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

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Keywords

Wide bandgap; Silicon Carbide (SiC); Gallium Nitride (GaN); Environment; Life Cycle Analysis (LCA); energy efficiency; Greenhouse Gas (GHG); Global Warming Potential (GWP); End of life (EoL); criticality; critical raw material (CRM).

Abstract

The environmental aspects and impacts of wide bandgap (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 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 considering the energy demand and greenhouse gas

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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/.

[2] https://www.bmk.gv.at/.

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.

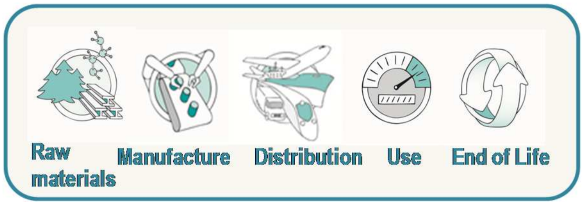

Figure 1: Life cycle stages of a product [3].

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 adoption 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 (PV inverters), consumer electronics (power supplies), data centers (Uninterrupted power supplies), motor systems (Variable speed drives), and the electric automotive sector (Drive-trains and charging infrastructure). WBG power devices have the 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 technologies for SiC devices (encapsulation materials, joining techniques, etc.) and resulting reliability limitations [4]. 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 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 End of life 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.

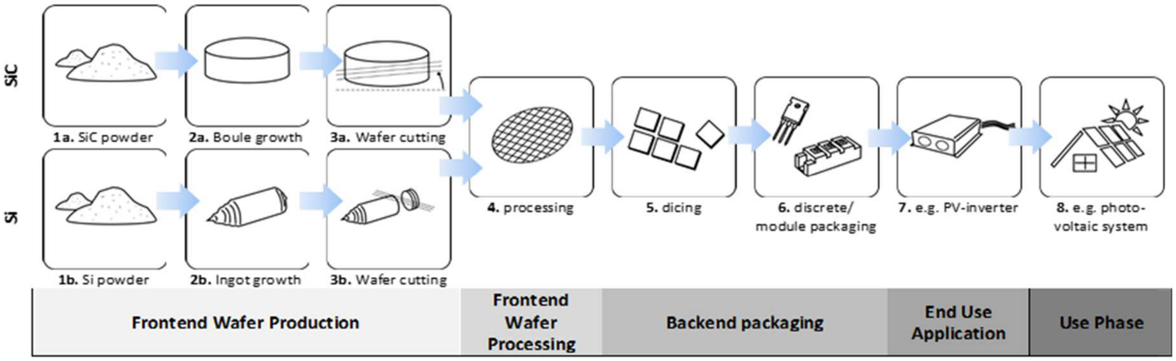

Figure 2: Life cycle stages of Si and SiC power semiconductors [1].

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. 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 describing 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 reviewing relevant literature.

Concerning the **raw material supply** of WBG, afformentioned literature research was done to explore 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 photovoltaic (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 and mobile phones. Evaluating these 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 is presented in section 3.3.

An example of the **distribution** phase is presented for different chargers using a realistic transport scenario. The results, in terms of the impact indicator Global Warming Potential (GWP), are shown in Table 3, and discussed in section 3.4. 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 were 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.

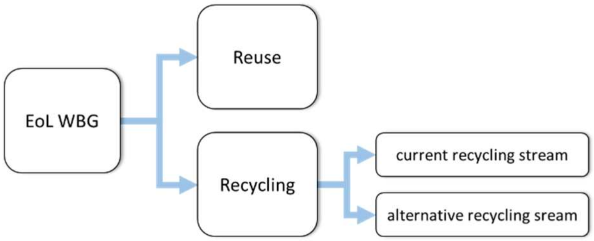

Figure 3: Investigated EoL routes for WBG.

3 Results and discussion along the WBG life cycle stages

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

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 and quality to be used for high-end applications such as semiconductors or photovoltaic panels [8].

The annual demand for Silicon in the EU was estimated at around 400 kt in 2020, with the potential to double up to 800 kt by 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 in countries with cheaper available energy, like Norway, where electricity generation is based on hydropower and geothermal energy. China on the other hand, has a large, unused overcapacity for Silicon production which could more than double today's global production 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 is less advantageous from the point of view of the GHG emissions.

GaN is based on the element Gallium, which is much less abundant on earth compared to Silicon (0,0019% of the earth's crust [12]). Gallium is produced exclusively as a by-product from the production of other metals, mainly Aluminium and Zinc [8]. The available Gallium in Bauxite reserves (Aluminium ore) is estimated between 210.000 t and 700.000 t, in Sphalerite reserves (Zinc ore) it is 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 to be around 40 tonnes in 2016, and is expected to increase 17-fold by 2050 [14]. EU's reliance on imported 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 emerging countries, mainly China [8,16]. Globally, the production of Gallium 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 the 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, semiconductors with WBG technology were still a niche [4]. Accordingly, their 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 US$ for SiC and 1,8 billion US$ 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 production process saves about 70% of the CO_2 emissions in SiC wafer production [20].

In the current state of the art for the production of SiC devices, 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 environmental impacts. Alternative innovative device designs (GaN JFET), could become even 90% smaller in the future, compared to pure Silicon devices (e.g., Si MOSFET) [24].

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

Table 1: Impact of adopting WBG on design and on Global Warming Potential [2].

Component	**Typical application[3] (g)**	**Reduction in weight [4] (g)**	**Global Warming Potential savings (kg CO_2-eq)** using data from [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

Power converters are likely to have the highest environmental impact during the use phase. As example, the LCA information about the PV inverter Fronius Tauro shows that 72% of the total product carbon footprint (PCF) is due to the use phase [26], and for the PV inverter Fronius Symo GEN24 plus, 43,9% of the total PCF occurs in the use phase [27].

It is obvious that higher efficiency leads to energy savings in the use phase. The higher these savings are, and the higher the GHG emissions of the country's energy mix (e.g., in kg CO_2-eq / kWh), the higher the savings in the use phase. The recent PECTA study of consumer chargers also showed that approximately 50% of the total GWP is caused by the losses in the use phase of a conventional Si based charger, for a use scenario of 1500 charging cycles of a laptop, using the electricity mix of Austria [2]. Table 2 shows selected results for the laptop chargers, including the energy and GHG emsissions savings. The energy savings for a single

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[3] 65W USB-C charger based on conventional Si technology.

charging event seems to be rather small, but as there are billions of laptops used worldwide, the overall, possible GWP reductions of switching to more efficient charging equipment should not be neglected.

Table 2: Impact of adopting WBG on the energy consumption, energy efficiency and Global Warming Potential of chargers in the use phase.

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		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

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

3.4 Distribution

As products are transported over longer distances (e.g., Asia to Europe) and in large quantities, the environmental impact of transport tends to become relevant. Higher power density e.g., due to the adoption of GaN, enables the design of smaller devices. This reduction in volume and weight leads to a reduction of environmental impact of transport in terms of GHG emissions. This is illustrated in Table 3 for different types of chargers. The results show that, the newer chargers incorporating GaN achieve higher power densities, leading to GWP reductions in the distribution phase of about 30%, between the Nano II 715 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: Impact of adopting WBG on the distribution phase of chargers.

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	1xUSB C	1x USB C	2xUSB C 1xUSB 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

* Scenario calculated combining 4000 km airplane freight, 4000 km sea freight and 900 km lorry; using data from [28].

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 of 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 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]. 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+[4], 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, GaN and SiC semiconductors from WEEE are considered to be too contaminated to be recycled as "electronic grade" materials [5]. 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 on the economical re-use of WBG has not been found. Two major issues associated to reusing EoL WBG semiconductors 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 possibly 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

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[4] https://gagendta.de/index.php/gagendta/

electronic components (ECs) might cause damage to components, making their reuse even more difficult. Even if electronic components could be collected properly, desoldered without any damage and tested to verify specific functionality, the “receiving” (new) product needs to be designed for incorporating this re-used component. From a technical point of view, modularity at the printed circuit board level could be a solution for this kind of issues. Modular PCBs lead to bigger product designs [44], due to the required additional connectors, but the use of WBG could balance this increase in size due to its smaller components and higher achievable power density of the topology, 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 [1,2].

PECTA research has shown that WBG based semiconductors are advantegous from an environmental perspective, compared to Si based semiconductors. As indicated before, it is plausible that the environmental impacts of WBG due to energy demand in the production phase are the same or even lower than for conventional power semiconductors, considering the same functionality provided. The 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 producing WBG semiconductors, are increasingly sourced from non-EU countries, and the trend is likely to continue for these materials. Current electric and electronic design as well as the EoL legislation do not seem to support the recycling of SiC and GaN. As no economical recycling technologies to recover these materials exist, and no economic reuse of WBG components is performed, it becomes even more essential to use WBG containing applications 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 questions, which will be further investigated in PECTA, in relation to developing posible policy measures to support 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 components with WBG and CRMs content?

What are the most effective measures to improve the knowledge on the availability and recoverability of CRMs in waste streams?

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

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