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

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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/.

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

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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.

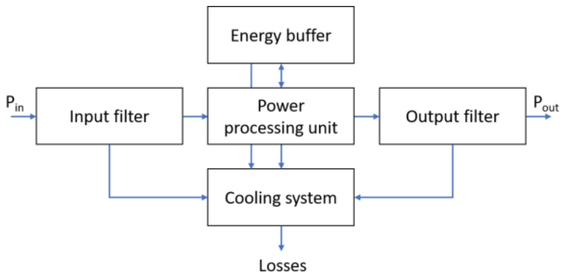

Figure 1: Functional structure of power converters, [adapted from [16]]

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.

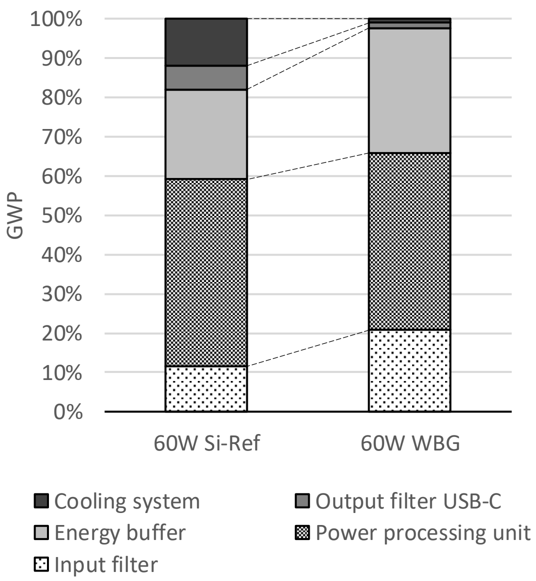

Figure 3: Environmental impact of material- and manufacturing phase for the 60W Si-Ref and 60W WBG chargers

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.

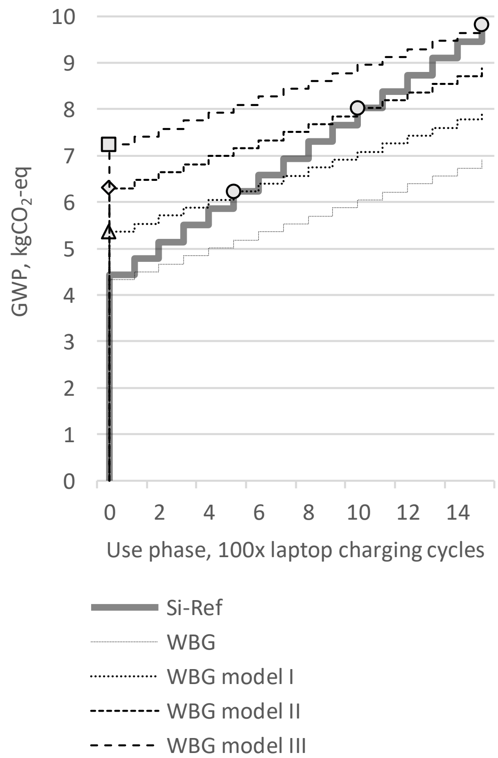

Figure 4: GWP break-even analysis for the 60W Si-Ref and the 60W WBG charger, including three additional (WBG) scenarios

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].

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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/.