.

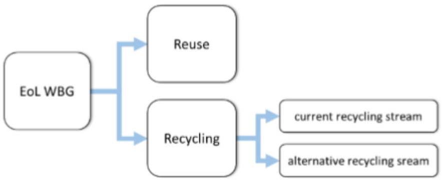

Figure 3: investigated EoL routes for WBGs.

3 Results and discussion along the WBG life cycle stages

The results presented in this chapter are discussed in sub-section, following the Life Cycle stages for WBG devices. The environmental impacts of the life cycle stages manufacturing, distribution, application, and use phase are strongly related to the product design. The other life cycle stages are discussed with a stronger material-based perspective.

3.1 Raw Materials supply

SiC is based on the element Silicon, the second most abundant element on earth after Oxygen (28% of the earth's crust [7]). The total resources and reserves for silicon are not quantified worldwide but are estimated to be "very large" [7]. Silicon is reduced from Silica quartz, but only a small fraction of around 7% of high purity Silica quartz, mainly sedimentary quartz, is available in suitable volume, quality, and amenability to be used for high-end applications such as semiconductors or photovoltaic panels [8].

The annual demand for Silicon in the EU was estimated for around 400 kt in 2020 and has the potential to double up to 800 kt in 2050 [9]. 63% of EU's Silicon demand is reported to be imported from non-EU countries, like Norway, China, and Brazil [8]. [10] reported that high purity Silicon would be sufficiently available in the EU and has a potential to be supplied by the EU itself, but the energy intensive production is currently mainly concentrated to countries with cheaper available energy, like Norway, where electricity generation is based on hydropower and geothermal energy. China on the other hand, has a huge unused overcapacity for Silicon production that could more than double today's global production amount of around 3 Mt, which leads to unfair market conditions and a global material supply risk [9]. The production of semiconductors in China is bound to the existing electricity mix of this country, which relies mainly on fossil fuels [11], and as such less advantageous from the point of view of the GHG emissions.

GaN is based on the element Gallium, whose abundance on earth is low compared to Silicon (0,0019% of the earth's crust [12]). Gallium is produced exclusively as a by-product of other metals production, mainly Aluminium and Zinc [8]. The available Gallium in Bauxite (Aluminium ore) reserves are estimated between 210.000 t and 700.000 t, in Sphalerite (Zinc ore) reserves its around 1000 t [13]. Up to 95% of the potential Gallium reserves in Bauxite and Zinc ores remain unused due to missing technologies, refining infrastructures, or economic reasons [10, 13].

The annual demand for Gallium in the EU was estimated for around 40 tonnes in 2016 and is expected to increase 17-fold by 2050 [14]; EU's import reliance for Gallium is reported to be 97%, which translates into a supply disruption risk for the EU [12]. China has more than 80% of the worldwide low-purity Gallium production capacity [15]. The last Gallium production plant in Europe was closed, due to high operating costs and intense competition of cheaper material supplies from third countries, mainly China [8, 16]. Globally, Gallium production is mainly concentrated in China, and this situation is not expected to change in the future [13]. [16] pointed out that in Europe there are no significant Gallium resources that could be mined, although some unrecovered deposits in Poland are reported. Silicon and Gallium are both rated as critical raw materials (CRM) by the European Union [17].

For the application in semiconductors, Gallium and Silicon need to be purified to "electronic grade", with ultra-high purity between 6N and 11N [12, 18, 19]. Consequently, several purification steps are necessary to reduce all impurities to a specific threshold, which makes the production of these electronic grade materials a very energy intensive process [19].

3.2 Manufacturing of WBG devices

Less than a decade ago [4], semiconductors with WBG technology were still a niche. Accordingly, the manufacturing technology is not as advanced as for conventional (Silicon) MOSFETs or IGBTs, which, among others, have been the basics of power electronics for decades.

Market forecast sees a tremendous growth for WBG devices (Revenues of 10 billion for SiC and 1,8 billion for GaN by 2027) [4].

This growth promise spurred further research and investment, and production is continuously improving (e.g., transition to 200mm wafers), in terms of cost and quality as well as on the reduction of environmental impact due to less production losses, better utilization of production lines or new production technologies. As example, SmartSic® from Soitec, makes better use of the energy-intensive SiC substrate by at least a factor of 10, compared to the conventional wafer made of SiC substrate. This novel process saves about 70% of the CO_2 emissions in SiC wafer production [20].

In the current state of art of SiC devices production, important aspects and variables with regard to environmental impacts and energy consumption in the manufacturing were the growth of SiC boules, the smaller wafer diameters, and a significantly smaller usable height (thickness of the SiC boule). The process yields, in terms of material losses for the growth of the boule, the kerf losses from wafer cutting, and the processing losses due to faulty dies, all have an influence on the environmental and energy "burdens" of the (SiC) die leaving the production line [1].

WBG power semiconductors show advantegous electrical and physical properties (e.g., faster switching, lower resistance, higher operating temperature) compared to standard Silicon power semiconductors [21]. Therefore a smaller die is required for a given functionality of the power semiconductor, meaning more devices can be produced from one wafer. This leads directly to further savings in materials, manufacturing energy and environmental impacts.

For SiC, the smaller die size is advantageous considering that growing the SiC boule is the most energy intensive step in the manufacturing [1]. Die size reductions of about 50% can be reached [4]. Other research states 56% in their study [22], or even up to 77% assumed by industry [23]. For GaN, die size reductions of 58% are stated [23]. Further improvements to the semiconductor structure result in further die size reduction. For example, the use polycristalline ultra high conductivity SiC substrate (as in SmartSic®) brings 20% further reduction of dies (compared with conventional SiC dies) [20].

Besides the die size reduction, also the device design is different, from a vertical structure (e.g., Si MOSFET) to lateral structure (current GaN devices e.g., GaN on Si HEMT), using less layers [24], which reflects again the use of less materials, manufacturing energy and lower the environmental impacts. Alternative innovative device designs (GaN JFET), could get up even to 90% smaller in the future, compared to pure Silicon devices (e.g., Si MOSFET) [24].

In summary, it can plausible to estimate that e.g., the environmental impact of WBG due to energy demand in production may be the same or even lower than for conventional power semiconductors. Similar estimations and trends were also presented in an recent industry driven study [22], which reported GWP values for a Si IGBT Module of 26,4kg CO_2-eq, and for a SiC MOSFET Module, with 11 kg CO_2-eq [25].

3.3 Application design and Use

In general, the effect of using WBG on the design of applications brings the possibility to increase the switching frequency, which enables size and weight reductions of components to increase e.g., the power density and costs, an improved energy efficiency, or even both, a increased power density and higher efficiency [2]. Typical GWP savings due to smaller components are shown in Table 1. Power converters are likely to have the highest environmental impact during the use phase. A clear example is the PV inverter Fronius Tauro, which shows 72% of the total product carbon footprint (PCF) in the use phase [26], the PV inverter Fronius Symo GEN24 plus, withh 43,9% of the total PCF in the use phase [27]. The case study of consumer chargers, also showed that approximately 50% of the GWP is caused by the losses in the use phase of a conventional Si based charger (for 1500 laptop charging cycles, with the electricity mix of Austria) [2].

Table 1: Environmental savings due to WBG's impact on design [2].

Component	**Typical application[2] (g)**	**Reduction in weight [4] (g)**	**Global Warming Potential (GWP) savings (kg CO_2-eq) [28]**
Transformer	45,08	9,00	0,05
Common mode filter inductor	4,99	-0,50	-0,02
Differential mode filter capacitor	1,07	0,21	0,01
Heat sink, aluminium	19,60	9,80	0,18

It is obvious that higher efficiency leads to energy savings in the use phase. The higher these savings are, and the higher the specific environmental impact of the country's energy mix (e.g., in kg CO_2-eq / kWh), the greater the environmental savings in the use phase. See Table 2 for results of GWP for laptop chargers, as an example for a consumer application.

The energy savings for a single charging event of a laptop seems to be rather small, but as there are billions of laptops used worldwide, the overall, possible GWP reductions of switching to more

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[2] 65W USB-C charger based on conventional Si technology

efficient charging equipment should not be neglected.

There is also great potential for savings in industrial power conversion applications. A study focusing on a traction application for trains reports losses due to SiC based modules of 0,21 kWh and for Si based modules of 0,50 kWh for a typical commuter train drive cycle. Savings of 59% of lossess are stated [29]. Extrapolated to a year, 1,49MWh is saved per module [29]. This would lead to reductions of the GWP of 840,50 kg CO_2-eq, for the case of a use phase with high voltage electricity mix of Germany [28].

Table 2: Energy and GWP savings in the use phase, laptop charger as WBG application.

Application	**Efficiency [2]**	**Energy consumption [2]**
Si based charger	70% - 88% during charging cycle	10,921 Wh losses per charging cycle
GaN charger	83,5% - 94% during charging cycle	5,231 Wh losses per charging cycle
Energy savings due to implementing WBG application		5,690 Wh losses per charging cycle
GWP savings - use in Austria [28]		1,87E-03 kg CO_2-eq
GWP savings - use in China [28]		6,05E-03 kg CO_2-eq

3.4 Distribution

If applications are transported over long distances (e.g., Asia to Europe) and in large quantities, the environmental impact of transport tend to become relevant. Higher power density e.g., due to the application of GaN, enables the design of smaller devices. This reduction in volume and weight leads to a reduction of environmental impact in terms of GWP, in the transport phase. This is illustrated for the case of different types of chargers, in Table 3.

Results clearly show that, the newer chargers incorporating GaN, achieve higher power densities, leading to GWP reductions in the transport phase of about 30%, between the Nano II 751 and the Neue Dawn. Secondly, it is once again clear that user behaviour is also relevant, i.e. over dimensioning of the charger should be avoided (see Nano II 713 and Nano II 715). Finally, multifunctionality reduces the need to purchase and use different chargers, which also leads to reductions in resources use, environmental impacts and waste, when considering the system on a larger scale.

Table 3: Environmental impact (in terms of GWP) for the distribution phase of selected chargers [28].

Charger	**Anker Nano II 713 [30]**	**Anker Nano II 715 [30]**	**Anker Nano II 735 [30]**	**Neue Dawn [31]**
Technology	GaN	GaN	GaN	Si
Functionality	1x USB C	1x USB C	2x USB C 1x USB A	1x USB C
Power (W)	45	65	65	60
Weight (excl. packaging (g)	73	119	141	171
Power density, approx. values (kW/dm^3)	0,80	1,00	0,90	0,39
Distribution scenario, GWP (kg CO_2-eq)	0,23	0,38	0,40	0,55

3.5 End of Life

Although the End of life is also dependent on the type of product (end-use application), it is likely that electric and electronic equipment and products are treated in the same process and disposal routes. Today, around 42% of waste electrical and electronic equipment (WEEE) is properly collected and prepared for recycling within the European Union. Worldwide this rate only reaches 17% [32]. The collected WEEE generally enters a mechanical separation and sorting facility, where hazardous and removable parts (e.g., batteries, cables, housings) are separated before shredding. The shredded materials are sorted using eddy current separators, magnets, and optical sorters, generating material fractions containing plastics, ferrous and non-ferrous metals. Dust and residues include other unsorted materials. The material fractions might be further recovered in pyrometallurgical plants or sent to incineration, depending on their content type and concentration [33].

Printed circuit boards (PCBs) in WEEE carry materials such as Gallium, Silicon, and Tantal as well as precious metals like Platinum and Gold. PCBs commonly end-up in pyrometallurgical processes, most of which are optimized for the production of large quantity metals like Copper, and therefore, are not suitable for recovering materials in lower concentrations, as is the case for Gallium and Silicon. Si and Ga usually find their way into the dusts or in slags, and their recycling is therefore less viable [34]. In essence they (Si and Ga) are generally lost, or remain in recovered materials as impurity, lowering its quality [33, 35].

Missing information on the material composition of (electronic) product hampers the targeted collection, the sorting, and recycling at EoL [10]. Aside from the EU's WEEE Directive, legislation especially concerning the EoL treatment for **critical raw materials**, or for semiconductor materials, is in general missing [36]. The recycling rate of Gallium at EoL is reported to be below 1%, for Silicon the recycling rates are unknown [15]. Current electric and electronic design as well as the EoL legislation do not seem to support the recycling of SiC and GaN. Gallium from GaN is difficult to recycle due to its water, acid and alkali resistance at room temperature. For GaN and other Gallium containing wastes streams there are hydro, pyro and bio-metallurgical recycling methods, with the hydrometallurgical recycling being the preferred method to recover Gallium from electronic waste in China [37]. The hydrometallurgical and bio-metallurgical methods successfully tested with GaN containing LEDs at laboratory scale, to extract Gallium, are presented in [38]. Environmental aspects and impacts associated with the use of chemicals in the hydrometallurgical process were not investigated in PECTA. In the EU project gagendta+, an innovative electrohydraulic fragmentation (EHF) was used to separate electronic components (ECs) from EoL PCBs. Sorting and pyrolysis processes were used to generate more homogenous and higher concentrated fractions from these ECs. These fractions were further refined in a process chain of biosorption and electrolysis. Gallium and Indium could be extracted with optimized solution formulations. Results from treating real EoL materials are though still missing [33].

According to experts [5], GaN and SiC semiconductors from WEEE are considered to be too contaminated to be recycled as "electronic grade" materials. The recycling and purification is not seen as environmentally advantageous, as the energy demand will increase exponentially the more dispersed and contaminated the materials are [12, 39, 40].

Research activities focusing on the recycling of EoL SiC at EoL are lacking. Some research publications deal with recycling the waste from the production of SiC [41, 42], others deal with Silicon recycling from EoL photovoltaic panels (where a much higher concentration and mass of Silicon is given) [43]; but these topics are not directly in the scope of the PECTA Task. The re-use of new WBG materials has also been investigated in this PECTA task. Extensive documentation of the economical re-use of WBG has not been found. Two major issues associated to reuse EoL WBGs are, first the energy and labor-intensive reverse logistics and disassembly (which might be also an issue from an environmental perspective) and second, the remaining service lifetime and reliability. Concerning the functionality of EoL semiconductors (with WBG), specific tests would need to be performed, bringing a challenge in terms of different product designs, and labor intensity, as automatic reliability tests work best with uniform product designs. Permanently tracking these components while they are in use would require additional hardware and thus (critical) resources, in addition to the extra weight. According to experts, the devices are generally designed to last as long as they should, and are not designed for a second use [5]. The desoldering process of electronic components (ECs) might cause damage to components, which makes their reuse even more difficult. Even if components could be collected properly, desoldered without any damage and tested to confirm specific functionality, the "receiving" (new) product needs to be designed for incorporating this re-used component, and there must be a market for electronic products with reused components. If dissassembled components lead to a bigger product design [44] the use of WBG could promote the development of easier reuseable parts, due to its smaller size, compared to common Si based technology.

Summary and outlook

The approach of the PECTA task presented in this paper is to develop a better understanding of the environmental aspects and impacts along the whole life cycle of WBG materials and devices using this new technology. The most widespread WBG materials Silicon Carbide (SiC) and Gallium Nitride (GaN) are in the focus, and the trade-offs that result from their adoption when replacing Si semiconductors are as well of interest for policy-makers.

Since conducting a full LCA requires extensive and solid data resources, which often are not available due to the state of development of WBG, the task followed a streamlined LCA, but also modelled energy demand for specific applications and scenarios, following a life cycle thinking approach.

Research has shown that WBG based semiconductors are advantegous from an environmental perspective, compared to Si based semiconductors. Smaller die sizes of SiC (and GaN) devices seem to balance out the higher energy demand for their SiC boule production compared to conventional Si boule production. The smaller and more efficient dies allow for smaller and more efficient units. Reduction of GHG emissions have been demonstrated in the distribution, application and use phases.

High purity Gallium and Silicon, essential for WBG semiconductors, are increasingly sourced from non-EU countries, and the trend is likely to continue for these materials. As no economical recycling technologies to recover these materials exist, and also no economic reuse of WBG components is performed, it is even more essential to use WBG containing products as long as possible, reducing the need for new Silicon and Gallium. In March 2023, the European Critical Raw Materials Act [14] was introduced with the aim of diversifying and strengthening the EU's CRM supply chains and promoting the circular economy of these materials [14]. Based on own research and industry experts inputs [6], the authors present the following points for policy makers to consider with respect to a wider adoption of WBG technology.

Which could be the measures to increase the interest and the possibilities for research, and development of WEEE collection and recycling facilities, and secondary material markets, especially for more efficient and economical CRM recycling technologies?

How would a sustainable products regulation (e.g., the EU ESPR [45]) consider important design aspects to ease the disassembly and separation of CRMs at the product’s End of Life, to improve the sorting of waste streams and increase CRM material concentrations in waste streams?

Measures, such as the use of secondary CRMs or a universal chip design, would need to be evaluated, also in terms of a higher reusability of components. Could information in the EU Digital Product Passport [45] further support collection and recycling of power electronic components, to increase the probability of reuse of such componnets with WBG and CRMs content. What are the most effective measures to improve the knowledge base on availability and recoverability of CRMs in waste streams?

The expansion of PECTA´s work for a new term of 5 years will allow its experts to continue investigating some of these aspects in more detail and disseminating key results.

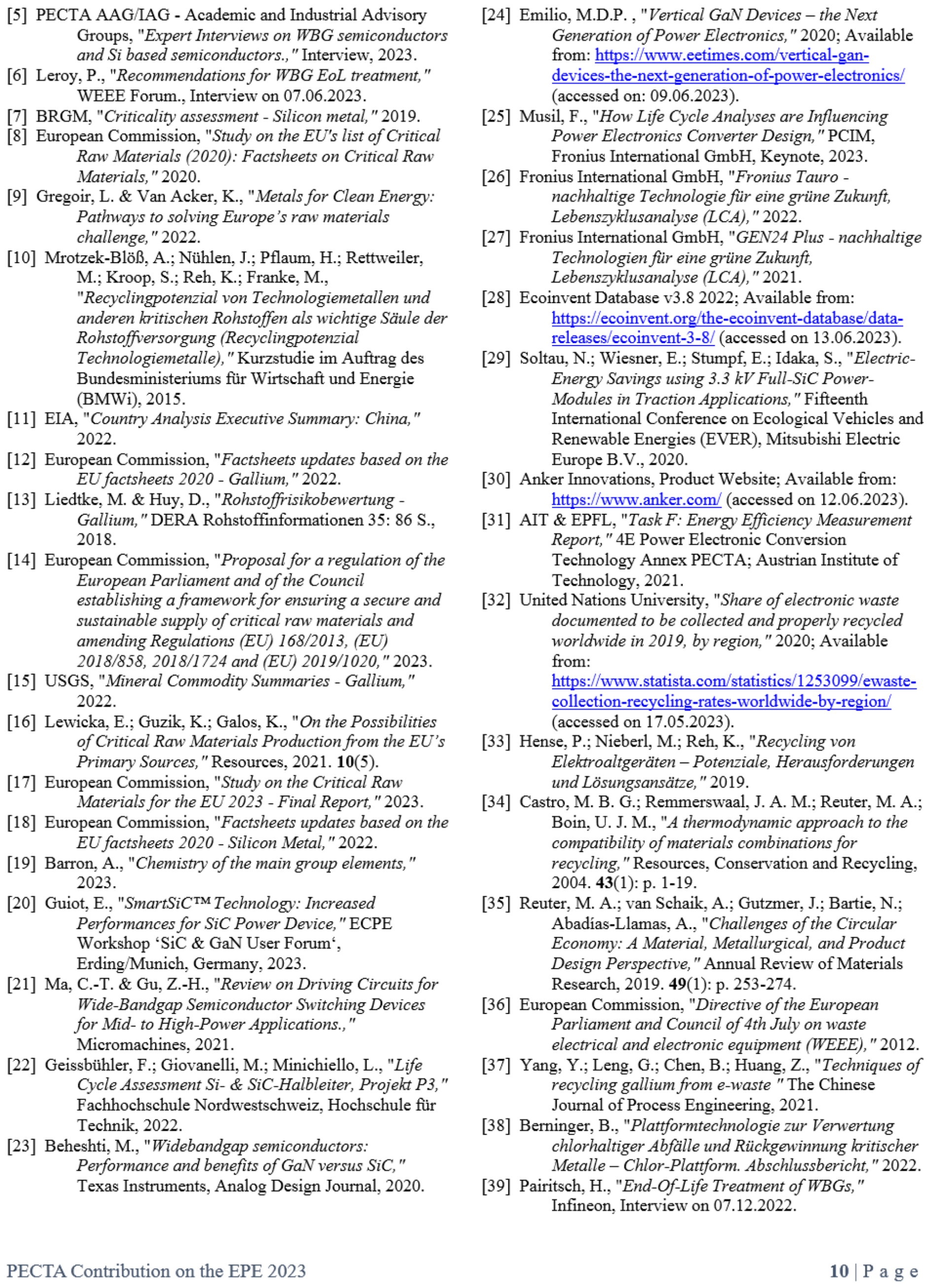
References

[1] Diaz, A.; Schmidt, S.; Glaser, S., "*A "life cycle thinking" approach to assess differences in the energy use of SiC vs. Si power semiconductors,"* 2021.

[2] Glaser, S.; Diaz, A.; Makoschitz, M., "*Design aspects and environmental impacts of using Wide Band Gap based semiconductor technology in consumer chargers,"* 2023.

[3] Diaz, A., "*Energy and environmental related Life Cycle Assessment (LCA),"* internal document, 2021.

[4] Markoschitz, M.; Krischan, K.; Bergmann, P.; Diaz, A.; Brüninger, R., "*Wide Band Gap Technology: Efficiency Potential and Application Readiness Map,"* 4E Power Electronic Conversion Technology Annex (PECTA), 2020.



[5] PECTA AAG/IAG - Academic and Industrial Advisory Groups, "*Expert Interviews on WBG semiconductors and Si based semiconductors.,*" Interview, 2023.
[6] Leroy, P., "*Recommendations for WBG EoL treatment,*" WEEE Forum., Interview on 07.06.2023.
[7] BRGM, "*Criticality assessment - Silicon metal,*" 2019.
[8] European Commission, "*Study on the EU's list of Critical Raw Materials (2020): Factsheets on Critical Raw Materials,*" 2020.
[9] Gregoir, L. & Van Acker, K., "*Metals for Clean Energy: Pathways to solving Europe's raw materials challenge,*" 2022.
[10] Mrotzek-Blöß, A.; Nühlen, J.; Pflaum, H.; Rettweiler, M.; Kroop, S.; Reh, K.; Franke, M., "*Recyclingpotenzial von Technologiemetallen und anderen kritischen Rohstoffen als wichtige Säule der Rohstoffversorgung (Recyclingpotenzial Technologiemetalle),*" Kurzstudie im Auftrag des Bundesministeriums für Wirtschaft und Energie (BMWi), 2015.
[11] EIA, "*Country Analysis Executive Summary: China,*" 2022.
[12] European Commission, "*Factsheets updates based on the EU factsheets 2020 - Gallium,*" 2022.
[13] Liedtke, M. & Huy, D., "*Rohstoffrisikobewertung - Gallium,*" DERA Rohstoffinformationen 35: 86 S., 2018.
[14] European Commission, "*Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020,*" 2023.
[15] USGS, "*Mineral Commodity Summaries - Gallium,*" 2022.
[16] Lewicka, E.; Guzik, K.; Galos, K., "*On the Possibilities of Critical Raw Materials Production from the EU's Primary Sources,*" Resources, 2021. **10**(5).
[17] European Commission, "*Study on the Critical Raw Materials for the EU 2023 - Final Report,*" 2023.
[18] European Commission, "*Factsheets updates based on the EU factsheets 2020 - Silicon Metal,*" 2022.
[19] Barron, A., "*Chemistry of the main group elements,*" 2023.
[20] Guiot, E., "*SmartSiC™ Technology: Increased Performances for SiC Power Device,*" ECPE Workshop 'SiC & GaN User Forum', Erding/Munich, Germany, 2023.
[21] Ma, C.-T. & Gu, Z.-H., "*Review on Driving Circuits for Wide-Bandgap Semiconductor Switching Devices for Mid- to High-Power Applications.,*" Micromachines, 2021.
[22] Geissbühler, F.; Giovanelli, M.; Minichiello, L., "*Life Cycle Assessment Si- & SiC-Halbleiter, Projekt P3,*" Fachhochschule Nordwestschweiz, Hochschule für Technik, 2022.
[23] Beheshti, M., "*Widebandgap semiconductors: Performance and benefits of GaN versus SiC,*" Texas Instruments, Analog Design Journal, 2020.
[24] Emilio, M.D.P. , "*Vertical GaN Devices – the Next Generation of Power Electronics,*" 2020; Available from: https://www.eetimes.com/vertical-gan-devices-the-next-generation-of-power-electronics/ (accessed on: 09.06.2023).
[25] Musil, F., "*How Life Cycle Analyses are Influencing Power Electronics Converter Design,*" PCIM, Fronius International GmbH, Keynote, 2023.
[26] Fronius International GmbH, "*Fronius Tauro - nachhaltige Technologie für eine grüne Zukunft, Lebenszyklusanalyse (LCA),*" 2022.
[27] Fronius International GmbH, "*GEN24 Plus - nachhaltige Technologien für eine grüne Zukunft, Lebenszyklusanalyse (LCA),*" 2021.
[28] Ecoinvent Database v3.8 2022; Available from: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/ (accessed on 13.06.2023).
[29] Soltau, N.; Wiesner, E.; Stumpf, E.; Idaka, S., "*Electric-Energy Savings using 3.3 kV Full-SiC Power-Modules in Traction Applications,*" Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), Mitsubishi Electric Europe B.V., 2020.
[30] Anker Innovations, Product Website; Available from: https://www.anker.com/ (accessed on 12.06.2023).
[31] AIT & EPFL, "*Task F: Energy Efficiency Measurement Report,*" 4E Power Electronic Conversion Technology Annex PECTA; Austrian Institute of Technology, 2021.
[32] United Nations University, "*Share of electronic waste documented to be collected and properly recycled worldwide in 2019, by region,*" 2020; Available from: https://www.statista.com/statistics/1253099/ewaste-collection-recycling-rates-worldwide-by-region/ (accessed on 17.05.2023).
[33] Hense, P.; Nieberl, M.; Reh, K., "*Recycling von Elektroaltgeräten – Potenziale, Herausforderungen und Lösungsansätze,*" 2019.
[34] Castro, M. B. G.; Remmerswaal, J. A. M.; Reuter, M. A.; Boin, U. J. M., "*A thermodynamic approach to the compatibility of materials combinations for recycling,*" Resources, Conservation and Recycling, 2004. **43**(1): p. 1-19.
[35] Reuter, M. A.; van Schaik, A.; Gutzmer, J.; Bartie, N.; Abadías-Llamas, A., "*Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective,*" Annual Review of Materials Research, 2019. **49**(1): p. 253-274.
[36] European Commission, "*Directive of the European Parliament and Council of 4th July on waste electrical and electronic equipment (WEEE),*" 2012.
[37] Yang, Y.; Leng, G.; Chen, B.; Huang, Z., "*Techniques of recycling gallium from e-waste* " The Chinese Journal of Process Engineering, 2021.
[38] Berninger, B., "*Plattformtechnologie zur Verwertung chlorhaltiger Abfälle und Rückgewinnung kritischer Metalle – Chlor-Plattform. Abschlussbericht,*" 2022.
[39] Pairitsch, H., "*End-Of-Life Treatment of WBGs,*" Infineon, Interview on 07.12.2022.

[40] Schäfer, P., "*Recycling – ein Mittel zu welchem Zweck?,"* Springer Spektrum, 2022.

[41] Gopala Krishna Murthy, H. S., "*Evolution and present status of silicon carbide slurry recovery in silicon wire sawing,"* Resources, Conservation and Recycling, 2015. **104**: p. 194-205.

[42] Hossain, S. T.; Johra, F. T.; Jung, W.-G., "*Fabrication of Silicon Carbide from Recycled Silicon Wafer Cutting Sludge and Its Purification,"* Applied Sciences, 2018. **8**(10).

[43] Peplow, M., "*Solar Panels Face Recycling Challenge,"* ACS Cent Sci, 2022. **8**(3): p. 299-302.

[44] Pamminger, R.; Glaser, S.; Wimmer, W.; Podhradsky, G., "*Guideline development to design modular products that meet the needs of circular economy,"* CARE Innovation 2018, 2018.

[45] European Commission, "*Proposal for a regulation of the european parliament and of the council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC,"* 2022.